Co-published by
Institute of Fluid-Flow Machinery
Polish Academy of Sciences
Committee on Thermodynamics and Combustion
Polish Academy of Sciences

http://www.imp.gda.pl/archives-of-thermodynamics/

ARCHIVES
OF THERMODYNAMICS

Possibilities of energy storage in residential photovoltaic installations - Overview

Karol Mzyk[a*]

[a]Cracow University of Technology, Department of Energy, al. Jana Pawła II 37, 31-864 Kraków, Poland
[*]Corresponding author: karol.mzyk@doktorant.pk.edu.pl

Received: 30.05.2023 revised: 16.01.2024; accepted: 31.03.2024

Abstract

World widely, efforts of governments and industry focus on the global sustainability. Facing global warming and rapidly growing electricity demand, it is crucial to develop technologies that will allow humanity use planet resources in the most efficient way, which is possible. Energy storage systems are vast and common concepts nowadays, concerning also small residential energy systems with renewable energy sources like photovoltaic installations. This paper describes different solutions for this issue. Characteristics of mentioned methods include basic features and values, advantages and disadvantages, estimated investing (CAPEX) and operating (OPEX) costs for the investors and issues related with environment like efficiency and emissions. As researched in the document, current technologies base on well-known solutions implemented in residential installations but also there is also possibility to develop new methods and combine few of them to use any possible energy surplus, later when it is needed the most. Description of various energy storage system includes both technical and commercial aspects. As most of storage applications differ from each other, choosing proper energy storage system implies economic and environmental benefits. The review has provided sufficient information to conclude that there is no one-size-fits-all solution to store electricity. Suitable solution should be selected based on size of the installation, geographical conditions as well as economic possibilities. For examined energy storage systems there is still necessity of further research and development but overview of those presented in the article, makes it possible to deduce comparison and conclusion.

Keywords: Energy storage; Residential photovoltaic installations; Technical and commercial aspects

Vol. 45(2024), No. 2, 213–230; doi: 10.24425/ather.2024.150867

Cite this manuscript as: Mzyk, K. (2024). Possibilities of energy storage in residential photovoltaic installations – overview. *Archives of Thermodynamics*, 45(2), 213−230.

1. Introduction

The research field of electricity storage systems has significantly advanced in the last few years. However, there are still research gaps that need to be examined and improved. One of the key issues is an efficiency-cost ratio; while many storage technologies currently coexist, their efficiency and cost-effectiveness still require further development. Additionally, durability and environmental impact of energy storage systems are also aspects under constant research, as it is crucial to deeply understand a long-term durability and environmental footprint (e.g., materials used, recycling of the whole system, etc.). To investigate these topics, further experimental research is required. As the globe transitions towards cleaner energy solutions (e.g., photovoltaics, wind turbines), integration of storage systems with renewable energy installations remains quite a challenge. Nowadays, the electricity grid is filled with renewable energy sources. Most of these installations are launched in households, creating a new role in the Energy Market – that of a prosumer. In the past, the electricity grid was very straightforward. There were two types of grid users: producers (big energy concerns and companies) and consumers. Due to this simplicity, the energy system used to be stable most of the time. Of course, there were critical situations for some electricity grids, causing blackouts on various dates, like on August 14, 2003. At 04:00 PM (during time of increased energy consumption, discussed in paragraph 3.1.), Northeastern states of the USA (Ohio, Michigan, Pennsylvania) and Southeastern parts of Canada (Ottawa, Montreal, Toronto) faced one of the biggest power grids shut down in the 2 000 s. Power shortage lasted for 2 days for most of the regions, but some of these areas lacked electricity for 4 days until systems were back to normal state. These circumstances contributed to at least 11 deaths [1]. It caused great disturbance in the US stock market and affected an enormous volume of trades and great price losses. This example shows how national energy systems impact the lives of every citizen, as well as national markets.

As mentioned before, modern energy systems are full of renewable energy sources, relying heavily on weather conditions. The higher the percentage of that kind of installation, the more unstable the grid is. In Europe, a trend can be noticed. Most countries must meet the requirement of renewable installation percentage in the whole energetic production system. In the case of Poland, the European Parliament expects that as a part of the European Union, the percentage of renewable energy production will rise to 32% by 2030 [2]. The newest reports show that by 2020 Poland has reached 16.13% [3] of this criterion (energy produced by renewable sources) according to Central Statistical Office. This score is questionable for the European Parliament because of one of the assumptions, which states that wood used to generate heat at households in furnaces and fireplaces counts as a renewable energy source. Discussion about the accuracy of this assumption is not a subject of this paper, but this decision helped to avoid penalties. On the other hand, these requirements forced the government to make progress in terms of a cleaner energy system. It can be accomplished within two independent levels. Macro scale level, which consists of the modernisation of existing power plants (mostly based on coal) by building new turbogenerator units powered by gas or other alternative fuels like RDF (Refuse-Derived Fuel). The micro-scale level is more individual, and it is based on households and small renewable energy installations. This led to many “citizen-friendly” campaigns, which allowed the building of photovoltaic installations or solar thermal collectors in many households. These programs were extremely popular and led to greater awareness of consumers and creating of prosumers – electricity grid users with possibilities to generate and consume electricity in a scale of their own demand.

Photovoltaic installation is one of the most common small systems integrated on a small scale, which is because all the campaigns help investors to fund that kind of power source. Before the law revision planned for the year 2022, refund and terms of billing allowed to achieve SPBT (Simple Payback Time) in the range of 6−7 years [4]. Updated terms of billing extended this value to about 11 years, which means that PV installation working on terms after revision will take 4−5 years more to pay back than before the revision.

These two examples of the USA electricity blackout and the Polish share of renewable energy are the main reasons why energy storage is such a critical issue in modern energy systems. An efficient energy storage system could make national grids more stable (macro-scale) and make small PV installations even more profitable for investors (micro-scale). Discussion about various methods lasts for decades, and this paper brings an analysis of one traditional and two alternative approaches. The conducted review aims to describe, confront and escalate mentioned research gaps with possible solutions, providing insights for researchers, policymakers as well as industry stakeholders. Based on the review, the identification of the best practices and implementation examples will be described. Secondly, the evaluation of opportunities and threats of each solution will be analysed. Lastly, providing some innovative solutions may be a sufficient choice after further research.

2. Review materials and methodology

The rapid growth of intermittent renewable energy sources, such as wind and solar, has led to increased interest in electrical energy storage. The research is based on a literature review of various journal articles, conference publications and chapters of books. All of the mentioned materials referred to electricity storage systems subject.

The methodology of this review includes a collection of available scientific research, articles and reports. The below steps have been taken to proceed with the paper. The first step involved the definition of what aspects of electricity storage need to be investigated in this research. To provide a comprehensive analysis, both technical and economic principles of different applications were described. Next, based on reliable scientific databases, such as Science Direct, Research Gate, and Google Scholar, a suitable bibliography has been selected and analysed. Publications have been selected based on date, subject matter, innovation, and reliability.

The review begins with an indication of electricity consumption data according to databases provided by third parties and also based on personal research data, as well as a description of Photovoltaic installations used in residential systems. With basic values of energy consumption defined, elaboration of chosen energy storage systems has been conducted, including both technical and economic advantages and disadvantages, as well as possibilities of implementation for analysed residential systems.

3. Household energy consumption and systems

Before focusing on energy storage analysis, unified starting conditions and assumptions shall be determined. A semi-detached house domiciled by a family of 4 people, with a standard power connection of 16 kW, has been selected as a basic model for this research. This means that electricity is used to power basic home appliances and induction hob. Households’ energy consumption is the main factor which is required for this study. In this research, energy consumption data from several Polish households has been used to show characteristics and crucial points of higher and lower energy demand.

3.1. Energy consumption characteristics

Figure 1 shows the average electricity demand of the studied sample household throughout the year. The maximum power (around 3 kW) is used for a brief period of time due to simultaneous usage of some of the most energy demand equipment (e.g., induction hub, dryer, electric kettle). Most of the time during the entire year, consumption is lower and caused by devices like lighting and fridges.

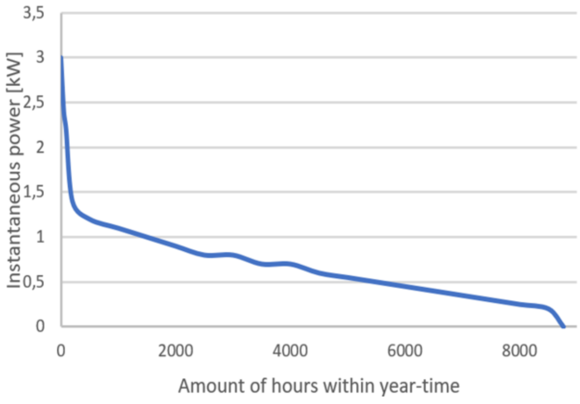

Fig. 1. Number of hours of instantaneous power demand.

Figure 2 represents the average energy daytime consumption. This characteristic is closely related to the activity of residents and their work type.

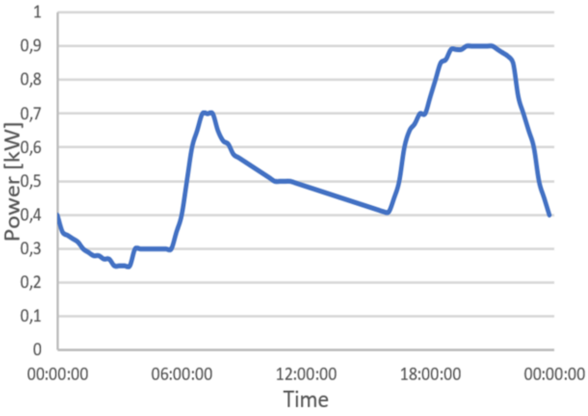

Fig. 2. Instantaneous power demand during daytime.

In the case of our example (and it is the most common example), the Fig. 2 shows us two peak points. At 06:00, energy consumption rises as residents prepare to leave for work, and after 07:30, energy demand signifyingly drops. The next peak is affiliated with work return and evening activity in households. Data from Figs. 1 and 2 allows us to estimate the average annual energy demand, which is equal to 4 500 kWh.

3.2. Photovoltaic installations used in households

This paper focuses on statistics and data from Poland (Central Statistical Office). In November 2020, photovoltaic (PV) installation power in Poland reached 3 954.96 MW [3] (Central Statistical Office, 2022). However, another 1 000.00 MW is assumed as the power of small household micro-installation [5], which indicates the total power of PV systems in Poland at the level of 4 954.96 MW. Energy production from PV installation increased from 710.67 GWh (in 2019) to 1 957.92 GWh, which shows the significant development of this energy source. According to recent studies and simulations [6], if 30% of all households in Poland have independent small PV installations (about 6 kW), analysis shows a significant reduction of maximal hourly energy demand for those households because of demand covered by PV installation, no power grid. In the case of months from April to August, this demand drops accordingly by 50, 23, 85, 68 and 19 MWh. This scenario where 30% of households own small PV installation, reduces the demand by about 50% in May and by 7% in December [6]. Considering the fact that rural households consume about 7% of total energy consumption in Poland, even though the scenario shown above will impact national energy demand, it can result in a sample standard deviation ratio at a level from 13.5% to even 20% (in December).

However, even with this scenario, there is still one major problem, which will be even more significant if the percentage of household PV installations increases above 30%. This problem is energy surplus, as an increasing amount of residential PV installations will lead to excess energy being generated on the national power grid scale. PV installations have similar conditions on vast regions that can cause major grind disturbances. The reason of this excess energy production is a fact that it is impossible to cover all of the PV energy production during the day with consumption, as it is shown in Fig. 2. Figure 3 shows how increasing number of PV installations in households (in percentages) will correspond with energy surplus production ration (energy surplus to energy produced by system).

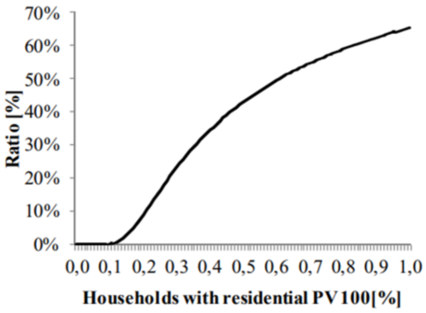

Fig. 3. Energy surplus to generated energy ratio of PV system depending on number of PV installations [7].

Considering the situation where 10% of households use PV installation to generate electricity according to Fig. 3, there is no impact on energy surplus exported to the energy system grid and examined ratio is close to 0. However, above 10% this impact rises greatly and for theoretical conditions where 100% of households use PV, ratio reaches about 70%. Therefore, 70% of generated energy is exported to grid as a surplus. As PV installations are small and are used by 10% of households' energy surplus can be easily used and controlled by national power grid. The more of these installations are plugged to power grid, the more notable this energy surplus issue become and one of the most promising solutions for this problem seem to be energy storages.

4. Energy storage different technologies and benefits

Every single fossil fuel can be determined as an energy storage, even simple kettle filled with water has a features of energy storage. Wherever there is energy conversion to different type of energy and this energy is not consumed instantly (or where there is a process which consume energy to cover demand or lower the energy consumption at different time or place) – we can speak of energy storage. Several global factors driven interests to this prosses, two of them are: increased energy consumption each year with increasement of energy production from renewable sources of energy and lower cost and greater access to storage technologies like lithium-ion batteries. In most of the countries (also in Poland) pumped hydropower technology is a main form of storage significant amount of energy. In Poland, there are currently six primary pumped-storage power stations: Żarnowiec (716 MW), Porąbka-Żar (500 MW), Solina-Myczkowce (200 MW), Żydowo (167 MW), Niedzica (92 MW), and Dychów (90 MW) power plants. Its role in power grid is really simple and well-known from 1907 (in Switzerland). During production peaks electricity is used to pump water to upper reservoir, usually located hundreds meter above lower reservoir (also supply water source) – e.g. in Żarnowiec, the reservoirs have a level difference of 125−108 meters. During increased demand of electricity this process is reversed and whole facility works as a normal water power plant. Water flow through the pipelines in Żarnowiec during the discharge cycle can reach 700 m^3/s.

Energy storage equipment and applications are increasingly popular topic during scientific conferences and also commercial presentations. In Google Scholar 17 900 articles for phrase "energy storage" has been found in years 2000−2005. In period of 2015-2020 this number of papers changed to 75 600. These solutions play relevant part in power grid optimization by cutting peaks and filling valleys of energy demand. Storages also lowers energy surplus to generated energy ration in almost every renewable energy source (not only PV installations). Increased economic efficiency and also flexibility of small residential energy installation can be also achieved. Implementation of wide range of small, decentralized storages will require also "smart grids" solution where one centralized national power grid is replaced by many deferent smaller power grids in a local scale. Even nowadays, with such cheap costs of lithium-ion batteries (in September 2021, the cost of lithium-ion batteries was approximately in the range of 100 to 200 per kilowatt-hour ($/kWh)) there is still problem to use efficient technical solution too store greater amounts of energy or smaller (residential) amount of energy, simultaneously and without huge value of CAPEX (Capital Expenditures). To consider cost of stored energy, a few parameters need to be described. First of which is cost of maximum power output ($/W) – related with CAPEX and cost of energy produced ($/Wh) – related with OPEX (Operating Expenditures). Along these it is also crucial to consider system lifetime and recharge cycles amount determined by energy losses and material properties. Final factor describing energy storage technology is cost of maintenance and reliability, both of them can determine usage of particular technology to different sectors like national power grid, industrial power grid, residential power grid. Last but not least factor – round-trip efficiency and it is percentage of electricity put into the storage, which is later retrieved, the higher this factor is the less amount of energy is lost within storage process.

A few types of energy storages technologies can be described such as: mechanical energy storage, compressed-air energy storage, thermal energy storage, electrochemical energy storage. One of the large-scale mechanical storages was mentioned before – pumped hydropower plants. In case of this technology cost of maximum power output is estimated by 1 000.00–2 500.00 $/kW, there is no cost of energy being produced as electricity to supply pumps is cheaper than that produced during demand valley. Its round-trip efficiency factor equals 70−85% [8]. This solution has one major limit – geographical location. Such installation requires special shape of landscape to be effective enough – which means there is no place for this technology on small residential scale. Thermal storage requires about 1 250−1 500 $ per every kW of storage installed, cost of energy refund is at level of 20−30 $/kWh. Round-trip efficiency of this technology is one of the lowest – about 33% [8]. The main disadvantage is that only heat can be stored using such technology, there are no geographical requirements and present technology is well developed in that kind of systems and devices, this energy storage technology is widely used in heat water supply installations.

To use the full possibilities of variable renewable energy (VRE) sources it is crucial to develop efficient energy storage technologies. According to performed research in United Kingdom showing that implementation of energy storage system alone itself can reduce annual electrical bills by 25−35% [9], only by benefiting from electricity tariff (low prices on valleys and unaffordable prices on peaks). Moreover, when integrated with PV installation those savings can increase even to 41−74% [9], depending of course on many factors like weather conditions, electricity prices and tariffs policy regulations. The new European Union Renewable Energy Directive (2018/201) are one of the main documents in Europe that focuses on the problem of increasing renewable energy self-consumption, asking member countries to rely on energy storage installations. As electricity prices raising each year, achieving global "all-time heights" (ATH) prices at the turn of 2021 and 2022 a significant rise of energy storage interests occurred. For instance, after electricity prices raised in Germany, about 65 000 home PV-batteries [10] were installed only in 2019. Also declining price of battery systems caused vast impact on this rapid growth. Figure 4 illustrates energy produced by PV systems self-consumption in solar PV system alone and with implementation of electricity storage system based on li-ion batteries.

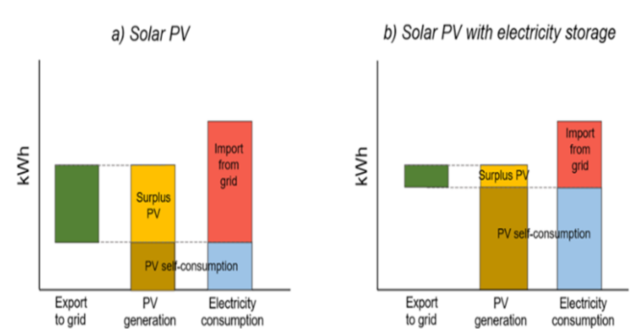

Fig. 4. Illustration of energy storage benefits in terms of PV self-consumption [9].

Also, Fig. 5 shows how different residential energy systems (with PV alone, with energy storage) affect the energy consumption curve/production curve under time of use (ToU).

To summarize all different energy storage systems, Table 1 shows comparison of different energy storage technologies in terms of: CAPEX cost [\$/kW], OPEX cost [\$/kWh], round-trip efficiency, charge, and discharge rates any other features, that can determine storage technology choice.

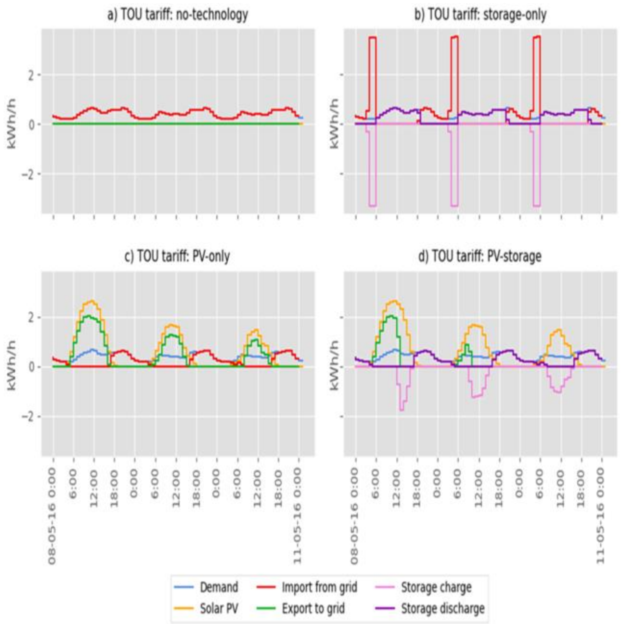

Fig. 5. Energy conversion through the day for different residential energy systems [9].

Table 1. Energy storage technologies and parameters [8].

Technology	Cost [\$/kW]	Cost [\$/kWh]	Round-trip efficiency [%]	Charge/Discharge rates	Cycles/product lifetime	System size	Key limitations
Pumped hydro	1 000–2 500	–	70–85	Rate specified by maximum rated power: $6–4\cdot10^6$ kW	20+ years	$6–4\cdot10^6$ kW/ $10^2–10^7$ kWh	Geographically limited
Compressed air	1 000–2 800	–	With natural gas: Energy ratio: 0,8; <55% efficiency. Adiabatic compression alone: 70-75%	Charging: 0.25–0.65 C Discharging: 0.04–0.5 C	20–30 years	1–110 000 kW/ 2 640 000 kWh	Geographically limited, historically dependent on natural gas
Thermal storage	1 250–1 500	20–30	33	0.05–0.33C	25–40 years	100–280 000 kW/ 1 000–1 100 000 kWh	Typically paired with concentrated solar systems
Flywheel	250–300	1 000–5 000	90–95	10–35C	20+ years	100–250 kW/ 3–25 kWh	High energy costs, self-discharge rate
Lithium-ion batteries	250–500	175–225	80–85	0.03–6C	10–20 years	1–40 000 kW / 10–120 000 kWh	Dependent on minerals
Sodium-ion batteries	250–500	250–300	90–95	0.05–0.8C	20+ years	10–50 000 kW / 20–300 000 kWh	Dependent on minerals, larger ion size (more expansion)
Vanadium flow battery	150–400	125	75–95	0.1–0.66C	20 years	5–5 000 kW/ 40-10 000 kWh	Additional system hardware, high storage material cost
Iron flow battery	150–400	7	≤70	0.16C	20+ years	10kW/60kWh	Additional system hardware, high storage material cost
ZnBr flow battery	150–400	10	65–75	0.16–0.5C	10 years	3–1 000 kW/ 50–6 000 kWh	–
Lead acid	250–500	100–300	81	0.025–2C	5–10 years	2–10 000 kW/ 7–10 500 kWh	Low energy density and specific capacity, battery useful like highly dependent on cycling behavior
Capacitors	25–50	10 000–20 000	75–95	2–720C	20+ years	28–4 000 kW/ 3.5–150 kWh	Excellent power density and cycle life but very low energy density, limit the duration of charging and discharging cycles without extreme cost

For residential usage, consumers savings form electricity storage system highly depends on evolution of the electricity and energy systems. Investor before storage system implementation should not only focus on storage capacity but also how this system fill corresponds with possible renewable energy sources. Regarding domestic circumstances and residential PV installation some of those storage technologies seem to be more suitable. For the purpose of this paper in further analysis and research of three chosen technologies will be made: battery energy storage, hydrogen fuel cell, compressed air and hydrogen energy storage.

5. Battery energy storage

Regarding coming changes on energy market battery energy storage are more common with every year, in specific batteries based on lithium-ion technology. The main appliances of this technology include emergency power supply (UPS), current and frequency stabilization of power grid, increasing of renewable energy sources self-consumption. In present times battery (lithium-ion) energy storage market is increasing and there is prediction that in 2022 it will rise by 11%, in 2023 by 13% and by 16% in year 2024 [11].

5.1. Battery energy storage specification

Due to electrochemical processes of energy conversion, it is possible to store energy surplus generated by PV residential systems and to raise self-consumption of those installations. Growing popularity of this solutions is based on high energy density (150–500 Wh/dm^3) [11] and high efficiency (round-trip efficiency) reaching even 97% [11]. However, Li-ion batteries have high self-discharge rate at level of 8–31% [12], which results of energy leakage during time. In terms of life cycles lithium-ion batteries can withstand 1 000 to even 10 000 of cycles [11]. Table 2 introduces different batteries and their parameters in terms of energy storage.

Table 2. Battery energy storage examples based on Soltec company solutions [11].

Type and brand	Capacity [kWh]	Mass [kg]	Dimensions [mm]	Modularity
Huawei, Li-ion, LFP	5.00	51.8	670×150×600	up to 3 units
Pylontech, Li-ion, BD	3.552	35.5	296×296×450	up to 4 units (min. 2)
BYD, Li-ion, LFP	2.56	38	585×233×298	up to 15 units (min. 2)
Sofar, Li-ion, BD	2.25	30	515×480×125	up to 10 units (min. 4)

Most of energy battery storages system construction include two elements: physical batteries groups and power conversion system [13]. Group of batteries are installed in waterproof container to protects cells from weather conditions. Depending on storage capacity groups can be organized in bigger modules where each module is configured as an individual cell [14]. Along those modules there is also system that protects those call from variant circumstances like high temperature, high voltage. One of each is BMS (Battery Management System) and other TMS (Thermal Management System). They are responsible for monitoring parameters and protecting from situations mentioned in previous sentence, which can lead to battery performance and efficiency reduction. Moreover, those monitoring systems are responsible for SOC (State of Charging) control. Depending on the application, the power conversion system consist of DC/DC conversion and/or DC/AC conversion (DC - direct current, AC - alternating current). In power converter there are rectifiers and inverters along with output power filters and transformers. Figure 6 represents visual scheme of standard battery energy storage system.

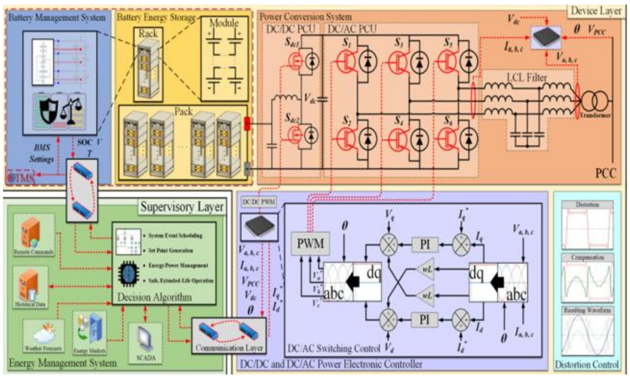

Fig. 6. Battery energy storage system elements [13].

Battery Energy Storage Systems (BESSs) shown in Fig. 6, consist of two main elements: the physical battery pack(s) and the interfacing Power Conversion System (PCS). The battery pack is typically housed in a weather-resistant container and comprises battery racks containing multiple battery modules, each with specific configurations of individual battery cells. Monitoring and protective systems are implemented to ensure battery safety and performance. The PCS includes various components, such as DC/DC and/or DC/AC, Power Conditioning Units (PCUs), DC and/or AC filters, and, for most AC systems, a step-up transformer. The complete system-level architecture of the BESS used in grid-connected Microgrids (MG) is depicted in Fig. 6. At the device layer, the battery pack is configured to achieve a certain voltage and capacity. The Battery Management System (BMS) and Thermal Management System (TMS) continuously monitor and protect the battery racks and cells from voltage, temperature, and SOC fluctuations that could affect battery performance. In the power conversion sublayer, various components like DC/DC converters, DC/AC inverters, passive LCL filters, and step-up/down transformers are employed based on the specific application. A power electronic controller integrated into the PCS handles the switching of the converter and inverter circuitry, utilizing Pulse Width Modulation (PWM) for inversion. The supervisory layer comprises an Energy Management System (EMS) that gathers data from both internal and external sources of the BESS. Internally, the BMS, TMS, and power electronic controller provide readings on temperature, voltage, current, DC link voltage, and measurements at the Point of Common Coupling (PCC). Externally, the EMS may receive information from system operators, historical data, weather forecasts, and energy markets. Based on the collected data, the EMS interprets and makes decisions by setting specific control points for conversion, BMS/TMS/PCS operation, and parameter limits. These decisions aim to optimize system performance and extend battery lifetime. Communication facilitates the exchange of information between the EMS and various components for power flow management, battery protection, and maintenance. The continuous feedback loop allows for dynamic control during grid-tied and islanded operations, ensuring compliance with operational and performance guidelines.

Along the most popular type of battery – lithium-ion type batteries, there are several diverse types of rechargeable batteries that can be used in battery energy storage system. For instance, sodium-based batteries, flow batteries, nickel-based batteries, lead acid batteries, metal air batteries. Lithium-sulfur (Li-S) battery are lighter than Li-on batteries. Currently development of those batteries showed that they can reach density of 2 800 Wh/dm^3 [15] and this score downgrades Li-on battery in this regard. Another type of lithium iron phosphate (LFP) features in increased safety both for user and environment as they produce no waste. This kind of batteries also show successful life cycle of 2 000 cycles [16]. Lithium-air batteries have possibility to achieve 20 272 Wh/dm^3 [17]. In specific circumstances (if the oxygen supplied is not included in the calculation) this type of storage can provide density of 11 000 Wh/kg [17], which can be competitive with liquid fuels. These batteries can be found in appliances like personal electronics, electric vehicles and large-scale grid storage. Production of sodium-based batteries is cheap due to abundant natural resources of sodium salts. Sodium-sulfur (Na-S) battery features high efficiency and no self-discharge, which meant that there is no energy leakage during charged stance. However, the operating temperature for this batter in at 300°C to maintain the electrolyte in liquid state [18]. This fact crosses out this type of batteries as an energy storage system solution for residential PV installations. Flow batteries technology consists of two separated fluids with the membrane between them. They feature with flexibility in system design, good cost to capacity ratio, high efficiency fast responsiveness, long durability and reliability [19,20]. Among these group vanadium redox and zinc-bromine batteries can be found. Vanadium redox is the most promising technology of these flow batteries, which can be introduced on a commercial scale in the future. It uses same metal ions in both of electrolyte, the electrodes and membrane, this feature determines longer life [21] as cell capacity does not decrease over time. Figure 7 shows how diverse types of batteries are used in different kind of appliances, depending on storage time and power.

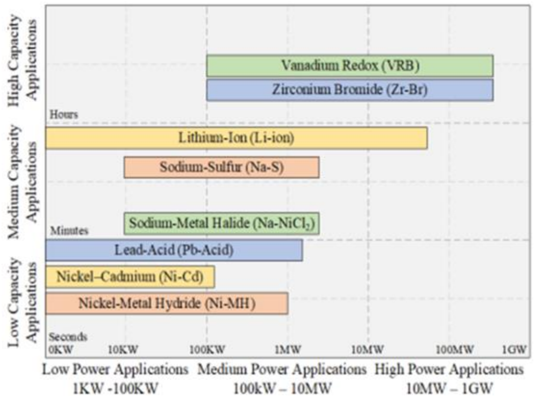

Fig. 7. Different types of batteries regarding storage time and power [13].

5.2. Battery energy storage market and benefits

Across last ten years lithium-ion batteries prices rapidly dropped down. In 2019 cost of this type of batteries was around 175–225 $/kWh [22], which was 13% less than in 2018 and even 80% than in 2012 [13]. As it is showed in this example cost of kWh reduced by almost 100% in 7 years, due to technology development and reducing manufacturing costs. According to predictions in 2025 the total cost of lithium-ion batteries can be established at level of 100 $/kWh. Among one of the most recognizable manufacturers of ESS based on lithium-ion batteries Samsung, BYD, LG, Huawei, Sofar Solar can be listed. Basing on prices of batteries, components, taxes, cost of the whole BESS working with lithium-ion batteries can be estimated and it reaches price of 535−1 095 $/kWh [13] depending on size. According to research conducted in Germany [23], the average installation for home energy storage systems in the country during 2020 consisted of 4 kW of power capacity and 8 kWh of storage capacity. However, due to a reduction in the price of these solutions and increased availability of the technology, the market for home energy storage systems experienced substantial growth. In 2019 alone, around 60 000 new units were installed, resulting in a total of approximately 185 000 units in the country [23]. Overall, these installations yield a total power capacity of 750 MW and a storage capacity of approximately 1 420 MWh. These figures are comparable to those of a medium-sized hydro-pump storage power plant, such as the Żarnowiec plant with a capacity of 716 MW. In 2019, the average price for medium-capacity storage (ranging from 5 kWh to 10 kWh) was estimated to be around 1 100 €/kWh. This cost estimation, which aligns with previous research from other references, e.g. [13], encompasses all expenses related to electronics, taxes, and installation services. We can also observe that 40% of battery home storage systems is coupled with heat pump installation and about 10% with electric car charging station [13]. According to researchers [24], BESS have enormous potential to develop and to help to create secure smart power grids, powered by renewable energy sources. Although significant progress has been made, certain crucial aspects still require improvement in BESS. Among the most vital challenges are enhancing the design of BESS DC-AC converters by incorporating advanced circuit technologies and ensuring reliable support for multiple grid services. Additionally, it is essential to develop accurate and simultaneous battery models to enhance the overall performance of BESS. Enhancing the design of BESS DC-AC converters requires advanced circuit technologies and functionalities to improve efficiency and reliability. A critical challenge is to ensure BESS can reliably provide multiple grid services simultaneously, necessitating sophisticated control strategies and energy resource management. Developing accurate real-time battery models is crucial for optimizing BESS performance, preventing overcharging, and extending battery lifespan. The potential improvements mentioned above will have a significant impact on both the economic and technological performance of battery energy storage systems. While these systems are becoming more widespread each year, certain issues remain that require resolution in order to fully optimize their capabilities.

6. Utilizing hydrogen for energy storage

Hydrogen energy storage systems are emerging as promising solutions for storing energy generated from renewable sources. These systems exhibit exceptional specific energy parameters, enabling them to store a substantial amount of energy per unit mass or volume. The high energy density of hydrogen makes it an attractive option for large-scale energy storage applications. Additionally, hydrogen storage systems boast long life cycles, meaning they can maintain their performance and capacity over an extended period, making them durable and reliable choices for energy storage needs. One of the key considerations for hydrogen energy storage systems is round-trip efficiency, which measures how efficiently the system converts electrical energy to hydrogen during charging and converts the stored hydrogen back to electricity during discharge. A high round-trip efficiency is essential to minimize energy losses and optimize the overall performance of the storage system. The cycle life of hydrogen storage systems is also crucial, as it determines the number of charge and discharge cycles the system can undergo before experiencing significant degradation. A longer cycle life ensures the system's longevity and economic viability. Safety is a paramount concern for hydrogen energy storage systems, given hydrogen's flammable nature. Rigorous safety measures must be in place for handling, storage, and transport to ensure secure operations. Cost considerations play a vital role in the widespread adoption of hydrogen storage.

The cost of production, distribution, and infrastructure for hydrogen can impact the competitiveness of this storage technology compared to other energy storage options. Scalability is an important feature of hydrogen energy storage, allowing it to be adapted to varying energy storage requirements, from small-scale applications in remote areas to large utility-scale installations. Integration with renewable energy sources is another critical parameter, as hydrogen storage can help stabilize intermittent renewable energy grids by providing a reliable energy buffer.

Finally, the environmental impact of hydrogen production and storage is essential in evaluating its sustainability. The overall carbon footprint and greenhouse gas emissions associated with hydrogen generation need to be minimized to ensure that hydrogen energy storage remains an environmentally friendly choice for the transition to cleaner and more sustainable energy systems. With ongoing research and advancements, hydrogen energy storage systems hold great promise as a key component in the future energy landscape, offering grid stability and enhanced renewable energy integration.

However, one of the barriers for customers to implement this technology to residential and industrial energy storage systems is its initial cost (CAPEX). This highly explosive gas (when mixed with oxygen) is widely used in chemical industry but with every year it increases its popularity across energetic sector. One of the types of evidence of growing hydrogen interest is number of scientific papers in Scopus database regarding hydrogen using keywords ”hydrogen energy production and storage”. In 1990 there were only 10 papers related to this issue and over 680 in 2021 [25]. Hydrogen is a common element on planet Earth; it is related to such substances like water and fossil fuels [26].

It has the highest energy density per kg of all the other known elements but has the lowest volumetric energy density among all other commonly used fuels – 0.01079 MJ/dm^3) [27]. Nowadays, over 95% of consumed hydrogen worldwide is obtained from fossil fuels like natural gas by a technique called steam reforming. This process requires the gas-steam mixture to reach a temperature between 700°C–1000°C. The process itself emits 10 kg of CO_2 into the atmosphere for every kilogram of produced H_2 [28]. Although this method makes hydrogen not as environmentally friendly and green as it seems, there are no doubts that this is the most economical way to obtain hydrogen on a larger scale. Even though the cost of the production is estimated at around 1.5 €/kg, which is three times higher than natural gas extraction [29,30].

However, there is one method that allows the receipt of clean, green hydrogen (without the emission of greenhouse gases). This process is called electrolysis, and it requires an energy supply to power the electrolyser. if this power is from renewable energy sources, we can qualify hydrogen as green and environment friendly. For example, if it is powered by a power grid which mostly relies on nuclear power, the hydrogen label is yellow – which means that this way of production is not that environmentally friendly [31] For the purpose of this paper, we will only discuss green-labelled hydrogen produced by residential PV systems.

There are several types of electrolysers mentioned before. The most common ones are: alkaline water electrolyser using an aqueous solution of sulphuric acid (H_2SO_4) [32], solid oxide electrolysers (SOE) operating at temperature above 773 K [33] and polymer electrolyte membrane usually called proton exchange membrane (PEM). This last type – PEM operates in lower temperatures than SOE, about 333–363 K [34]. There are plenty of advantages of PEM electrolyser. Its response time is almost instant, which means that the process of hydrogen production starts immediately after supplying power to the device.

Moreover, the theoretical efficiency of hydrogen production in the PEM system of 80% [35], which is high and provides a solid source of hydrogen when combined with a renewable energy source supply. This means that for every 100 units of electrical energy supplied to the PEM electrolyser, approximately 80 units of (chemical) energy stored within hydrogen gas can be generated, with the remaining energy lost as heat. The lifetime of such a system is also promising and reaches 60 000 hours; it depends mostly on membrane thinning [36]. An innovative electrolyser technology is in the works, aiming to achieve an energy consumption rate of 50 kWh per 1 kg of hydrogen (H_2) produced at the plant level within the next few years. To produce 1 kg of H_2, approximately 10 dm^3 of water is required. Furthermore, during this hydrogen production process, around 8 kg of oxygen (O_2) is generated per kg of hydrogen, along with approximately 10 kWh of potential heat per kg of hydrogen. Thanks to the possible modular design of the PEM system, it can be easily implemented in residential power supply systems. A detailed description of electrolysers can be found in paragraph 6.1.

As hydrogen can be generated from PEM supplied by the energy surplus of PV installations, there is the next step to use this green element as an efficient energy storage system and to store hydrogen itself. There are several methods to store hydrogen, and it can be in gas or liquid. Every solution differs in volume, pressure, and duration of the stored medium. There are also a few ways to store hydrogen as a gas. It can be achieved using tanks, cylinders, or natural underground caverns. Because the energy density of this gas is low, it is crucial to compress it into pressure above 700 bar.

The process of raising hydrogen pressure also requires vast amounts of energy. To compress hydrogen from 1 bar to 200 bar, there is a need to deliver about 7% of the energetic value of compressed hydrogen itself and even 10% to go up to 700 bar [37,38]. This means that the storage process itself immediately consumes 10% of the energy stored in this gas only during compression. Storing in huge underground caverns (e.g. abandoned mine shafts) allows for a reduction in investment costs (lower CAPEX expenses) and storage of abundant volume under even higher than seven hundred bar pressure.

Until 2016 there were about 672 underground gas storages worldwide, mostly for natural gas, which contain altogether about 424 billion cubic meters of gases [25]. However, an underground storage system has its geological limits. Because of its scale, it cannot be used as a residential solution. Storing hydrogen in cylinders and tanks in a compressed gas state provides a density of the substance at a level of 7–30 kg/m^3 – depending on compression pressure [39]. To increase this density, hydrogen can be stored in a liquid state to achieve a density of 70 kg/m^3. However, to change the state of gas to a liquid, the temperature must drop to –253°C [40], which requires a constant and high amount of energy to be supplied, as well as a high-tech vacuum-insulated tank. This method is not suitable for prolonged periods of storage because of the gradual decrease of the hydrogen volume stored inside the tank due to the boil-off effect [41]. The last of the hydrogen states that can be used in the storage process is the solid state. It can also be a hybrid or material-based method because it creates new substances due to the reaction of hydrogen and metal that results in the creation of metal hydrides [42].

Those substances enable to store hydrogen at high density due to extraordinarily strong bonds between metal and hydrogen atoms. Another advantage is the safety of that method of storage, due to storage in stable substances without the requirement of high pressure or low temperature during the entire process of storage. However, some of the metal hydrides still require these. Those parameters are required only during the phase of joining and splitting metal and hydrogen atoms. So-called reversibility is one of the key factors in choosing the proper metal-hydrogen combination substance, which means how strong bonds between atoms can be achieved and how much energy and time is required to change it back to separate metal and hydrogen, which can be used in further energy production. These days, one of the most promising metals to form metal hydrides is magnesium, which has been proven to have a low cost of usage and high reversibility [46].

Fig. 8 represents different methods of hydrogen storage systems and density.

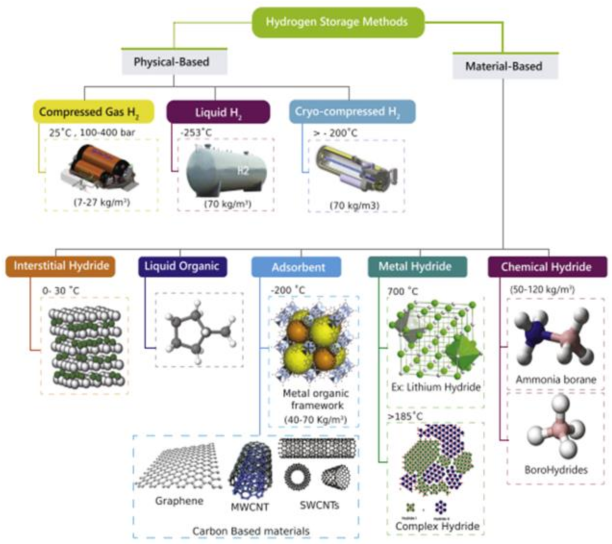

Fig. 8. Different methods of hydrogen storage [26].

6.1. Electrolysers and fuel cells

Hydrogen's energy is 140 MJ/kg, which is much higher than fossil fuels [43] The energy density of fossil fuels is as follows: anthracite coal – about 25–35 MJ/kg, lignite coal – about 10–25 MJ/kg, and natural gas 48−55 (MJ/kg). Many researchers seek the solution for future energetic crisis in this element.

Nowadays, global hydrogen production is estimated at around five hundred billion cubic meters [44]. However, the produced hydrogen is not used in electricity production. It is used especially in industries like the gas and crude oil sector, agriculture fertilizers industry, metal refining industry and others. Only a small amount of that hydrogen is used in fuel cells to generate electricity.

As mentioned before, hydrogen is often described as a green energy source which will replace fossil fuels in the future; however, over 96% of hydrogen is being produced by non-renewable processes, like steam methane reforming (SMR) [45]. In this technique, methane produced from natural gas is used. Gas is heated with steam (and with catalyst), in this mixture of carbon monoxide and hydrogen is produced. To really qualify hydrogen as an eco-friendly fuel (green hydrogen), it must be generated with the use of renewable energy.

These days, special attention has been given to the process of electrochemical splitting of water – electrolysis, powered by renewable energy sources. Taking into consideration residential installations, photovoltaics can be a perfect source of energy for electrolysis. Every decomposition of water in this process can be described by two separate processes (two half-cell reactions) taking place on an electrode with an energy supply. The first reaction is called the hydrogen evolution reaction (HER), and the second is the oxygen evolution reaction (OER). To perform these two reactions, electrocatalysts, made of precious metals like Au, Pt, Ag, etc., must be used in the electrolyser, making this method expensive regarding investment costs (CAPEX). The cost of an alkaline water electrolyser (AWE) is 500−1 000 USD/kW, and the lifetime of the system is 90 000 h. The production cost of a PEM electrolyser is 700–1 400 USD/kW [48]. In the next paragraph, three of the main electrolysis methods will be described in detail.

Alkaline water electrolysis is the most developed electrolysis methos known present days. It was invented in the year 1789 by two scientists, Troostwijk and Diemann [49]. This method can generate hydrogen at an operating temperature of 40−90°C. Substances like NaOH or KOH are used in AWE as electrolytic solutions with concertation range of 20−30% [50].

To separate two electrodes from each other, a special membrane made of asbestos is implemented to prevent the mixing of gas products. Cathodes, as the main elements of the application, are made of nickel material submersed into the electrolytes. At the cathode, surrounding parts of water are broken down into one molecule of hydrogen and two molecules of hydroxyl ions. Next, one of the products – the hydroxyl ion, moves in an anode direction, where four OH-molecules oxidize and produce one molecule of oxygen gas and two molecules of water with 4 free electrons. The primary principle of this reaction is hydrogen gas production on the cathode and oxygen production on the anode side. The main products of this reaction are separated by membrane or diaphragm mentioned before. The scheme of AWE electrolysis is shown in Fig. 9 [47].

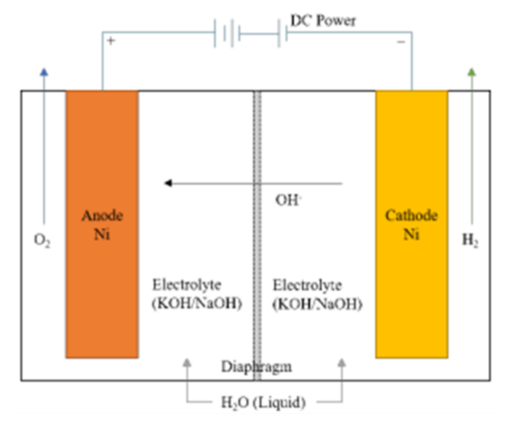

Fig. 9. Alkaline water electrolysis scheme [47].

Despite the fact that this method is one of the most advanced and developed regarding electrolysis, it still has some major disadvantages, as high water consumption - around 20 dm^3 per kg of H_2 produced, according to stoichiometry calculations, only 9 dm^3 of water is required to produce 1 kg of H_2. However, as water electrolysis generates heat, it requires more water as a cooling fluid. Confined current densities and low operating temperature and pressure indicate a low energy efficiency of 70−80%. During this process, corrosion from electrolytes occurs, as well as product (gases) migration throughout the diaphragm. However, it benefits from pure hydrogen and has no requirement for precious metals. Moreover, electrolysers based on the AWE method feature modularity that can increase the volume of production.

Considering the purity of hydrogen, the next method, called Solid-oxide electrolysis (SOE), can generate hydrogen with an even higher level of purity than AWE, with greater efficiency. This technology was implemented by Doniz and Erdle in 1980, and it is not as advanced and developed. There is still much of research ongoing at present times [51]. In SOE technology, instead of liquid NaOH electrolyte, solid ceramic electrolyte is used to increase its responsivity. This method operates at temperatures of 500−1 000°C and can withstand pressure up to 3 MPa; with those values, this technology is not yet commercialized for residential usage. The basic principle of SOE is based on the reduction of molecules of water into two molecules of H_2 and molecules of O_2 – ions, which move throughout the ceramic electrolyte to the anode side and oxidize, producing molecules of oxygen. SOE scheme is shown in Fig. 10 [47].

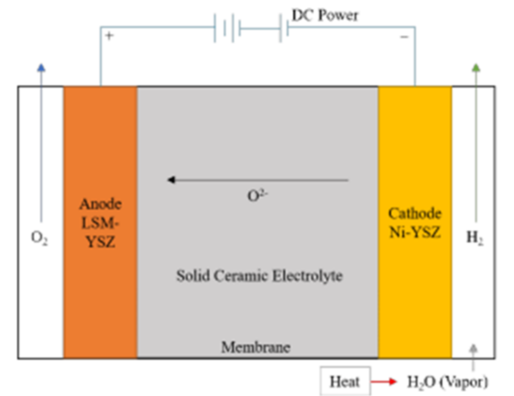

Fig. 10. Solid-oxide electrolysis cell scheme [47].

Among the most used materials for cathode nickel-zirconia and strontium, doped lanthanum magnetite can be found, and for the anode, zirconia is commonly used [52]. As main advantages, high efficiency (90−100%) and high output must be mentioned. Electrode degradation and usage of the ceramic electrolytes at a temperature of 1 000°C can be considered a disadvantage. As this technology is still in the development phase, there is still much research to perform.

Proton exchange membrane electrolysis (PEME) is the last method of electrolysis taken into consideration in this paper. PEME was discovered in 1966 as a replacement for alkaline water electrolysis. To prevent mixing of liquid special polymer electrolyte is used. This type of electrolyser operates in temperature range of 20−100°C [49]. Devices based on PEME usually operate at high pressure - about 40 MPa), allowing the reduction of the energetic demand of the whole process due to compression. The PEME process scheme is shown in Fig. 11 [47].

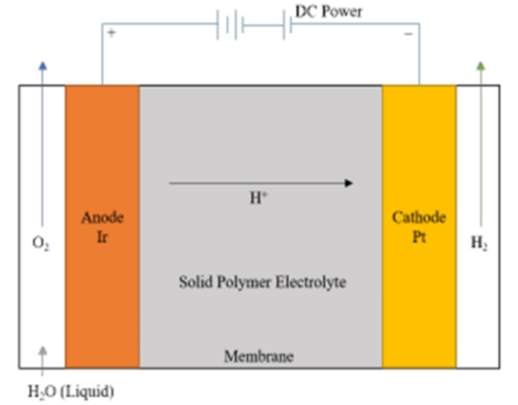

Fig. 11. Proton exchange membrane electrolysis scheme [47].

The main difference in this method is the principle, where it is an H^+ particle, which is moving throughout the membrane, not

OH^-. At the side of the anode, two particles of water H_2O oxidize to produce oxygen gas O_2 and four ions of hydrogen H^+, which move through the membrane. Next, two hydrogen (H^+) molecules are reduced on the cathode side to produce one molecule of hydrogen gas – H_2. For PEME cathode usually precious metals like Pt are used. However, for anode non-precious material like Ir can be used [53].

Electrochemical electrolysis is one of the fastest-advancing technologies nowadays. Scientists assume that it will be the main source of pure hydrogen in the next years. For now, PEME technology is the one that researchers are focusing on the most on implementing solutions that will allow the use of this technology commercially, while SOE technology is still in the experimental phase. Despite technology, one of the main challenges regarding electrolysis is the replacement of precious metals, which are rare, planned and expensive. Several techniques are currently under investigation where metal compounds and oxides such as Fe, Ni, Co and Mn based were used to replace precious metals for HER and OER electrodes half-cell reactions. Along with fuel cells, electrolysis is considered one of the main energy sources in the future, which will help to manage the surplus of energy from renewable energies and provide clean fuel for transportation.

In the global energy production transformation, there is also one type of device which will take a significant role, as a next step from electrolysis – fuel cells. Those devices, as mentioned before, convert hydrogen, generated by electrolysis, into electricity, which can be used to supply households' industry, etc. Energy conversion that takes place in fuel cell is one of a few where chemical energy stored in fuel I converted into electrical energy without any kind of concomitant emission of gases like CO_2, SO_2, NOx. This concept of fuel cell was invented by William R. Grove in 1839, electrochemist and layer [54, 55]. Grove used two electrodes made of platinum dipped into electrolyte. One of which hydrogen catalytic reaction occurred: $2H_2 \rightarrow 4H$ (ads) $\rightarrow 4H^+ + 4e-$. On the other electrode he noticed $O_2 + 4H^+ + 4e- \rightarrow 2H_2O$ reaction. Despite of reactions there is also electron movement throughout external circuit, which generated electricity. Term ”fuel cell” was used in 1889 by Ludwig Mond who researched Grove's invention and improved electro-chemical oxidation of hydrogen [56]. First practical hydro-oxygen fuel cell, which could be used commercially, was developed by Thomas Bacon in 1930. All Bacon's patents regarding fuel cell were licensed by company Pratt & Whitney and were used during Apollo 11 moon mission in 1969 to provide electrical power. Through all these years since first invention of fuel cell, today we can list several different types of fuel cells, among which Polymer Electrolyte Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Alkaline Fuel Cell (AFC), Phosphoric Fuel Cell (PFC), Reversible Fuel Cell (RFC), Direct Carbon Fuel Cell (DCFC) and Direct Methanol Fuel Cell (DMFC) can be listed.

Polymer electrolyte membrane fuel cell (or PEM) is one of the most accessible among fuel cells, although it has a lot of advantages: fast start-up and shut-down times, high power density, low noise pollution and low operating temperature – around 80°C. Researches predicts that this type of will be one of the main power sources for transportation in the future [57]. Due to not complex design PEM fuel cell can be used in simple installations and it requires minimal maintenance. Moreover, PEM fuel cell does not emit any kind of toxic gases during operation. Efficiency of PEM fuel cell can highly exceed efficiency of traditional heat engine. The electrical efficiency of PEM fuel cell can reach 40−60%, depending on purity of hydrogen. Fuel cell itself requires hydrogen-rich fuels and most of fuels like methane, methanol, gasoline, etc. which contain hydrogen, are not suitable for PEMFC operation [58]. This type of fuel cell has two key issues during operation, first issue relates to water management and second to heat management. The polymer barrier required specific hydration level to provide efficient work. However, when hydration level reaches higher value than required, water floods holes of both catalyst and gas diffusion layer of membrane and it causes disturbances in mass transportation – Fig. 12 [59]. So, it is crucial to balance hydration level of PEM fuel cell and eliminate process of fuel cell degradation. Heat management is related with resistance and losses of mass transport which can cause deviation of operating voltage from the nominal voltage and as a result fuel cell releases heat to environment and generate even more losses.

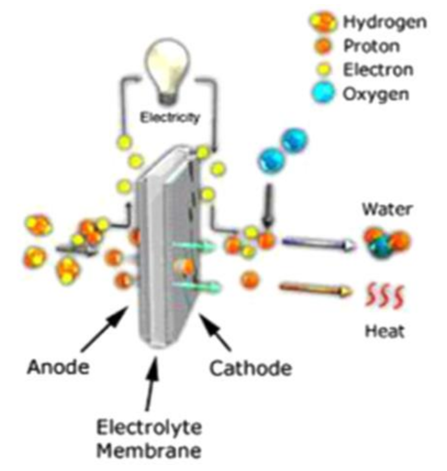

Fig. 12. Basic fuel cell scheme [59]

Solid oxide fuel cells are usually used in bigger installations such as cement plants and other industrial facilities. SOFC uses hard, non-porous ceramic alloy as electrolyte element, placed between electrodes. The shape of electrolyte can vary depending on application. SO fuel cell operates at much higher temperature ranges than PEM fuel cell, around 1 000°C (the same conditions as for SO electrolysis method). Electricity conversion process efficiency reached 50−60% [60]. SOFCs are considered high-performance hydrogen-driven solutions without air pollution. One of the biggest advances of ceramic electrolytes is their solid state. Due to that, electrolyte losses are not a significant concern [61]. One of the main disadvantages of this technology is the high-temperature requirement, resulting in personnel thermal protection and heat resistant materials. Due to these facts, start-up and shut-down times are longer than in the PEMFC solution. However, SOFC operating at lower temperature (800°C) are under development, reducing temperature impact.

Molten carbonate fuel cell can be fuelled with both natural gas and coal, so why is it compared with fuel cells that are associated with ”green” hydrogen electricity production? As mentioned before, all fuel cells have higher theoretical efficiency when compared with heat engines. The MCFC electricity production process can achieve 75% efficiency. This is due to the fact that they do not operate according to Carnot or Rankine cycles. MCFC has the potential to be integrated into applications like industrial electricity generation and military applications. It operates in the temperature range of 450°C to 650°C. This temperature allows the use of non-precious metal on both anode and cathode. A ceramic matrix with carbonate-salt impregnation is used as an electrolyte. Moreover, MCFCs are not vulnerable to CO and CO2 fuel cell poisoning, which allows them to fuel with gases produced from coal. However, MCFC technology is only suitable when large-scale continuous duty is required (with big hydrogen storage), which makes the technology perform better in industrial areas rather than residential systems.

An AFC features higher efficiency due to increased oxygen flow, which improves the electricity generation process. This type of fuel cell can be used with applications where higher current densities with lesser voltage losses are needed. The OPEX cost is relatively low, as most of the AFC parts are made out of low-cost materials. Alkaline fuel cell also has a long lifetime due to minor corrosion issues. To increase performance and reach an operating point with the highest efficiency possible, a catalyst in the electrolyte is required [62]. Carbon dioxide pollution is one of the main threats to this type of fuel cell. It must operate in a no CO_2 environment. After contact with carbon dioxide, carbonates are created, which can stop electrodes and result in electricity production failure. For this reason, fuel needs to be purified before application to remove all particles of CO_2. This type of cells were widely used by NASA during the Apollo mission in the 1960s.

The last type of fuel cell taken into consideration in this paper is Phosphoric Acid Fuel Cell (PAFC). In this solution, liquid phosphoric acid (H_3PO_4) is saturated into a matrix made out of silicon carbide. PAFC operates at a temperature range of 150−210°C. This type of electrolyte and temperature reduces the impact of carbon oxide and dioxide pollution, and fuel cells can be supplied with air instead of pure oxygen. Due to high-temperature, waste heat is produced, which can be used to heat and electricity cogeneration, resulting in up to 80% efficiency. Moreover, PAFC can operate in atmospheric and also high-pressure conditions. During the operation of every fuel cell type, water is produced and it is a significant concern in PAFC. Excess water must be removed to prevent electrolyte form being dissolved. Water removal is usually performed by air passing through the cathode and transporting water as vapour. When starting and during normal operation heat must be also removed but it can be later used to increase efficiency [63]. Based on the previous description of different fuel cell types, it can be concluded that the use of specific solutions is mostly related to the type of application. Table 3 lists several types of fuel cells with suitable applications where those can be used and also summarizes their advantages and disadvantages.

Table 3. Types of fuel cell divided by application type.

Fuel cell technology	**PEMFC**	**SOFC**	**MCFC**	**AFC**	**PAFC**
Power range	1 W−100 kW	0.5−400 kW	0.5−400 kW	0.5−400 kW	0.5−400 kW
Application	Portable, Stationary, Transportation	Stationary	Stationary	Stationary	Stationary
Examples	•Military systems •Stationary systems •UPS •e-Mobility	•Stationary systems combined with heat regeneration. •UPS	•Stationary systems combined with heat regeneration. •UPS	•Stationary systems combined with heat regeneration. •UPS	•Stationary systems combined with heat regeneration. •UPS
Advantages	•High power density in pressurized cell stack. •Operates easily with pressurized system due to mechanical properties of solid polymer electrolyte. •Low operating temperature (80°C) allows for cost-effective materials in cell stack.	•Highest efficiency (up to 80%). •No need for expensive materials. •Potential for long operative life cycle (to be demonstrated). •Simple cell structure streamlines production lines. •Very low emissions with hydro-carbon fuels. •Low noise production system.	•MCFCs achieve up to 45% efficiency. •Combined heat systems boost efficiency to 50%-60%. •Use hydrogen-rich fuels, no need for external reformer. •Low-cost materials.	•Simple cell structure •Fast start-up •Competitive construction costs •High electrical efficiency (65%)	•65,000+ hours operating life cycle (150ºC to 220ºC). •Electric efficiency up to 40%, can reach 60% with combined heat systems. •Partial immunity to carbon monoxide poisoning (low gas concentration). •Uses less pure hydrogen fuels.
Disadvantages	•PEMFC catalysts susceptible to CO poisoning (low operating temp.). •CO concentration must be reduced below 10 ppm with CO removal when using reformate from hydrocarbons or alcohols as fuel for PEMFC. •Effective water management is crucial for maintaining sufficient ionic conductivity and optimizing cell performance.	•High operating temperatures (above 600°C) with longer start-up times and material costs. •Vulnerable to thermal stresses and mechanical issues. •Sensitive to fuel impurities, leading to catalyst poisoning. •Limited durability and degradation at high temperatures. •Lower efficiency at partial loads.	•Short operative life cycle (corrosion, electrolyte loss, cathode dissolution). •Slow starting times (required temperature: 650°C). •No restart capability after shutdown.	•Requires pure hydrogen as fuel, limiting fuel source options. •Sensitive to carbon dioxide in the fuel, leading to performance issues. •Shorter lifespan and durability compared to some other fuel cell technologies. •Typically, bulky and heavy, making them less suitable for certain applications.	•Slower start-up times due to the phosphoric acid electrolyte characteristics. •Limited commercial availability and research compared to more established fuel cell types. •Higher cost and complexity of system components. •Bulkier and heavier, making them less suitable for certain applications.

6.2. Fuel cell energy storage

As described in previous paragraphs. Electricity can be generated from stored hydrogen using fuel cells, which can be divided into four main groups considering the type of electrolyte and temperature of work: MCFC, AFC, SOFC and most common one PEMFC [64]. Most the fuel cells operate at a temperature lower than 200°C [65]; regarding fuel cell type, its electrical efficiency can reach 45% and even 90% of efficiency can be reached with heat recovery, as the process performed by the fuel cell is highly exothermic [66]. However, the mentioned efficiency is related only to the discharging process of ESS (Energy Storage System) and does not cover electrolyser efficiency, energy needed to compress hydrogen and also hydrogen losses throughout the storage phase. When those factors are taken into consideration, the efficiency of the whole ESS itself can be estimated at around 25%-30%. Table 4 below illustrates a techno-economic comparison between PEM fuel cells and various sources of energy.

Table 4. Technoeconomic comparison of PEM fuel cell and different energy sources [67].

Transportation propulsion technology	Power level [kW]	Efficiency [%]	Specific power [kW/kg]	Power density [kW/l]	Vehicle range [km]	Capital cost [$/kW]
Proton exchange membrane fuel cell (on-board fuel processing)	10–300	40–45	400–1 000	600–2 000	350–500	100
Proton exchange membrane fuel cell (off-board hydrogen)	10–300	50–55	400–1 000	600–2 000	200–300	100
Gasoline engine	10–300	15–25	>1 000	>1 000	600	20–50
Diesel engine	10–200	30–35	>1 000	>1 000	800	20–50
Diesel engine/battery hybrid	50–100	45	>1 000	>1 000	>800	50–80
Gasoline engine/battery hybrid	10–100	40–50	>1 000	>1 000	>800	50–80
Lead-acid or nickel metal hydride battery	10–100	65	100–400	250–750	100–300	>100

Fuel cells, in most cases, include three main elements: an oxidant electrode (cathode), a fuel electrode (anode) and finally, an electrolyte placed between them. The electrodes are made of porous material covered with catalyst material (often platinum). Stored hydrogen is delivered as a gas-flow stream to the anode, where it reacts. The H_2 oxidizes to generate hydrogen ions and also electrons. Those ions migrate through the electrolyte. Meanwhile, electrons are forced to find their way through an external electrical circuit – generating electricity. Finally, on the cathode, electrons and hydrogen ions react with oxygen from air and form water as a waste product.

Fuel cells as an energy source have several unique features like no harmful emissions, high efficiency, modularity, static nature, and a vast range of applications. In terms of no harmful emission, the products of the reaction held inside the cell are only water, DC electricity and heat. However, in the case of fuel cells and their emissions, it is crucial to also consider their fuel – hydrogen, and the method of obtaining it. Regarding this description as hydrogen produced in electrolyser supplied by surplus form PV system, no-emission cells can be considered as real. Moreover, when hydrogen is produced by grid-supplied devices and the grid system itself relies on conventional fossil fuel power plants, then electricity produced by the fuel cells is more harmful to the environment than the production of the same amount of energy in a conventional way. According to research performed by Argonne National Laboratory [68] 3 000 000–3 500 000 BTUs (British Thermal Units) of energy from fossil fuels is required to produce 1 000 000 BTUs of energy in a fuel cell (using hydrogen from “non-green labelled” source), which is comparable or even less than conventional production of energy in coal power plants. However, the cost of fuel cell-based plants is incomparably higher than that of traditional coal-fired power plants. The high efficiency of the cell, compared to the heat engine, which is limited by the ideal Carnot Cycle, reaches higher values. It is because of the fact that the fuel cell as an electrochemical device is not limited by the cycle mentioned before, and it mostly depends on chemical energy content bound with the provided fuel. The modularity feature is possible due to the simple construction of the fuel cell. System power output can be easily controlled by changing a number of cells in the stack or changing the number of stacks in the complete system. It is also worth noticing that stacking and increasing the power output of cells does not affect the efficiency of the entire system, and this fact gives this solution enormous potential in terms of energy storage systems. Due to its nature, fuel cells as electrochemical devices can feature very static workflow. There are almost no dynamic parts that could cause vibrations or major faulty damage, which is why this source of energy is very reliable and also safe. However, as presented in Table 4, fuel cells are undoubtedly much more expensive than conventional sources of energy. The high price is determined by the usage of exceedingly rare materials as catalysts (mostly platinum), and delicate membrane manufacturing techniques. Experts estimate that the cost per one kW with a fuel cell must drop by 10 times [69] to successfully appear on the residual energy market. There is potential to lower the price as with every year, fuel cells are more likely to be “mass-produced”. Another issue is the durability of the cells as power-generating devices. It is assumed that for sustaining the power supply device, the durability of the fuel cell needs to be increased more than 5 times (of current durability) to achieve industrially reasonable, more than 60 000 h of lifetime.

6.3. Compressed air and hydrogen energy storage

One of the newest and also complex methods to store energy combines the traditional method of Compressed Air Energy Storage (CAES) with hydrogen fuel used to produce Synthetic Natural Gas (SNG). CAES system involves air compression during energy surplus, storage and then air expansion to receive energy in an analogous way as it takes place in pumped hydropower plants. CAES system can correspond with SNG from hydrogen to become an efficient energy storage system. Both components (compressed air and SNG produced from H_2) can be easily stored and used to produce energy, e.g., in gas turbines later, during energy demand valleys.

That kind of hybrid system, which relies indirectly on hydrogen production during energy storage, is called the Power to Gas to Power (P-t-G-t-P) system [68]. One of the newest ideas of energy storage called the Compression Air and Hydrogen Energy Storage (CAHES) system, combines both storage methods mentioned before, CAES and P-t-G-t-P system (or P-t-SNG-t-P for synthetic gas).

Figure 13 shows the scheme of the CAHES system. The entire system consists of several different devices with distinct roles. As a part of the P-t-SNG-t-P system, we can note water treatment installation, hydrogen generator, optional oxygen and hydrogen compressors, hydrogen tank, oxygen tank, mechanization unit, SNG and CO_2 compressor, combustion changer and finally, flue gas turbine. On the other side of this system, there is the CAES part, including an air compressor, heat exchangers, and compressed air turbine. There are also devices that fulfil the entire system and cannot be assigned as a part of only one subsystem; these are the water tank, generator, moisture separator, and compressed air tank. As Fig. 13 illustrates the CAHES system design scheme, it also represents three phases that feature most of the energy storage sub-systems.

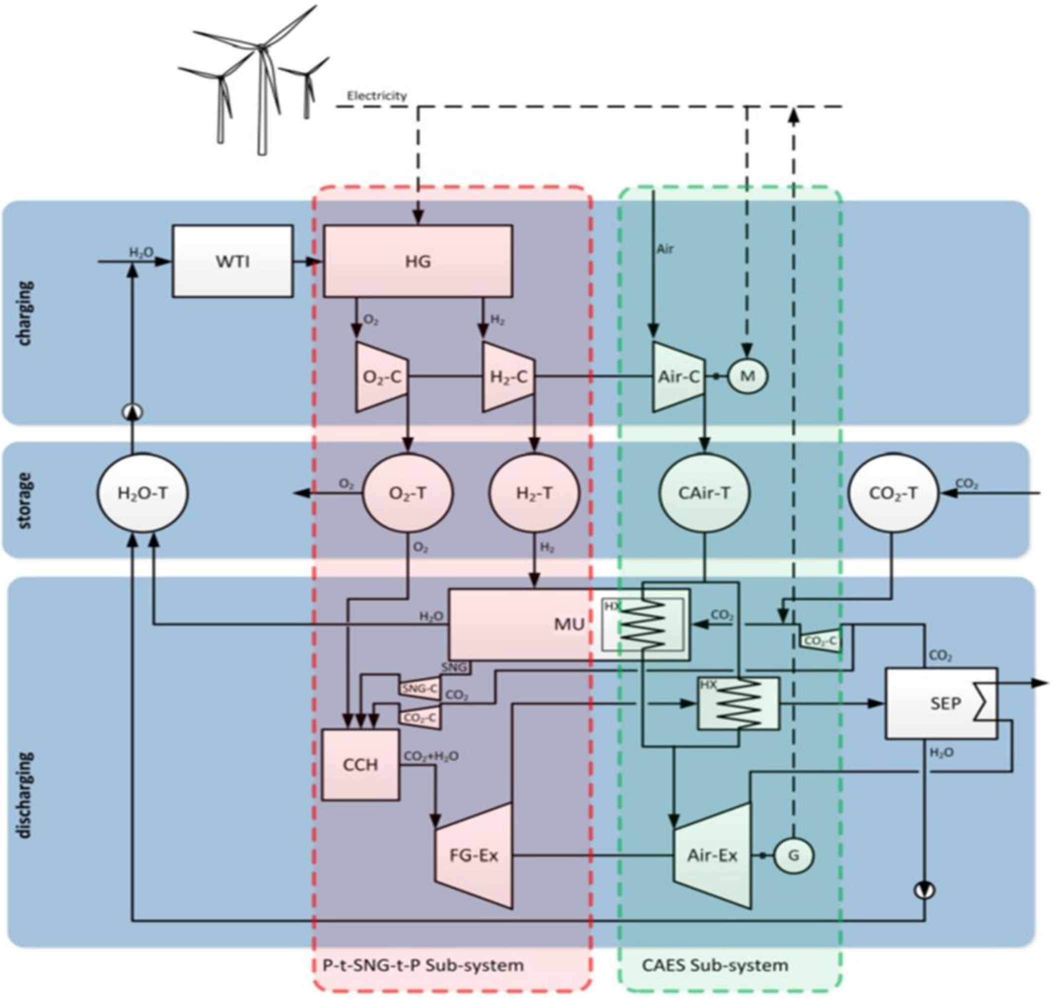

Fig. 13. CAHES system concept scheme.
CCH – Combustion Chamber, SEP – Moisture Separator, HG - Hydrogen Generator, MU - Methanation Unit, HX - Heat Exchanger, WTI – Water Treatment Installation, M – Motor, G - Generator Air-Ex (Air Expander), FG-Ex – Flue Gases Expander, O_2-T – Oxygen Tank, H_2-T – Hydrogen Tank, H_2O-T – Water Tank, CO_2-T – Carbon Dioxide Tank, Air-T – Compressed Air Tank, Air-C – Air Compressor, H_2-C – Hydrogen Compressor, O_2-C – Oxygen Compressor, CO_2-C – Carbon Dioxide Compressor, SNG-C – Synthetic Natural Gas Compressor [70].

The first subsystem consists of a hydrogen generator, water preparation installation, hydrogen and oxygen compressors, and storage tanks for hydrogen, oxygen, and water. The hydrogen generator operates during low electricity demand or increased renewable energy production. Hydrogen and oxygen are stored in H_2−T and O_2−T tanks at 30−40 bar. The hydrogen goes to the methanation unit, while oxygen is used as an oxidant for burned SNG in the SNGOCSs.

The Methanation Sub-system (MSs) receives a mixture of carbon dioxide and steam, a byproduct of flue gas drying during SNG oxycombustion. It includes three methanation reactors with heat exchangers. The Compressed Air Energy Storage Subsystem (CAESSs) includes a three-section air compressor (Air-C) with cooling sections. Atmospheric air is compressed to 4 000 kPa, and the pressure can be adjusted from 2 000 kPa to 6 000 kPa. The compressor's internal efficiency is 88%, with a 98% electromechanical efficiency. Compressed air can be stored in an underground tank and then divided into two streams: one is heated using the methanation process, and the other is heated by high-temperature flue gas. Both streams are directed into separate expanders.

The expanded air can be utilized to more efficiently dry exhaust gases before they enter the methanation process. The flue gases expander (FG-Ex) operates in the SNG Oxy-Combustion Sub-system, fuelled by SNG combustion in the combustion chamber (CCH). Oxygen from the electrolysis process is used for combustion. The expander's pressure is 4 000 kPa, and its temperature ranges from 800°C to 1 100°C.

The flue gases expand to 600 kPa, providing high-temperature gases for the HX exchanger inside MU (Methanation Unit) to heat the air in the CAESSs expander. The exhaust gas from the CCH is a mixture of CO_2 and H_2O. Under ideal conditions, the oxygen used for combustion matches the oxygen produced by the hydrogen generator in the MSs. The Drying Sub-system (DS) condenses water vapour in the flue gases from the FG-Ex by cooling them below the dew point. The flue gases are first cooled to 30°C in the standalone HX heat exchanger. Further cooling is achieved by optionally using the low temperature of the air, leaving the CAESS Air-Ex.

The first charging phase occurs during sunny weather and PV electricity generation surplus. The energy that cannot be used by residential devices right away is used to supply hydrogen electrolysers and air compressors. Both gases are then stored inside tanks.

However, according to Fig. 8 and section 6 of this paper, there is the possibility of implementing different methods of hydrogen storage. But those cases should be part of further research. Moreover, it could also be possible to use the produced hydrogen straightforwardly inside the mechanisation unit and then store SNG instead of H_2. As tanks are filled with PV energy surplus products, the second phase starts – storage itself. The last discharge stage is complex and covers several different processes like using hydrogen in methanization unit (if not performed in other phases), combustion of SNG inside the chamber, expansion of flue gases on the turbine, compressed air expansion, power generation from generator coupled with flue gas and compressed expanders, separation of moisture from flue gases. There are also minor processes which provide efficiency due to heat recovery in heat exchangers, like using heat generated inside the mechanisation unit to increase the temperature of compressed air heading to the air expander. According to research [69] CAHES system, presented in Fig. 13, can achieve an efficiency of 38.15% (2020 y), which is higher than P-t G(H2)-t-P sub-systems alone but is lower than CAES sub-system considered individually. The whole idea is covered by patent procedure [71]. Regarding efficiency of this CAHES system only puts many doubts to this idea and points to the superiority of energy storage methods like BESS or hydropower technology. However, as this technology is new and features with higher complexity, there are many parts that are under improvement and development, which can result in great efficiency grow as research continues.

7. Conclusions

The current global energy landscape is characterized by rapid energy price increases, frequent delivery disruptions, and geopolitical tensions, highlighting the urgent need for energy storage solutions to enhance energy sustainability. It is undeniable that energy storage systems will play a pivotal role in the future development of both residential and national energy grids. With the growing global electricity production from renewable but non-reliable sources, one of the major challenges in today's scientific landscape is to find the most efficient means to utilize any surplus energy that occurs and use it when needed by consumers. At the residential scale, energy storage solutions offer a promising avenue to improve the performance of photovoltaic installations, increasing the rate of auto-consumption. However, the range of energy storage methods discussed in this paper reveals that there is no one-size-fits-all approach for every application. While hydropower technology is well-suited for vast national grids, it presents technical limitations that make its implementation on a residential scale unfeasible.

Battery energy storage systems (BESS) emerge as a more accessible and effective solution for residential conditions. BESS boasts advantages such as low inertia, high reliability, and efficiency. Despite these benefits, the excessive cost and limited lifespan of BESS systems continue to hinder their widespread adoption for most domestic installations. Additionally, the environmental implications of batteries, containing substances harmful to the environment and generating considerable waste, raise concerns from an ecological standpoint.

The future of energy storage lies in innovative technologies based on hydrogen energy, which offer promising and environmentally friendly solutions when successfully implemented. However, the primary challenge surrounding hydrogen storage systems is their current implementation phase, with most hydrogen installations in early or mid-development stages. Accessibility to common consumers is limited, as certain devices required for such systems are not readily available. Furthermore, the investment cost (CAPEX) remains a significant barrier to widespread adoption. Nevertheless, the growing adoption of hydrogen energy technologies in the automotive and electrical sectors, coupled with mass production, is expected to drive down costs over time. Efforts to lower the cost of devices related to hydrogen energy, such as electrolysers and fuel cells, are witnessing a surge of research and publications. Scientists and researchers focus on optimizing hydrogen energy technologies to reduce expenses and promote broader accessibility. This research trend aims to replace precious materials like platinum with more readily available and cost-effective substances, contributing to cost reduction in hydrogen energy systems.

Lastly, the Compressed Air and Hydrogen Energy Storage (CAHES) method represents a unique combination of modern hydrogen-based technology with a more traditional compressed air-based approach. While CAHES is still under investigation and necessitates further research, it holds immense potential for significant improvement. This advancement could result in an efficient and cost-effective solution, viable for residential scale implementation alongside photovoltaic installations. A successful implementation of CAHES technology can lead to reduced energy costs and a more reliable and environmentally friendly energy system.

In conclusion, the current state of energy storage systems in residual installations presents a spectrum of viable options, each with its unique advantages and challenges. The increasing focus on hydrogen energy technologies, along with advancements in BESS and CAHES, represents a promising future for energy storage. Further research and innovation are necessary to optimize these solutions, making them more accessible, cost-effective, and environmentally friendly. As global demand for sustainable energy solutions intensifies, energy storage systems play a crucial role in shaping a greener and more resilient energy future.

Developing cost-effective solutions for long-duration storage systems is one of a key directions for the future researches in this field. While lithium-ion battery solutions dominate the market, they are not sufficient systems for extender storage requirements. Researchers should focus on alternative and innovative technologies. One of the crucial aspects that requires further investigation is post-lithium-ion battery technologies, which will not rely on lithium as a basic material. This element is currently widely sped; however, the lithium mining procedure generates high criticism and inequalities (especially in the regions of Africa). Materials Science and Engineering play a pivotal role in advancing electrical energy storage technologies. Researching new materials for electrodes, electrolytes, and separators to enhance energy density, cycle life, and safety is imperative. Additionally, exploring recycling and second-life applications for retired batteries can minimize environmental impact and optimize the costs of installations.

Along with the great development of artificial intelligence we witness these days, the development of advanced control algorithms for optimal energy usage, dispatch, and grid stability will also be a huge part of the next research. Future research may focus on enhancing predictive analytics capabilities by leveraging computer algorithms. These solutions can analyse vast datasets, including historical energy usage patterns, weather forecasts, market trends, and grid conditions, to provide accurate predictions of energy demand and supply dynamics. AI-driven predictive analytics can enable more efficient energy storage planning and management by predicting energy fluctuations with higher precision.

Interdisciplinary Collaboration is a key to addressing the multifaceted challenges in energy storage. Technological, economic, and social challenges can be solved collectively by fostering collaboration between researchers, engineers, policymakers, and industry stakeholders. By fostering collaboration among these diverse stakeholders, energy storage challenges can be approached from multiple angles, leading to more comprehensive and effective solutions. For example, researchers may develop new battery chemistries with improved performance, engineers can design efficient storage systems based on these innovations, policymakers can create supportive policies and regulations to incentivize deployment, and industry stakeholders can implement and scale up these solutions in the marketplace. In summary, the future of residential electrical energy storage research is characterized by an interdisciplinary approach that encompasses advanced battery technologies, seamless integration with renewable energy sources, smart energy management systems, grid-interactive capabilities, and sustainability considerations. By advancing research in these directions, we can unlock the full potential of residential energy storage to drive the transition towards a more sustainable and resilient energy future.

References

[1] Bouzzine, Y., & Lueg, R. (2021). The Shareholder Value Effect of System Overloads: An Analysis of Investor Responses to the 2003 Blackout in the US. *International Journal of Energy Economics and Policy*, 11(6). doi: 10.32479/ijeep.11756

[2] Blaszke, M., Nowak, M., Śleszyński, P., & Mickiewicz, B. (2021). Investments in Renewable Energy Sources in the Concepts of Local Spatial Policy: The Case of Poland. *Energies*, 14(7902). doi: 10.3390/en14237902

[3] Central Statistical Office. *Environment, Energy*. https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/ [accessed 17 Jan. 2022].

[4] Wciślik, S., & Kotrys-Działak, D. (2021). Thermal building upgrade with off-grid PV system: a Polish case. *Energy Efficiency*, 14, 70. doi: 10.1007/s12053-021-09980-x

[5] Gnatowska, R., & Moryń-Kucharczyk, E. (2021). The place of photovoltaics in Poland's energy mix. *Energies*, 14(5), 1471. doi: 10.3390/en14051471

[6] Jurasz, J. (2016). The impact of temperature variability on the demand for electric power in Poland in 2002−2015. *Przegląd Elektrotechniczny*, 1(9), 259–263. doi: 10.15199/48.2016.09.62 (in Polish).

[7] Jurasz, J., Krzywda, M., & Mikulik, J. (2016). How might residential PV change the energy demand curve in Poland. *E3S Web of Conferences*, 10, 00059. doi: 10.1051/e3sconf/20161000059

[8] Hittinger, E., & Ciez, R.E. (2020). Modeling costs and benefits of energy storage systems. *Annual Review of Environment and Resources*, 45(1), 445–469. doi: 10.1146/annurev-environ-012320-082101

[9] Zakeri, B., Cross, S., Dodds, P.E., & Gissey, G.C. (2021). Policy options for enhancing economic profitability of residential solar photovoltaic with battery energy storage. *Applied Energy*, 290, 116697. doi: 10.1016/j.apenergy.2021.116697

[10] PV Magazine International. *Germany has 200 000 solar-plus-storage systems*. https://www.pv-magazine.com/2020/04/21/germany-has-200000-solar-plus-storage-systems/ [accessed 18 Jan. 2022].

[11] Jarosiński, M., Godlewski, W., & Sierakowski, M. (2021). Cost-effectiveness of PV installations with battery energy storage and proposed changes in prosumer settlement. *Installation Market*, 9/2021 (in Polish).

[12] Popp, H., Attia, J., Delcorso, F., & Trifonova, A. (2014). Lifetime analysis of four different lithium ion batteries for (plug – in) electric vehicle. *Conference: TRA2014 Transport Research Arena*, 14−17 April 2014, Paris, France.

[13] Khalid, A., Stevenson, A., & Sarwat, A.I. (2021). Overview of technical specifications for grid-connected microgrid battery energy storage systems. *IEEE Access: Practical Innovations, Open Solutions*, 9, 163554–163593. doi: 10.1109/access.2021.3132223

[14] Wang, T., Zhao, Y., & Chen, J. (2018). A battery monitoring IC with an isolated communication interface for electric vehicles. *IEICE Electronics Express*, 15(12), 20180513–20180513. doi: 10.1587/elex.15.20180513

[15] Salkuti, S.R. (2020). Comparative analysis of electrochemical energy storage technologies for smart grid. *ELKOMNIKA (Telecommunication Computing Electronics and Control)*, 18. doi: 10.12928/telkomnika.v18i4.14039

[16] Simpson, A.G. (2024). *Parametric modelling of energy consumption in road vehicles*. University of Queensland Library.

[17] Dixon, J., Nakashima, I., Arcos, E.F., & Ortuzar, M. (2010). Electric vehicle using a combination of ultracapacitors and ZEBRA battery. *IEEE Transactions on Industrial Electronics (1982)*, 57(3), 943–949. doi: 10.1109/tie.2009.2027920

[18] Xie, P., Sun, F., Wang, L., & Liu, P. (2019). A review on China's Energy Storage Industry under the "Internet Plus" initiative. *International Journal of Energy Research*, 43(2), 717–741. doi: 10.1002/er.4234

[19] Yuqing, Y., Bremner, S., Menictas, C., & Kay, M. (2018). Battery energy storage system size determination in renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*, 91(8), 109–125. doi: 10.1016/j.rser.2018.03.047

[20] Jingmei, S., Fang, D., Hong, Z., & Mei, C. (2015). Introduction to Electrochemical Energy Storage and Conversion. In book: *Electrochemical Energy: Advanced Materials and Technologies*, Chapter 1. CRC Press. doi: 10.1201/9781351228756

[21] Boparai, K., & Singh, R. (2018). Electrochemical Energy Storage Using Batteries, Superconductors and Hybrid Technologies. In

book K. Boparai, & R. Singh, *Reference Module in Materials Science and Materials Engineering*. doi: 10.1016/B978-0-12-803581-8.11277-9

[22] Bloomberg New Energy Finance. (2019). *A Behind the Scenes Take on Lithium-ion Battery Prices*. https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/ [accessed 17 Jan. 2022].

[23] Figgener, J., Stenzel, P., Kairies, K.P., Linßen, J., Haberschusz, D., Wessels, O., Robinius, M., Stolten, D., & Sauer, D.U. (2021). The development of stationary battery storage systems in Germany – status 2020. *Journal of Energy Storage*, 33, 101982. doi: 10.1016/j.est.2020.101982

[24] Stecca, M., Ramirez Elizondo, L., Batista Soeiro, T., Bauer, P., & Palensky, P. (2020). A comprehensive review of the integration of battery energy storage systems into distribution networks. *IEEE Open Journal of the Industrial Electronics Society*, 1, 46–65. doi: 10.1109/ojies.2020.2981832

[25] Lebrouhi, B.E., Djoupo, J.J., Lamrani, B., Benabdelaziz, K., & Kousksou, T. (2022). Global hydrogen development - A technological and geopolitical overview. *International Journal of Hydrogen Energy*, 47(11), 7016–7048. doi: 10.1016/j.ijhydene.2021.12.076

[26] Li, H., Ma, C., Zou, X., Li, A., Huang, Z., & Zhu, L. (2021). On-board methanol catalytic reforming for hydrogen Production: A review. *International Journal of Hydrogen Energy*, 46(43), 22303–22327. doi: 10.1016/j.ijhydene.2021.04.062

[27] Sdanghi, G., Maranzana, G., Celzard, A., & Fierro, V. (2019). Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. *Renewable and Sustainable Energy Reviews*, 102, 150–170. doi: 10.1016/j.rser.2018.11.028

[28] Chouhan, K., Sinha, S., Kumar, S., & Kumar, S. (2021). Simulation of steam reforming of biogas in an industrial reformer for hydrogen production. *International Journal of Hydrogen Energy*, 46(53), 26809–26824. doi: 10.1016/j.ijhydene.2021.05.152

[29] Sanchez, N., Ruiz, R., Hacker, V., & Cobo, M. (2020). Impact of bioethanol impurities on steam reforming for hydrogen production: A review. *International Journal of Hydrogen Energy*, 45(21), 11923–11942. doi: 10.1016/j.ijhydene.2020.02.159

[30] Ma, Y., Wang, X. R., Li, T., Zhang, J., Gao, J., & Sun, Z.Y. (2021). Hydrogen and ethanol: Production, storage, and transportation. *International Journal of Hydrogen Energy*, 46(54), 27330–27348. doi: 10.1016/j.ijhydene.2021.06.027

[31] Scamman, D., & Newborough, M. (2016). Using surplus nuclear power for hydrogen mobility and power-to-gas in France. *International Journal of Hydrogen Energy*, 41(24), 10080–10089. doi: 10.1016/j.ijhydene.2016.04.166

[32] Zeng, K., & Zhang, D. (2010). Recent progress in alkaline water electrolysis for hydrogen production and applications. *Progress in Energy and Combustion Science*, 36(3), 307−326. doi: 10.1016/j.pecs.2009.11.002

[33] Khalid, F., & Bicer, Y. (2020). High temperature electrolysis of hydrogen bromide gas for hydrogen production using solid oxide membrane electrolyzer. *International Journal of Hydrogen Energy*, 45(9), 5629–5635. doi: 10.1016/j.ijhydene.2019.01.293

[34] Yoon, S., Ahmed, F., Zhang, W., Ryu, T., Jin, L., Kim, D., Kim, W., & Jang, H. (2020). Flexible blend polymer electrolyte membranes with excellent conductivity for fuel cells. *International Journal of Hydrogen Energy*, 45(51), 27611–27621. doi: 10.1016/j.ijhydene.2020.07.076

[35] Węcel, D., & Ogulewicz, W. (2011). Study on the possibility of use of photovoltaic cells for the supply of electrolysers. *Archives of Thermodynamics*, 32(4), 33–53. doi: 10.2478/v10173-011-0030-4

[36] Gago, A., Bürkle, J., Lettenmeier, P., Morawietz, T., Handl, M., Hiesgen, R., Burggraf F., Beltran P., Friedrich K.A.(2018). Degradation of Proton Exchange Membrane (PEM) Electrolysis: The Influence of Current Density. *ECS Transactions*, 86 (13). doi: 10.1149/08613.0695ecst

[37] Zivar, D., Kumar, S., & Foroozesh, J. (2021). Underground hydrogen storage: A comprehensive review. *International Journal of Hydrogen Energy*, 46(45), 23436–23462. doi: 10.1016/j.ijhydene.2020.08.138

[38] Wolf, E. (2015). Large-Scale Hydrogen Energy Storage. In *Electrochemical Energy Storage for Renewable Sources and Grid Balancing* (pp. 129–142). Elsevier doi: 10.1016/B978-0-444-62616-5.00009-7

[39] Olabi, A.G., Bahri, A.S., Abdelghafar, A.A., Baroutaji, A., Sayed, E.T., Alami, A.H., Rezk, H., & Abdelkareem, M.A. (2021). Large-vscale hydrogen production and storage technologies: Current status and future directions. *International Journal of Hydrogen Energy*, 46(45), 23498–23528. doi: 10.1016/j.ijhydene.2020.10.110

[40] Hassan, I.A., Ramadan, H.S., Saleh, M.A., & Hissel, D. (2021). Hydrogen storage technologies for stationary and mobile applications: Review, analysis and perspectives. *Renewable and Sustainable Energy Reviews*, 149, 111311. doi: 10.1016/j.rser.2021.111311

[41] Zheng, J., Zhou, H., Wang, C.G., Ye, E., Xu, J. W., Loh, X.J., & Li, Z. (2021). Current research progress and perspectives on liquid hydrogen rich molecules in sustainable hydrogen storage. *Energy Storage Materials*, 35, 695–722. doi: 10.1016/j.ensm.2020.12.007

[42] Andersson, J., & Grönkvist, S. (2019). Large-scale storage of hydrogen. *International Journal of Hydrogen Energy*, 44(23), 11901–11919. doi: 10.1016/j.ijhydene.2019.03.063

[43] Chi, J., & Yu, H. (2018). Water electrolysis based on renewable energy for hydrogen production. *Cuihua Xuebao/Chinese Journal of Catalysis*, 39(3), 390–394. doi: 10.1016/s1872-2067(17)62949-8

[44] Acar, C., & Dincer, I. (2014). Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *International Journal of Hydrogen Energy*, 39(1), 1–12. doi: 10.1016/j.ijhydene.2013.10.060

[45] Lee, B., Heo, J., Kim, S., Sung, C., Moon, C., Moon, S., & Lim, H. (2018). Economic feasibility studies of high pressure PEM water electrolysis for distributed H2 refueling stations. *Energy Conversion and Management*, 162, 139–144. doi: 10.1016/j.enconman.2018.02.041

[46] Sun, Y., Shen, C., Lai, Q., Liu, W., Wang, D.W., & Aguey-Zinsou, K.F. (2018). Tailoring magnesium based materials for hydrogen storage through synthesis: Current state of the art. *Energy Storage Materials*, 10, 168–198. doi: 10.1016/j.ensm.2017.01.010

[47] Pinsky, R., Sabharwall, P., Hartvigsen, J., & O'Brien, J. (2020). Comparative review of hydrogen production technologies for nuclear hybrid energy systems. *Progress in Nuclear Energy*, 123(103317), 103317. doi: 10.1016/j.pnucene.2020.103317

[48] Shiva Kumar, S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*, 8, 13793–13813. doi: 10.1016/j.egyr.2022.10.127

[49] Balat, M. (2008). Possible methods for hydrogen production. *Energy Sources Part A Recovery Utilization and Environmental Effects*, 31(1), 39–50. doi: 10.1080/15567030701468068

[50] Rashid, M., Al Mesfer, M., Naseem, H., & Danish, M. (2015). Hydrogen production by water electrolysis: a review of alkaline

water electrolysis, PEM water electrolysis and high temperature water electrolysis. *International Journal of Engineering and Advanced Technology*. 4(3), 80−93.

[51] Ursua, A., Gandia, L.M., & Sanchis, P. (2012). Hydrogen production from water electrolysis: Current status and future trends. *Proceedings of the Institute of Electrical and Electronics Engineers*, 100(2), 410–426. doi: 10.1109/jproc. 2011.2156750

[52] Anwar, S., Khan, F., Zhang, Y., & Djire, A. (2021). Recent development in electrocatalysts for hydrogen production through water electrolysis. *International Journal of Hydrogen Energy*, 46(63), 32284–32317. doi: 10.1016/j.ijhydene.2021.06.191

[53] Cheng, J., Zhang, H., Chen, G., & Zhang, Y. (2009). Study of IrxRu1−xO2 oxides as anodic electrocatalysts for solid polymer electrolyte water electrolysis. *Electrochimica Acta*, 54(26), 6250–6256. doi: 10.1016/j.electacta.2009.05.090

[54] Grove, W.R. (1838). *On a new voltaic combination*: To the editors of the Philosophical Magazine and Journal. *The London and Edinburgh Philosophical Magazine and Journal of Science*, 13(84), 430–431. doi: 10.1080/14786443808649618

[55] Thomas, J.M. (2012). W.R. Grove and the fuel cell. *Philosophical Magazine*, 92(31), 3757–3765. doi: 10.1080/14786435. 2012.691216

[56] Mond, L., & Langer, C. (1890). A new Form of Gas Battery, *Proceedings of the Royal Society of London*, 52(46), 296–304.

[57] Jannelli, E., Minutillo, M., & Galloni, E. (2007). Performance of a polymer electrolyte membrane fuel cell system fueled with hydrogen generated by a fuel processor. *Journal of Fuel Cell Science and Technology*, 4(4), 435–440. doi: 10.1115/1.2756568

[58] Luo, Y., Shi, Y., & Cai, N. (2021). Bridging a bi-directional connection between electricity and fuels in hybrid multienergy systems. In *Hybrid Systems and Multi-energy Networks for the Future Energy Internet* (pp. 41–84). Elsevier.

[59] Sharaf, O.Z., & Orhan, M.F. (2014). An overview of fuel cell technology: Fundamentals and applications. *Renewable and Sustainable Energy Reviews*, 32, 810–853. doi: 10.1016/j.rser. 2014.01.012

[60] Magar, Y.N. (2006). *Convective Cooling and Thermal Management Optimization of Planar Anode-Supported Solid Oxide Fuel Cells*. M.S. Thesis. University of Cincinnati.

[61] Polat, C., & Kilinc-Ata, N. (2008). Market Opportunities for Hydrogen Solid Oxide Fuel Cells (SOFC): A Review of the Literature and the Future Market Trends. *Business & Economics Conferences (EABR) and Teaching & Education Conferences (TLC).* 23−26 June 2008, Salzburg, Austria.

[62] Vang, J.R., Andreasen, S.J., & Kær, S.K. (2012). A transient fuel cell model to simulate HTPEM fuel cell impedance spectra. *Journal of Fuel Cell Science and Technology*, 9(2). doi: 10.1115/1.4005609

[63] Breeze, P. (2017). An introduction to fuel cells. In *Fuel Cells* (pp. 1–10). Elsevier. doi: 10.1016/B978-0-08-101039-6.00001-7

[64] Baik, K.D., & Yang, S.H. (2020). Improving open-cathode polymer electrolyte membrane fuel cell performance using multi-hole separators. *International Journal of Hydrogen Energy*, 45(15), 9004–9009. doi: 10.1016/j.ijhydene.2020.01.040

[65] Wong, C.Y., Wong, W.Y., Ramya, K., Khalid, M., Loh, K.S., Daud, W.R. W., Lim, K.L., Walvekar, R., & Kadhum, A.A.H. (2019). Additives in proton exchange membranes for low- and high-temperature fuel cell applications: A review. *International Journal of Hydrogen Energy*, 44(12), 6116–6135. doi: 10.1016/ j.ijhydene.2019.01.084

[66] Tu, B., Qi, H., Yin, Y., Zhang, T., Liu, D., Han, S., Zhang, F., Su, X., Cui, D., & Cheng, M. (2021). Effects of methane processing strategy on fuel composition, electrical and thermal efficiency of solid oxide fuel cell. *International Journal of Hydrogen Energy*, 46(52), 26537–26549. doi: 10.1016/j.ijhydene.2021.05.128

[67] Gaines, L.L., Elgowainy, A., & Wang, M.Q. (2008). *Full fuel-cycle comparison of forklift propulsion systems.* Office of Scientific and Technical Information (OSTI), ID 946421. doi: 10.2172/946421

[68] Al Rafea, K., Elsholkami, M., Elkamel, A., & Fowler, M. (2017). Integration of decentralized energy systems with utility-scale energy storage through underground hydrogen–natural gas co-storage using the energy hub approach. *Industrial and Engineering Chemistry Research*, 56(8), 2310–2330. doi: 10.1021/acs.iecr.6b02861

[69] Bartela, Ł. (2020). A hybrid energy storage system using compressed air and hydrogen as the energy carrier. *Energy*, 196, 117088. doi: 10.1016/j.energy.2020.117088

[70] Bartela, Ł., Chmielniak, T., & Kotowicz, J. (2018). *A way of integration of energy storage systems using in hydrogen and compressed air*. Patent No. PL 235565 B1, Poland (in Polish).