**UNIVERSITY OF DEBRECEN**
**FACULTY OF ENGINEERING**
**DEPARTMENT OF**
**MECHANICAL ENGINEERING**

# COMPARISON AND EVALUATION OF ENERGY STORAGE SYSTEMS

**THESIS**

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Debrecen
2024

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| | |
|---|---|
| $C$ | Battery's volume |
| $\eta_c = \frac{\int_o^{td} I_d dt}{\int_o^{tc} I_c \, dt}$ | Columbic efiiciency |
| $\eta_v = \frac{V_d}{V_c}$ | Voltage efficiency |
| $\eta_B = \eta_v \eta_c$ | Round trip efficiency |
| $\Delta E$ | Retrievable kinetic energy |
| I | moment of inertia |
| Ω | angular velocity/speed |
| ω^2 max | maximum flywheel speed |
| ω^2 min | minimum flywheel speed |
| $P_S$ | Power from the SMES |
| $P_B$ | Power from the battery |
| $P_{grid}$ | Grid power |
| $E_{ini}$ | Initial stored capacity |
| $E_{max}$ | Maximum storage capacity |
| $P_{dis}\, P_{ch}$ | Charge and Discharge power value |
| $\eta_{ch} P_{ch}$ | charge and discharge efficiency valu |

# INTRODUCTION

Energy storage has been a challenge since the revolution of renewable energy. Energy storage systems are crucial for integrating renewable energy sources into the power grid. The growing presence of variable renewable resources requires the implementation of extensive energy storage systems to guarantee the long-term reliability and stability of the power grid[1].

Currently, photovoltaic (PV) power plants are experiencing the most rapid growth among renewable energy sources globally. The rapid expansion of photovoltaic (PV) sources is adversely impacting the control of the electric power system. An approach to alleviate this impact is to store the energy produced by photovoltaic (PV) systems during periods of surplus electricity in the electrical grid and distribute it to the grid when needed, namely during peak periods of the daily load curve[2]. This challenge is described in a chart called the "Duck curve" as shown below:

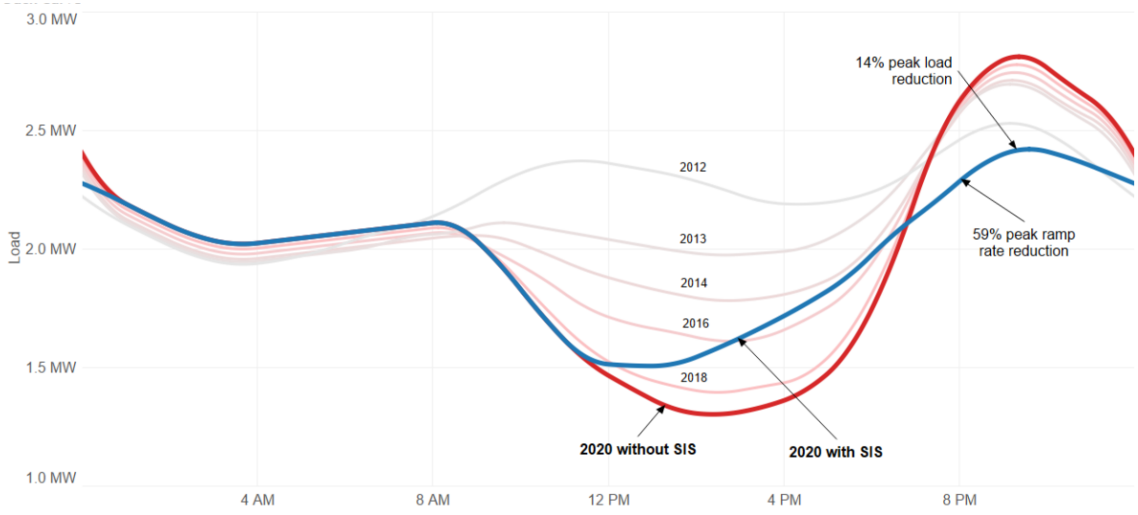



Fig. 1.0 The Duck Curve [3]

From the curve, it is shown that at midday, when PV electricity supply is high, the power demand is low, and when the demand is high in the morning or night, the supply is low. With this cycle, the energy supply at midday goes to waste. On the other hand, the peaks of demand should be supplied from either stored energy or from surplus capacities of (traditional) power generation.

To lessen this impact, PV energy can be stored during times of grid oversupply and fed back in during times of peak demand on the daily load curve [2]. As the curbing measures of the challenges faced in energy supply and demand progress, it becomes increasingly apparent that energy storage will be crucial in the push to increase the integration of variable renewable sources into power infrastructures around the world.

Regardless of the way these efforts to mitigate it are carried out, it is becoming evident to all parties involved that energy storage will play a crucial role in the endeavor to enhance the Integration of varied renewable sources into worldwide power grids. Strategically implemented storage technologies can decrease the highest level of electricity demand, enhance everyday dependability, offer backup power during generation interruptions, lower costs for consumers and utilities by alleviating load balancing difficulties, reduce emissions and enhance the integration of distributed and renewable energy into the power system.
[4]. Storage systems are designed to store surplus energy and release it when there is a high demand for electricity. They also help to reduce the intermittent nature of solar energy. Storage provides significant benefits to the energy industry. Storage has a beneficial impact on both off-grid and grid-connected setups by enhancing the use of photovoltaic (PV) systems [5].

# 1. ENERGY STORAGE TECHNOLOGIES

Energy storage technologies comprise a variety of systems that are crucial for maintaining grid stability, incorporating renewable energy sources, and addressing changing energy needs. These technologies can be categorized into different groups according to their operational principles and uses. Energy storage can be classified into different types based upon the form of energy stored. These categories include electrical energy storage, magnetic energy storage, mechanical energy storage, thermal energy storage, electrochemical energy storage, and chemical energy storage [6].

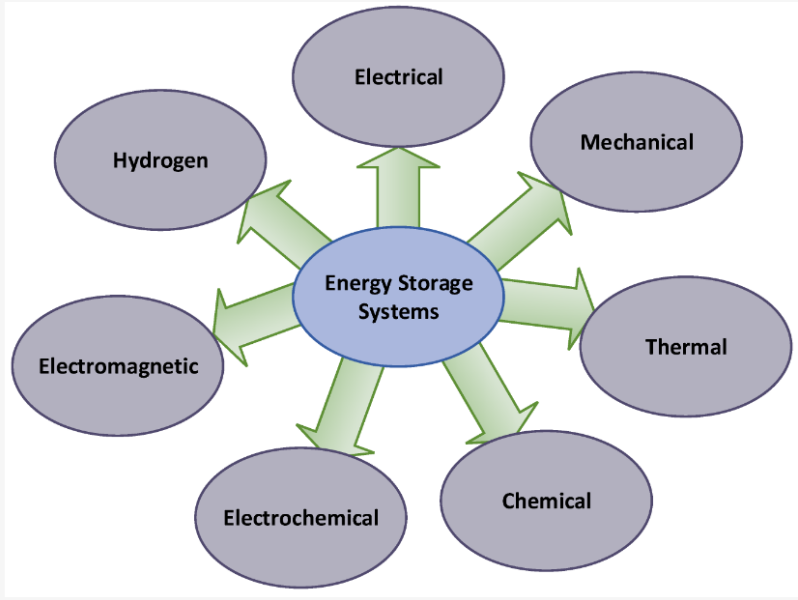



Fig. 1.1 Classification of energy storage sytem [7]

## 1.1. Mechanical Energy Storage

### 1.1.1. Flywheels (FESS)

Flywheels store energy in the form of kinetic energy and are commonly used in various applications such as energy storage systems and transportation. They work by spinning a rotor at high speeds, which stores the energy in its rotational motion. This stored energy can then be released when needed, providing a reliable and efficient source of power. Flywheel-based energy storage systems are suitable whenever numerous charge and discharge cycles are needed with medium to high power during short periods (seconds) [8]. Flywheels offer several advantages over other energy storage methods, including high power density, fast response times, and long cycle life. They are also environmentally friendly as they do not produce any emissions during operation. Flywheels exhibit rapid response times for both charging and discharging operations; however, they are limited in their ability to store large amounts of energy. This characteristic renders them more appropriate for grid quality control. In addition, they exhibit low resistance to external mechanical impacts that cause vibrations and subsequently lead to power loss,

results in major changes in both the amplitude and frequency of the output voltage [9].

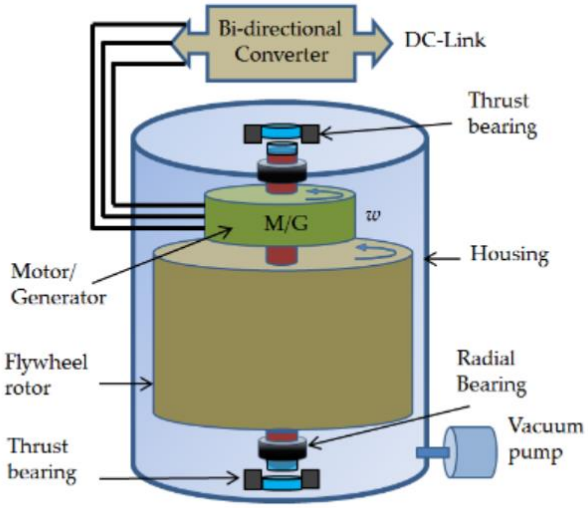



Fig.1.1.1 How a flywheel works [10]

The motor generator function efficiently extracts energy from the rotor during power outages or periods of low energy. This causes the rotor to slow down. Additionally, the FES system can be utilized for both planned, long-term energy supply and emergencies. Unlike several alternative energy-storage methods, this process of charging and discharging can be repeated without any observable deterioration or aging mechanism.

Challenges

The initial appeal of FESS designs is both compelling and distinctive. During the period from the 1950s to the 1970s, municipal buses were subjected to testing as a potential mobile power source. However, none of these buses proved to be successful, and consequently, all of them were subsequently removed from service. Among the multiple reasons mentioned, there is a distinction between starting or stopping a traditional engine in the workshop to assess its performance and having to initiate or terminate the rotation of a rotor and wait. There were discussions on implementing FESS (Flywheel Energy Storage System) in conventional automobiles equipped with a compact internal combustion engine to initiate the rotation of the rotor, even when the vehicle was stationary. Nevertheless, individuals expressed unease over the concept of a rotating rotor located in the vehicle's trunk, even when equipped with an additional protective enclosure. This enclosure also contributed to the overall weight of the vehicle. Subsequently, there were problems with the handling of the vehicle caused by gyroscopic forces [10].

Although flywheel-based energy storage may initially appear appealing, it poses several significant obstacles. The amount of energy stored is directly proportional to the moment of inertia of the rotor wheel and the square of the rotational speed. Therefore, it is desirable to have a relatively high rpm, often ranging from 50,000 to 100,000 rpm. The rotor is subjected to clear material strains, which have major

effects in terms of both micro-failures and macro-catastrophes, both in the short and long term [11].

The chamber housing the rotor must be a vacuum to prevent air-induced friction, which could lead to excessive heating of the rotor. Traditional ball or mechanical bearings are not suitable for this application; Therefore, an active closed-loop magnetic-levitation bearing is used [10].

### 1.1.2. Pumped hydro storage (PHES)

Pumped hydro energy storage is the predominant energy storage method utilized inside energy systems on a significant scale [12]. It involves using excess electricity to pump water uphill into a reservoir, and then releasing the water downhill through turbines to generate electricity when demand is high. Pumped hydro storage systems have a long lifespan and can provide large amounts of energy for extended periods of time, making them an important component of grid stability and renewable energy integration.

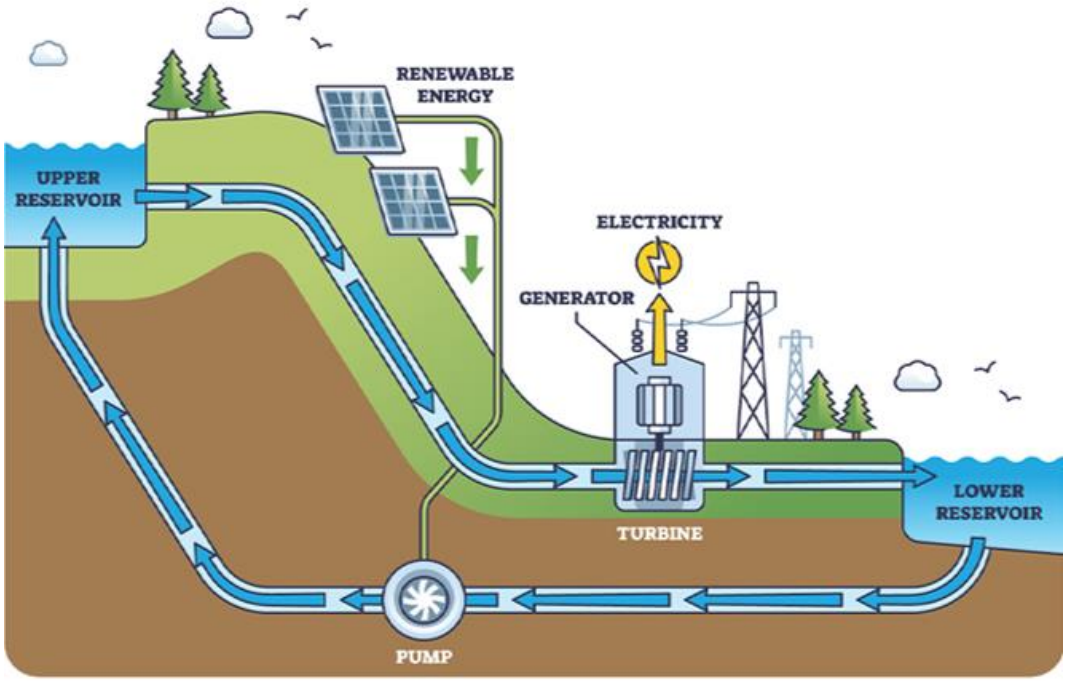



Fig. 1.1.2 Pumped hydro storage [13]

Due to its large capacity, PHES is used in storing and producing energy on a large scale, but it has the geographical challenge as it requires some geographical features like good elevation difference and access to water source [9]. The installation of pumped hydro storage plants might incur high expenses because of the requirement for substantial infrastructure. Notwithstanding these limitations, pumped hydro storage continues to be a key technology for ensuring the dependability of power grids, facilitating the incorporation of renewable energy sources, and enabling large-scale energy storage.

### 1.1.3. Compressed air energy storage (CAES)

Compressed air energy storage (CAES) has been widely recognized as a well-established and very promising technique for the storage of energy on a large scale [14]. It is considered one of the most mature technologies for grid-scale storage.

A-CAES is a highly efficient and environmentally friendly method for integrating renewable energy sources and managing peak energy demands. This technology is characterized by its substantial capacity, efficient operation, and little carbon emissions [15]. The system has the capability to store and release energy through the compression and expansion of air, without relying on a thermal fluid.

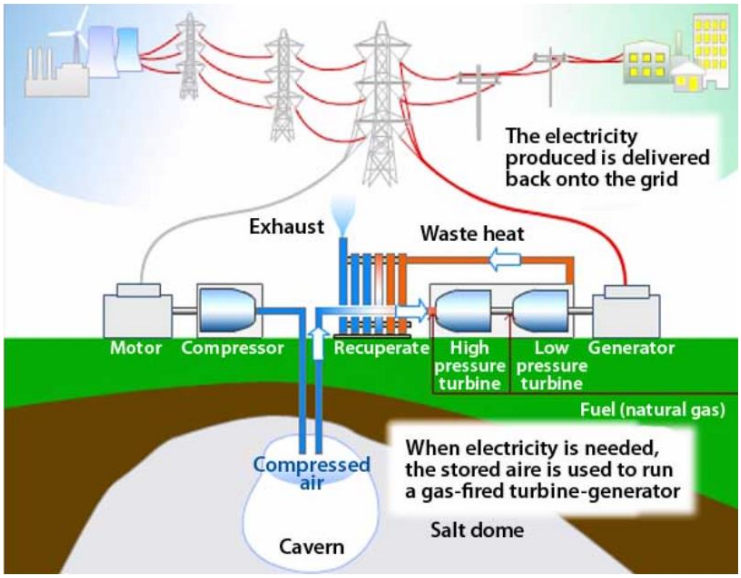



Fig. 1.1.3 How a CAES works [16].

*Table 1 Characteristics of mechanical energy storage options* [4]

| Energy storage echnology | Energy Efficiency (%) | cost | Discharge time | Self-discharge per day | Energy Density (Wh/kg) | cycle life | Power rating (MW) |
|---|---|---|---|---|---|---|---|
| Flywheel | 95 | | Milli-seconds-15min | 100% | 100-130 | >125,000 | 0-1 |
| PHES | 65-80 | $1700-$5100/kW | 1-24h+ | Very small | 0.3 | 75years | 100-5000 |
| CAES | 50 | o | 1-24h+ | small | 10-30 | 40years | 5-400 |

## 1.2. Electrochemical Energy Storage

Electrochemical energy storage is a key part of making sure that renewable energy sources are stable and reliable. It does this by storing excess energy when production is high and releasing it when demand is high. Additionally, progress in this area has led to the creation of batteries that perform better and cost less, which makes them perfect for powering portable electronics and accelerating up the acceptance of electric transportation [17]. Electrochemical storage devices are in the form of batteries.

### 1.2.1. Conventional batteries

Battery storage plays a crucial role in the utilization of solar power by addressing the intermittent nature of solar energy [18]. The integration of battery systems with solar power offers numerous benefits, including managing peak demands, improving grid reliability, and facilitating the integration of renewable energy sources. Several types of batteries are being explored for grid applications.

Sodium-sulfur batteries are commercially available, has a high energy density and also field proven and have been used for grid-scale energy storage, but one challenge is the shuttle effect, which refers to the migration of polysulfide species between the cathode and anode during charge and discharge cycles, and also sodium sulfur has a high operating temperature, this can lead to capacity loss and poor cycle life, although, strategies to immobilize polysulfides and prevent their migration have been explored to mitigate this issue [19].

The power output of a Redox flow battery can be easily adjusted by changing the size of the electrode and the flow rate of the electrolyte, allowing for more flexibility in meeting different power demands. Redox-flow batteries offer the advantage of scalability and suitability for large-scale storage, but it has a low energy density and expensive compared to other batteries [20].

Lead acid batteries are the most used in energy storage including PV system, it is the oldest rechargeable battery in existence, widely available, deep discharge capability, good performance at high and low temperatures, cheap and easy to manufacture and suitable for off grid application [19]. However, it has low specific energy, long charge and is not environmentally friendly [9].

Maybe the most spreading type of batteries now is Lithium ion, although the lithium element is rare, but it is the most used currently. They can be made smaller and lighter, have a high energy density and low self-discharge rate [21]. It can overheat and cause an explosion if not properly managed, long-time availability of Lithium is not ensured [22].

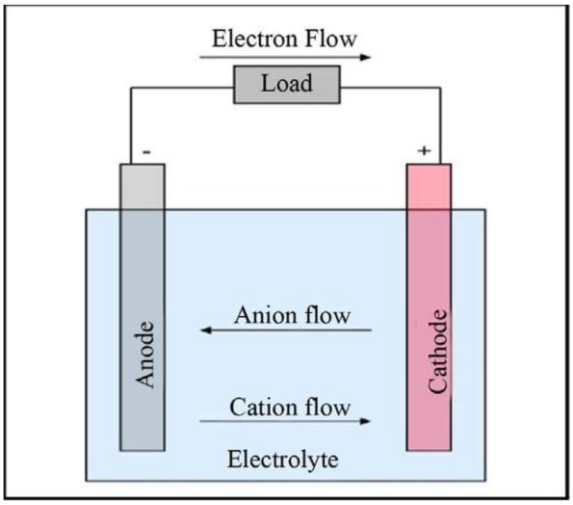



Fig. 1.2.1 Operation of a battery [23]

*Table 2 Characteristics of electrochemical storage options* [24]

| Energy storage technology | Energy Efficiency (%) | cost | Discharge time | Self-discharge per day | Energy Density (Wh/kg) | cycle life (cycles) | Power rating (MW) |
|---|---|---|---|---|---|---|---|
| Lead acid | >70 | ○ | Seconds-hours | 0.1-0.3% | 30 -50 | 1500 | 0-20 |
| Lithium ion | ~90 | $2500-$3900/kW | Minutes-hours | 0.1-0.3% | 150-200 | 5000 | 0-100kW |
| Sodium sulphur | 75-90 | ○ | ○ | 0.2 – 15% | >200 | 4500 | 15 – 100kW |
| Redox flow | 82 | ○ | Seconds-hours | small | 15 - 25 | >12,000–14,000 | 30kW-3MW |

*Table 3 Pros and Cons analysis of electrochemical storage options* [25] [26] [21]

| Technologies | Pros | Cons |
|---|---|---|
| Lithium ion | - Can be made smaller and lighter<br>-high energy density<br>-low self-discharge rate | -Thermal runaway<br>- Rare element |
| Lead aid | -wide availability<br>-deep discharge capability<br>-suitable for off-grid application | -No maintenance<br>-cheap and easy to manufacture<br>-Good performance at high and low temperatures |
| Sodium sulfur | -commercially available<br>-high energy density | -Shuttle effect<br>- High operating temperature |
| Redox flow | -long lifecycle<br>-suitable for large scale storage | -Limited life cycle<br>-high maintenance requirements<br>-low energy density |

## 1.3. Electromagnetic Energy Storage

### 1.3.1. Supercapacitors

Supercapacitors, which are also called ultracapacitors or electrochemical capacitors, are energy storage devices that are getting a lot of interest because of their high-power density, have a long lifespan, and charge and discharge quickly. Instead of chemical reactions, supercapacitors store energy by separating positive and negative charges on the electrodes' surfaces. Because of their special way of working, supercapacitors can store and release energy quickly and efficiently. This makes them perfect for uses that need short bursts of power, like electric cars and regenerative braking systems [27].

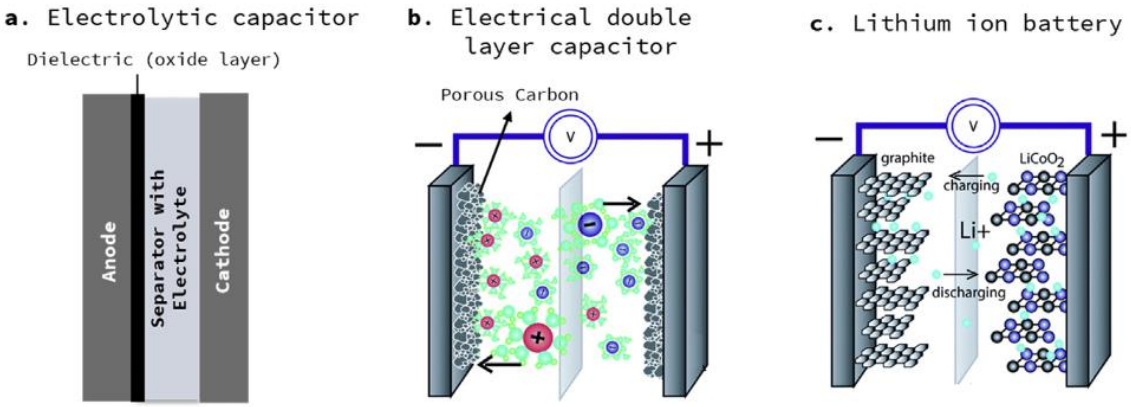



Fig.1.3.1 Illustrations of (a) electrolytic capacitor, (b) super-capacitor, and (c) lithium-ion battery [28].

### 1.3.2. Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage (SMES) is an energy storage system that utilizes a superconductor to store energy in the form of direct current (DC) electricity. This is achieved by moving current through the superconductor, which in turn creates a DC magnetic field to store the energy. [9].

The utilization of magnetic energy storage systems has garnered a lot of interest owing to its potential in boosting the efficiency and durability of power systems, particularly when integrated with renewable energy sources. Superconducting Magnetic Energy Storage (SMES) has been identified as a very promising technology for energy storage due to its ability to provide rapid reaction and achieve high energy density. Furthermore, the implementation of Superconducting Magnetic Energy Storage (SMES) has been suggested as a means of stabilizing power flow in microgrids that incorporate solar generating [29]. Moreover, the significance of Superconducting Magnetic Energy Storage (SMES) in boosting the performance of dynamic systems has been confirmed, highlighting its potential to increase the stability and dependability of power systems [30].

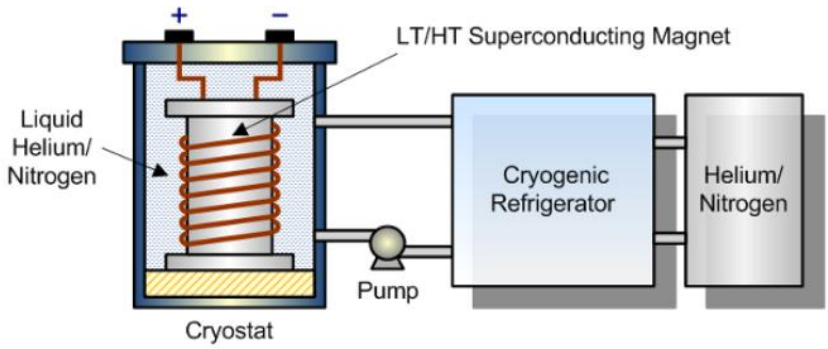



Fig. 1.3.2 Illustration of an SMES system [31]

*Table 3 Characteristics of electrical storage options* [4]

| Energy storage technology | Energy Efficiency (%) | cost | Discharge time | Self-discharge per day | Energy Density (Wh/kg) | cycle life | Power rating (MW) |
|---|---|---|---|---|---|---|---|
| Super-capacitor | 95 | | Minutes | 10-20% | <50 | 10k – 100k | 10kW |
| SMES | >95 | 1000-10000 $/kWh | Milli-seconds to minutes | Very high | 20 MW/hr | 20+ years | 20-40MW [**Error! Reference source not found.**] |

## 1.4. Power to Gas Storage System

Power-to-Gas (PtoG) energy storage is an exciting breakthrough that converts excess or intermittent power into gaseous hydrogen. It is used for storing energy for a long time and managing grid congestion. Power-to-Gas technology may be suitable for seasonal energy storage purposes, particularly in cases where energy is generated during periods of low demand, such as the winter season, and stored for later use during peak demand days in the summer. By harvesting surplus energy to generate hydrogen through the process of water electrolysis, it is possible to store and distribute energy within the current natural gas systems, allowing for use at the desired time and location, which in turn allows for seamless integration of renewable energy sources such as solar or wind power [32].

The P2G process encompasses the conversion of electrical energy into gaseous energy carriers, such as hydrogen or methane, by means of water electrolysis and, if desired, methanation. This process offers enhanced adaptability to the electrical system and serves as an economically viable method for long-term energy storage [33].

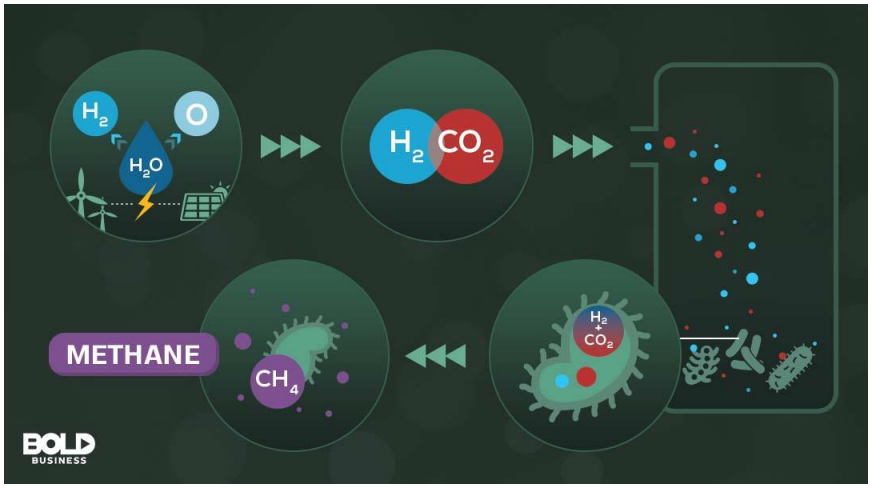



Fig. 1.4 A power to gas system [34]

### 1.4.1. Hydrogen fuel cell

Hydrogen (H2) is the most abundant element in the universe (75%), the lightest, and the one with the highest density (ρ) of energy around 120 kJ/g. Hydrogen is not considered a sustainable energy source; rather, it serves as a means of storage and energy delivery. It can be derived from either renewable sources or fossil fuels. Hydrogen gas (H2) has a high degree of versatility due to its ability to be stored in large amounts and its nonpolluting nature. The combustion of hydrogen only releases moisture, hence exhibiting an acceptable environmental impact [9].

Fuel cells are electrochemical devices that facilitate the conversion of chemical energy that's present in a fuel, such as hydrogen, into electrical energy by means of an electrochemical process. These devices possess notable attributes such as great energy efficiency, low emissions, and reduced operational noise, rendering them appealing for a wide range of uses, including mobility, stationary power generation, and portable electronics. Fuel cells possess the capacity to fundamentally transform the way we generate power for our vehicles and households. This is because of the way they generate electricity without involving the process of combustion, so leading to a decrease in the emission of greenhouse gases and an enhancement in the quality of air. In addition, fuel cells possess the benefits of easy refueling and extended lifespans in comparison to conventional batteries, rendering them a highly attractive prospect for the attainment of a sustainable energy future [35]. The utilization of hydrogen in fuel cells currently constitutes a very little proportion in the market, although it holds significant potential for future expansion.

*Table 4 Characteristics of Power to Gas storage options*

| Energy storage technology | Energy Efficiency (%) | Discharge time | Self-discharge per day | Energy Density (Wh/kg) | cycle life | Power rating (MW) |
|---|---|---|---|---|---|---|
| Hydrogen fuel cells | 40 – 60 | Seconds-24h+ | Almost zero | ~33.6 | ○ | 0-50MW |

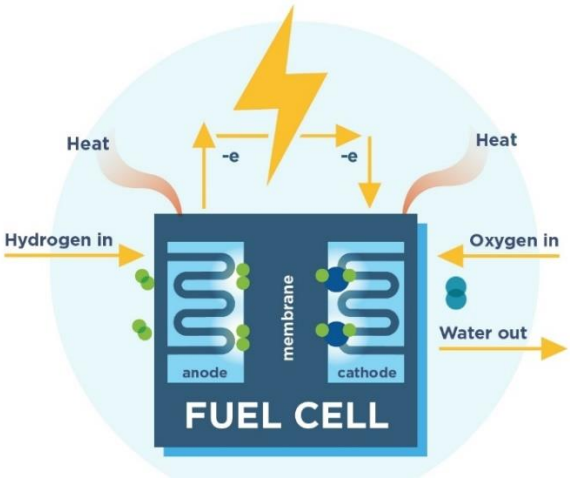



Fig. 1.4.1. Hydrogen fuel cell [36]

## 1.5. Thermal Storage

Thermal energy storage (TES) is mostly used in concentrated solar power plant, In the field of thermal energy storage (TES), materials are commonly classified into

three distinct categories: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (THS). Sensible heat storage encompasses materials such as water, air, oil, rocks, brine, concrete, sand, and soil. It involves storing thermal energy within the storage medium by increasing temperature without undergoing any phase transformation [37]. Latent heat storage involves the use of organic and inorganic substances, eutectics, and low-melting-point metals. It is important to think about the materials and uses of phase change energy storage to figure out the cost, power density, and discharge time of latent heat storage. Phase change materials (PCM), also referred to as latent heat storage, are favored over sensible storage due to their notable storage density and limited phase transition range [38]. Phase change materials (PCMs) are very important in latent heat thermal energy storage systems (LHS) because they can take in, store, or release a lot of latent heat through changes in phase [39]. Nevertheless, phase-change materials (PCMs) exhibit the drawback of possessing low thermal conductivity. Both sensible and latent heat storage systems have the capability to store heat for a specific duration, often lasting a few hours. These thermal energy storage (TES) systems are incapable of retaining energy for an extended duration, such as a whole season. Specifically, they lack the ability to accumulate excess energy during the summer months, characterized by longer periods of sunlight, and subsequently utilize this stored energy throughout the winter season. In terms of achieving the desired objective, THS is considered a more feasible option due to its utilization of high-energy-intensive endothermic processes [40]. The gas-solid reaction is used in thermochemical heat storage methods. Thermochemical heat storage (THS) exhibits considerable potential as a method for the effective conversion and storage of underutilized thermal energy. It presents numerous benefits in comparison to alternative energy storage methods, including a relatively high energy density which can reach levels up to ten times higher than that of latent heat storage. and the ability to store energy for extended periods of time at ambient temperature conditions [41]. Thermochemical heat Storage (THS) possesses the capability to be employed in forthcoming power generation facilities that operate at elevated temperatures.

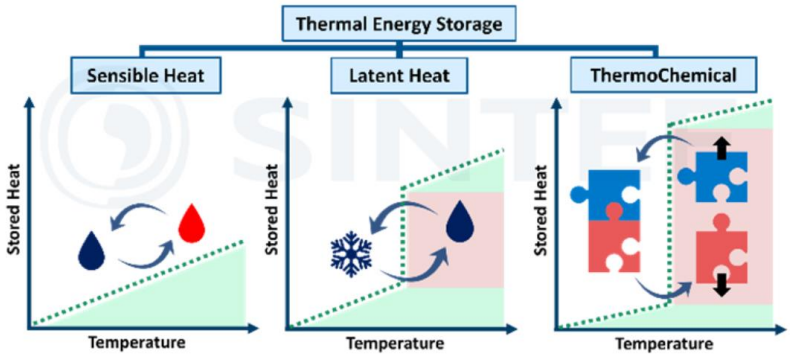



Fig. 1.5 Classification of TES systems and the heat stored with temperature variation [42].

Concentrated Solar Power (CSP) systems are highly efficient in using focused sunlight to heat a thermal storage medium to high temperatures, thus generating heat for thermal energy storage (TES). After focusing the intense sunlight onto the receiver, the thermal storage material inside the receiver is heated. The thermal storage medium can consist of either a liquid, such as molten salts, oil, or a heat transfer fluid (HTF), or a solid substance, such as rocks or concrete. The selection of the thermal storage media is contingent upon parameters such as the desired temperature, thermal durability, and cost-efficiency [43].
When there is a requirement for thermal power, the heat that is stored can be removed from the storage media and used as desired. This can be accomplished by passing the warmed thermal storage medium via a heat exchanger to transfer the thermal energy to a working fluid, such as water or oil, or straight to the final application.

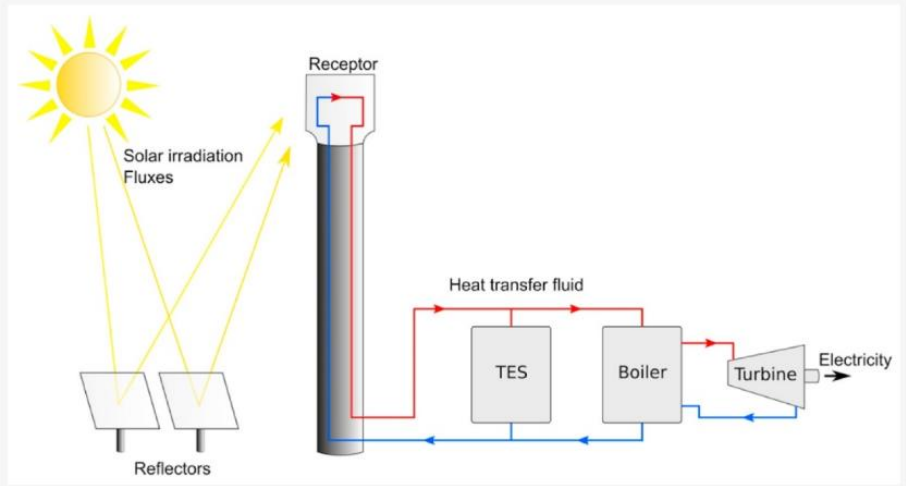



Fig. 1.6 A CSP and TESS [40]

*Table 5 Characteristics of thermal storage options* [44]

| TES System | Capacity (kWh/t) | Power MW) | Efficiency (%) | Storage period (h, d, m) | Cost (€/kWh)) |
|---|---|---|---|---|---|
| Sensible (hot water | 10 – 50 | 0.001 - 10 | 50 – 90 | Days-months | 0.1 – 10 |
| PCM | 50- 150 | 0.001 – 1 | 75 – 90 | Hours - months | 10 – 50 |
| Chemical reactions | 120 - 250 | 0.01 - 1 | 75 - 100 | Hours - days | 8 - 100 |

# 2. APPLICATIONS

## 2.1. Small scale applications (household, mobile and small businesses)

The daily consumption patterns of residential households exhibit a range of fluctuations. Typically, there are two distinct periods of high consumption observed: one occurring in the morning between the hours of 6 and 8, and another taking place in the evening at approximately 20 hours. The observed peak largely arises because of the population's active working period. During the morning peak, there is a notable surge in household demand as individuals wake and engage in various chores, such as showering, cooking breakfast, and preparing for their daily work or educational commitments. Likewise, the evening peak manifests because of individuals' reentry into their residences following their daily engagements, resulting in an upsurge in energy consumption for activities such as meal preparation, use of electronic devices, in addition to using grid electricity, a hybrid system can be used to better control usage. The implementation of a hybrid system supports the integration of renewable energy sources, such as solar power, thereby enabling a reduction of energy consumption derived from the grid. With the utilization of solar energy during daylight hours, homeowners and small business owners can minimize their dependence on conventional electricity sources and potentially decrease their overall energy expenses. Furthermore, the capacity to effectively oversee and track consumption patterns via a hybrid system offers significant data for enhancing energy utilization and generating well-informed decisions regarding future energy investments.

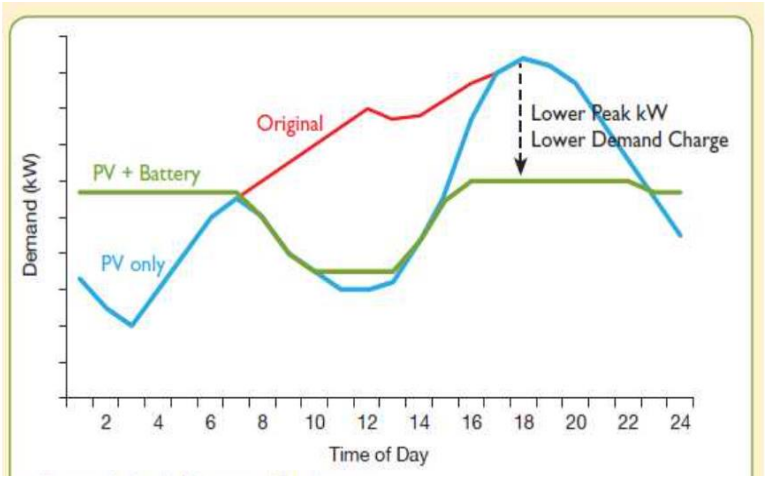



Fig. 2.1 Peak demand reduction with PV system and battery storage [4]

## 2.2. Large scale (industrial and commercial)

To assess the influence of storage on commercial and industrial applications, it is imperative to consider the specific daily consumption profile being targeted. This

profile can vary significantly depending on the nature of the application in question. It can be proposed that the highest level of consumption in commercial and service buildings occurs throughout the period of 9:00 AM to 7:00 PM. In the context of various industries, it is important to note that the peak consumption levels may vary, depending on the specific industry in question. There are those that engage in a continuous work schedule of 24 hours per day, 7 days per week, while others adhere to a more conventional work schedule of 9 hours from 9 am to 6 pm, 5 days per week.

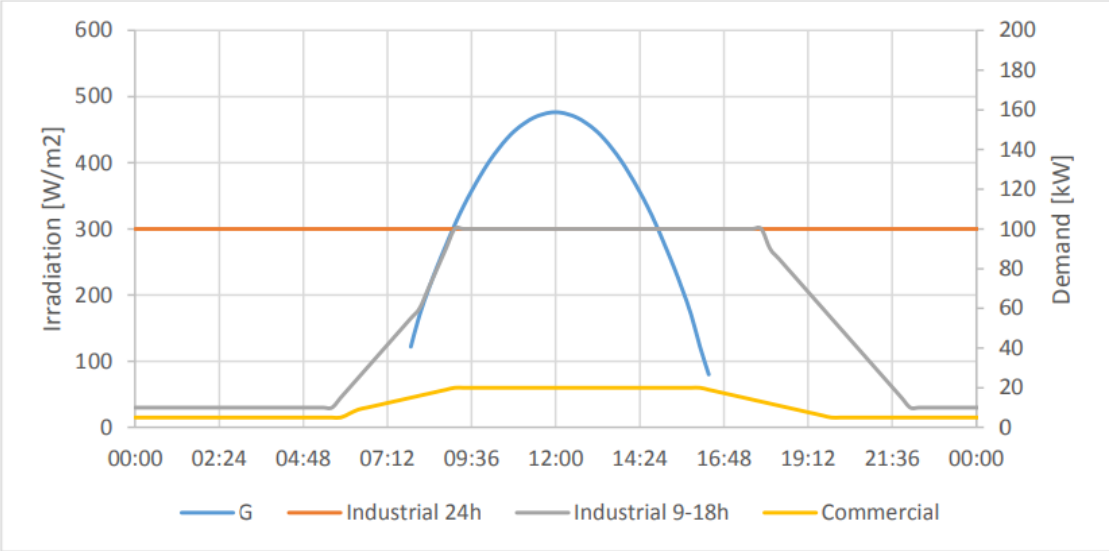



Fig. 2.2 Industrial and commercial energy demand [9]

To achieve balance, it is necessary to incorporate a hybrid system consisting of photovoltaic panels and batteries, especially hydrogen fuel cells mostly because of its high efficiency, low emission, and large storage capacity. In the context of an industrial application, the contracted power of 100 kW for example, the power supply in question would remain uninterrupted for a duration of 24 hours, concerning industries that work during nighttime or those who operate from 9-18hours. In the latter case, there would be an additional residual usage of around 6 kW. Residual consumption covers some equipment that stays active throughout the night.

In the scenario of an industry operating continuously, a suitable strategy would involve the implementation of a hybrid system that combines direct energy consumption with the utilization of photovoltaic panels. This system would not only facilitate the direct utilization of energy but also incorporate battery storage capabilities. The batteries would experience discharge throughout the night period, specifically between the hours of 16:00 and 24:00. During off-peak hours, particularly between 0:00 and 7:00, it is preferable to use the grid as the cost of energy currently frame is somewhat lower.

The optimal method for commercial solar energy storage is the utilization of pumped hydro storage. The technology exhibits a notably efficient method for storing energy at a substantial scale, possesses a prolonged lifespan, and

demonstrates the capability to retain energy stored over extended periods, potentially spanning several decades. Furthermore, pumped hydroelectric storage systems possess the capacity to promptly adapt to fluctuations in energy demand, rendering them exceptionally versatile and dependable for commercial utilization. Moreover, this technology exhibits an environmentally conscious characteristic as it does not generate any gas emissions while in operation, so making a valuable contribution towards the attainment of a sustainable energy future.

The next example makes it clear where pumped hydroelectric storage systems stand in comparison to other ways to store energy. PHS systems in the USA made up 93% of utility-scale storage power capacity and over 99% of electrical energy storage in 2019. They were responsible for 553 GWh of energy storage. When all utility-scale energy storage projects, like batteries, flywheels, solar thermal with energy storage, and natural gas with compressed air energy storage, were added together by the end of 2019, they only added up to 1.6 GW of power capacity and 1.75 GWh of energy storage capacity. In terms of power capacity and energy storage capacity, these numbers show how important pumped hydroelectric storage systems are in the United States [45].

## 2.3. Maturity and durability of energy storage systems

Based on how well-developed each energy storage technology is, pumped hydro is the most developed and CAES (Compressed Air Energy Storage) is another well-established technology. Using pumped hydro has been around for a long time and is common all over the world. It is a safe and efficient way to store energy. On the other hand, CAES has also been shown to be a good way to store large amounts of energy. It does this by using compressed air to store energy and release it when it's needed. Both technologies have shown that they work, and they are now being improved and created to make them even more useful and cost-effective. Furthermore, batteries have shown promise as a possible way to store a lot of energy, and as technology keeps getting better, they become more efficient and cheaper. The stages and durability of the energy storage systems are shown in the figure below:

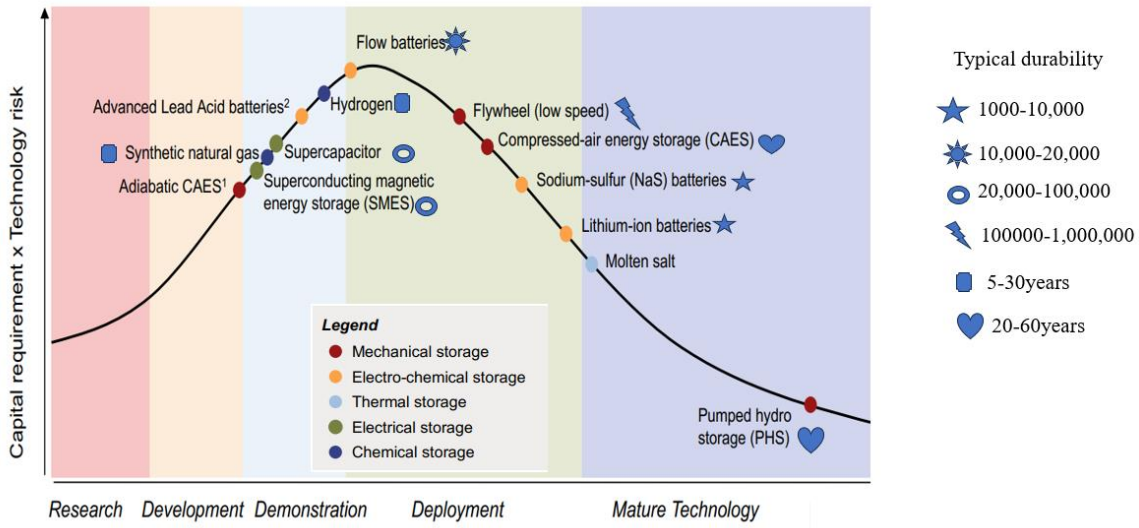



Fig. 2.3 Maturity and durability curve

# 3. CALCULATIONS OF BATTERY STORAGE OPTIONS FOR STATIONARY AND MOBILE USES

Governments around the world are implementing innovative measures to promote the adoption of renewable energy in response to the increasing global need for sustainable energy alternatives. Corresponding to this dedication, the Hungarian government has recently implemented the Solar Plusz program, an innovative initiative aimed at encouraging and facilitating the incorporation of solar photovoltaic (PV) systems into residential properties. Within this extensive program, there is a crucial focus on enabling users to fully utilize solar energy by integrating effective energy storage devices, including batteries.

The Solar Plusz program acknowledges the crucial significance of energy storage in maximizing the efficiency of solar power use. Energy storage, in the form of batteries, plays a vital role in reducing the irregularity that is inherent in the production of solar energy. Batteries improve the efficiency and economic feasibility of residential solar installations by enabling families to store surplus solar energy generated during peak sunshine and using it during times of low output or high usage. Battery energy storage systems (BESS) are the predominant kind of energy storage that may be incorporated into grid-connected photovoltaic (PV) systems. A battery is employed to store energy during periods when photovoltaic power is unavailable. Therefore, the selection of batteries in a PV system must match the load requirements. Determining the battery storage capacity for both mobile and stationary purposes require careful analysis to select the suitable battery size for a particular use case.

Hungary's "SEP’24" is a big step toward using renewable energy because it lets people use solar photovoltaic (PV) systems. As part of this innovative project, learning about the different kinds of PV technologies, figuring out battery sizing, and finding out how many households are qualified are all very important steps toward integrating renewable energy. In this study, we want to find out more about the different kinds of PV panels that are out there, the complicated factors that need to be thought about when choosing the right battery size, and the types of homes that can be a part of this innovative program. By breaking down these complicated parts, solar energy progress and the goals of the SEP’24 can be seen and how they can work together to help communities move toward a sustainable energy future.

## *3.1.* The framework

Under SEP’24, the government is committed to developing new domestic mini-power plants that facilitate the installation of solar panels and have the capability to store energy. The objective of the assistance program is to promote the generation and utilization of domestic resources for personal needs, as well as self-sufficiency from an energy perspective.

- The household power plant installation includes a 4-5 kW inverter and a 7.5-10 kWh storage tank.
- The power of the solar panels can be a maximum of 120% of the power of the inverter.
- The maximum level of support is 66% of the entire investment cost, with a cap of HUF 5,000,000.
- More than 15,000 households will receive support in this way.
- Exclusive support can only be provided for new investment.
- There are no limitations based on geographical boundaries [46].

The Hungarian government is targeting more than 15,000 household a beneficiary of this program [46]

There are some factors that determine and affect the consumption of energy in a household. The following factors are:

- Settlement size
- Housing tenure (ownership or rental)
- Number of children and adults residing in the housing
- Household income level
- Housing type
- Number of persons present during daytime hours [47]

## 3.2. Solar PV system design and sizing

### *3.2.1. Battery Parameters*

- Battery Voltage

Chemical processes in the battery, the concentrations of the parts, and polarization all play a role in determining the single cell open circuit voltage. The nominal voltage is the output voltage when the battery is balanced, which is also known as the recorded voltage across an open circuit.

You can get increased voltages by connecting more than one cell in series. For example, connecting 6 cells with a 2 V voltage in series will make a battery bank with a 12 V voltage.

- Change in voltage with discharge.

At the time of discharge, the output voltage changes because it depends on how charged the battery is. This change could be because of the discharge conditions, the concentration levels, or the polarization. We can see how the voltage changes with charging time for different types of batteries in Figure 12.

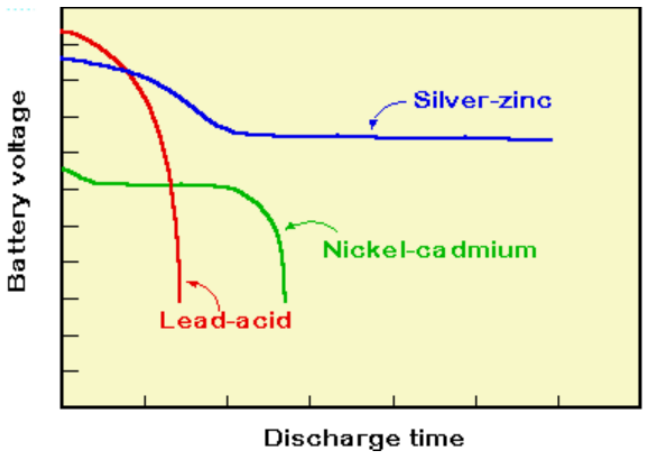



Fig. 3.1 Variation of voltage with discharge time [48]

- Cut-Off Voltage

Many types of batteries, like lead acid batteries, can't be discharged below a certain limit. If they are, they could get permanently damaged. This voltage is called "cut-off voltage". it changes based on the battery type, temperature, and rate of discharge.

- Effect of Temperature on Voltage

The Nernst Equation can be used to find the equilibrium battery voltage, which shows that the voltage of the battery will rise as the system temperature rises.

- Battery Charging and discharging parameters.

How the battery works changes based on how many times it has been charged and discharged.

- Battery state of charge (BSOC)

One of the most important things about batteries is their battery state of charge (BSOC). This is shown by the amount of energy that can be used as a share of the total battery capacity. As an example, a battery with a BSOC of 80% and a stated capacity of 500Ah will store 400Ah of energy.

- Depth of discharge (DOD)

As previously stated, the battery shouldn't be completely dead. Because of this, there is a measure called depth of discharge (DOD) that shows how much energy can be taken out of the battery. The manufacturer of the battery gives the DOD number that doesn't shorten the battery's life. Using DOD numbers higher than these will shorten the battery's life and make it less powerful. If the voltage of the battery is low, on the other hand, it will have a deeper drain for the same amount of energy used.

- Rates of charging and discharge

Charge and discharge rates are measured in amperes, which are coulombs per second and show how much energy is added to or taken away from the battery in each amount of time. In other words, it tells you how long it takes for the battery to fully charge or discharge.

Usually, this rate is shown as $\frac{C}{x}$

Where C = battery's volume

x = number of hours it needs to charge or discharge.

- Battery Efficiency

Battery efficiency is an essential aspect. The result is determined by two factors: coulombic efficiency and voltage efficiency. The overall efficiency of the battery is the multiplication of the two individual efficiencies.

The term "Coulombic efficiency" refers to the efficiency of a system in converting electrical charge into a desired chemical reaction or process.

The coulombic efficiency ($\eta c$) is the proportion of charge that is successfully recovered during the discharge of a battery, compared to the amount of charge pumped into the battery in its charging process. The efficiency may diminish because of losses caused by secondary reactions, such as water electrolysis. The coulombic efficiency typically ranges around 95% and can be calculated using the following equation:

$$\eta_c = \frac{\int_o^{td} I_d \, dt}{\int_o^{tc} I_c \; dt}$$

Where $t_d = discharge\ time$

$I_d = discharge\ current$

$t_c = charge\ time$

$I_c = charge\ current$

Voltage efficiency

The voltage efficiency ($\eta v$) is defined as a ratio of the average voltage while discharging ($Vd$) divided by the average voltage while charging ($Vc$).

$$\eta_v = \frac{V_d}{V_c}$$

The global or round-trip efficiency of the battery can be:

$$\eta_B = \eta_v \eta_c$$

## 3.3. **Calculation Steps:**

To calculate the energy demand using a case scenario of three rooms flat for a standard multi-class household in Debrecen below is the list of appliances and their power rating:

| Appliances | Power rating | Quantity | Total power (W) | Back up time (Hrs) | Total energy demand(W/hr) |
|---|---|---|---|---|---|
| TV set | 60 | 1 | 60 | 8 | 480 |
| Refrigerator(300l) | 150 | 1 | 150 | 18 | 2700 |
| heater | 200 | 1 | 200 | 8 | 1600 |
| Lighting bulbs | 15 | 10 | 150 | 8 | 1200 |
| miscellaneous | 30 | 1 | 30 | 4 | 120 |
| Electric cooker | 1000 | 1 | 1000 | 2 | 2000 |
| Total instantaneous Power | | | 1590 | | 8100 |

The energy demand = 8100W/h
Adding 20% system losses = 9720W/h

### *3.3.1. Solar module sizing*

To size the solar system, an average sunlight time must be known, in this study, the lowest season of sunlight production will be considered. In winter, we have an average sunlight hour of 3 to 2.5 hours daily. So, dividing the total energy demand by sunlight hours gives the number of modules needed.

$$\frac{9720}{3} = 3240W$$

This means 3240W is the total wattage of PV modules needed. With regards to the framework of the SEP'24, the power of the solar panels can be a maximum of 120% of the power of the inverter, which means a solar panel of maximum of 6kW. Using 400watts panels,

$$\frac{3240}{400}$$

8 panels of 400watts each are needed to give a power output of 3240W.

### *3.3.2. Inverter Sizing*

The inverter's capacity is typically determined by the total instantaneous power required. In an ideal or worst-case scenario, where all appliances are running simultaneously, the inverter should be able to power all appliances at once. Although it is unusual for all gadgets to be running at the same time, it is best to consider this extreme scenario when sizing a solar system.

Inverters do have inherent losses and exhibit a certain level of efficiency. Therefore, it is important to consult the inverter manufacturer to obtain accurate information regarding these parameters. The inverter efficiency refers to the rate at which direct current (DC ) power is transformed into alternating current (AC) power. In this scenario, it is generally recommended to use 50% if the efficiency of the inverter from the provider at the specific location is not known. The inverter size required can be determined by dividing the total instantaneous power by the inverter efficiency of 50 percent.

$$\frac{1590}{0.5} = 3180W$$

An inverter of 3500W is good since there are no inverters of 3180W, it's better to choose the next available bigger inverter.

### *3.3.3. Battery Sizing*

A simple calculation is used to estimate its size.

$$Battery\ capacity = \frac{energy\ demand \times autonomy\ days \times temp.compensation\ factor}{Load\ subsystem\ efficiency \times DoD(\%) \times DC\ voltage}$$

#### 3.3.3.1. Estimate System Losses

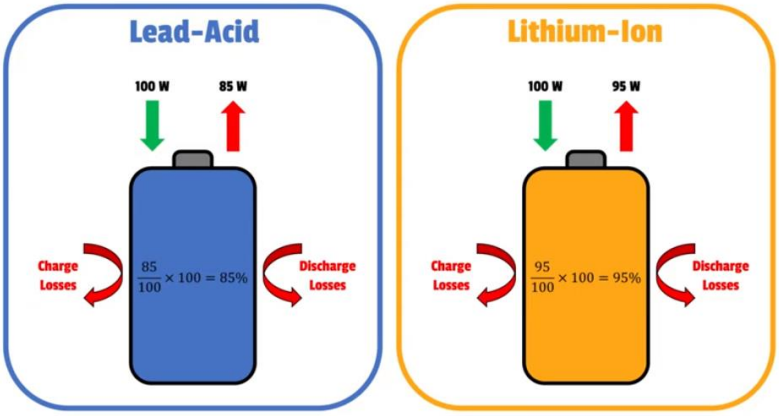
Sometimes we think we have an efficient appliance, but still there are losses that needs to be accommodated because more energy than the system needs will still be generated and some of the energy is lost in conversion, whether it's from DC to AC, from electrical energy to chemical energy such as a battery or transmission over a wire. There are also losses on the generation part of the solar system, but the focus here will be on the load subsystem efficiency which includes:

- round-trip battery efficiency
- wiring loss and
- conversion efficiency.

- round-trip battery efficiency

As known, no battery is 100% efficient, a round-trip efficiency factor is usually used to find out how much energy a battery keeps after it's been charged.

When a battery is charged and discharged, some power is lost. The round-trip efficiency for a lead acid battery is usually around 85%, while the round-trip efficiency for a lithium-ion battery is usually around 95%. These loss estimates are just based on the chemistry of each battery; for example, lead acid batteries usually work with lower electrical currents and take longer to charge.




For this example, a lead acid battery has a round trip efficiency of 85 percent which corresponds to a factor of 0.85.

a. wiring loss

Looking at cable losses that might happen as the electricity moves from the battery bank to the converter and back to the electrical wire. The voltage drops across a wire depends on how long it is, but we usually want less than a 2% to 3% voltage drop across the circuit. For this example, we'll say that the wire is 97 percent efficient, which is written as a factor of 0.97.

- Conversion efficiency

It takes a battery inverter to change the relatively low voltage of a battery bank to the standard AC voltage of 120 or 240 volts. Depending on the load level, battery inverters are usually less efficient than solar inverters, with efficiencies ranging from 92 to 94 percent. So, let's say the battery inverter in our AC-coupled system has 92% efficiency. Now, we'll add up all these system losses into a single factor. To do this, we'll multiply 0.95 for the round-trip efficiency by 0.97 for the wiring losses by 0.92 for the conversion efficiency. This gives us an overall load subsystem efficiency of 85%, or 0.85.

$$roundtrip\ efficiency \times wiring\ losses \times conversion\ efficiency = load\ sussystem\ efficiency$$

$$0.95 \times 0.97 \times 0.92 = 0.85$$

### 3.3.3.2. Choose a system voltage.

Most off-grid battery banks are either 12, 24 or 48 volts. 12-volt systems are generally used with smaller maximum demands while 24- and 48-volt systems provide the widest options. While higher voltages are available, we'll consider these smaller system voltages in this research since we have a relatively small energy demand of about 22 and a half kilowatt hours per day.

How is the voltage used in a system decided?
The first consideration may be what voltage the electrical loads are using, if a DC load having a specific voltage like 12 volts is directly powered, then a 12-volt battery bank is needed.

| | |
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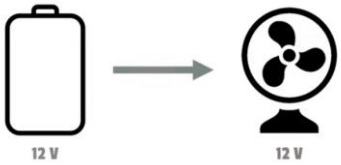
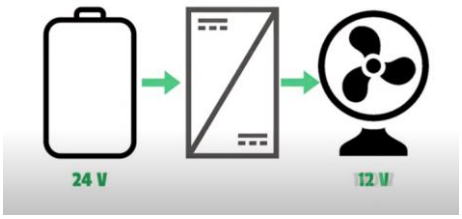
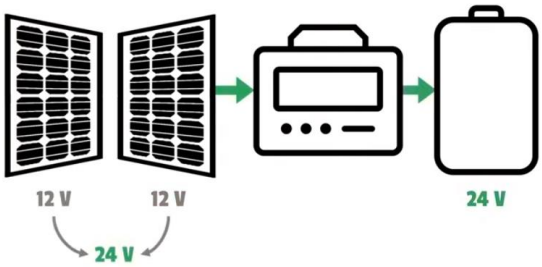
|  |  |
| 1. The same voltage | 2. Higher voltage |

Higher voltage systems like a 24-volt system can't run 12-volt appliances without a converter, and that may increase the cost of the system.

If an inverter is being used on the other hand to convert from DC to AC, then the inverter may require a certain voltage coming from the input and higher outputs from the inverter generally require higher DC inputs. A 2000-watt inverter for example, may be available in 24-volt DC while a 6000-watt inverter may require 48-volt DC.
The solar array must also produce a higher voltage than the battery bank, a 12-volt solar panel for instance generally can't be used with a 24-volt battery.



It is important to note that a 24-volt charge controller could be half the size of a 12-volt controller, which may reduce costs. So, if the solar panels are relatively far from the battery bank, then the gauge of the copper wire could be reduced by using a higher voltage, this is because of higher voltage levels. result in a lower electrical current. So, if large loads are being pushed and have a 24- or 48-volt system then a smaller less expensive wire could be used to reduce the cost of the system.
With these considerations in mind, a nominal 24volt battery bank will be considered.

#### 3.3.3.3. Days of Autonomy

The duration of time we want to run the electrical appliances using the battery bank during periods of low solar radiation, commonly referred to as days of autonomy, is a measure of how many days we expect to have no or limited sunlight. This ensures that sufficient power is obtained to sustain the electric loads, even when solar output is reduced.

A perfect timeframe usually ranges from three to five days. When determining the days of autonomy, it is important to examine several criteria, including the historical weather data specific to your locality. You may observe that your website experiences consecutive periods of inclement weather lasting for three, four, or even five days.

If a shorter duration is selected, but a longer period of self-sufficiency is chosen, the cost of the system may significantly increase.

In this scenario, we will choose a three-day autonomy period that will ensure an ample reserve of power for the specific application and location at present.

#### 3.3.3.4. Thermal Losses

It is vital to know that some losses are due to heat because that 25 degrees Celsius cell temperature is unlikely unless it is in a very cold place to be true on a sunny day. Even in wintertime, panels heat up about 25 to 35 degrees above the ambient temperature. So, this is wintertime here in Debrecen, where the daytime temperatures are hovering around -5 to 10 degrees. So, in fact, the losses are quite small, and the winter season is a kind of a bonus for this design. But if it is in a hotter climate, the losses will be higher. It's in the data sheet for the solar modules.

Although batteries are usually rated at $77^{O}F$ or $25^{O}C$, their capacity tends to decrease at lower temperatures. To address this, a battery temperature compensation factor can be utilized, which can be found in the manufacturer's specifications or other resources such as the IEEE standard[49].

| Temperature (°F) | (°C) | Battery Temp Multiplier |
|---|---|---|
| 80 | 26.7 | 1.00 |
| 70 | 21.2 | 1.04 |
| 60 | 15.6 | 1.11 |
| 50 | 10.0 | 1.19 |
| 40 | 4.4 | 1.30 |
| 30 | -1.1 | 1.40 |
| 20 | -6.7 | 1.59 |

Fig 3.4.5 Temperature correlation factor [49]**Error! Reference source not found.**

For this example, storing lead acid battery in a room having an average winter temperature of 50°F. This temperature corresponds to a temperature correction factor of 1.19.

### 3.3.3.5. Depth of discharge

The depth of discharge refers to the extent to which the battery bank can be drained. Batteries are not intended to be fully discharged, and their lifespan increases when they are drained less. Battery makers typically include a depth of discharge chart for each battery.

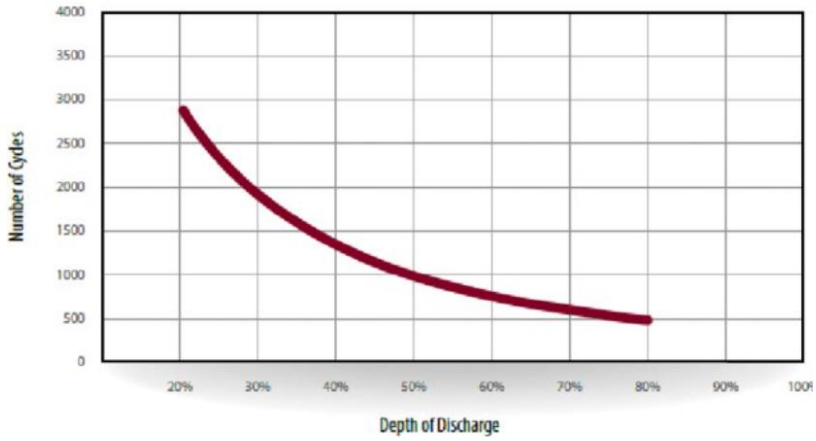
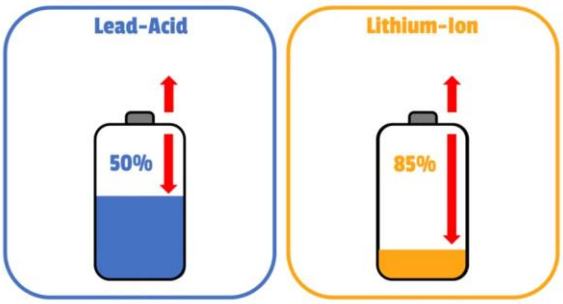



Fig. 3.4.6 Depth of discharge versus life cycle [4]

Lead acid batteries are often acknowledged to have a maximum depth of discharge of 50 percent, whereas lithium-ion batteries can be discharged to approximately 85 percent of their rated capacity without experiencing significant deterioration in their lifespan. A lead acid battery with a power output of 1000 watts, for instance, typically provides approximately 500-watt hours. In contrast, a

lithium-ion battery can deliver around 850-watt hours. Consequently, to achieve the same capacity, a greater quantity of lead acid batteries may be required.




However, there is a trade-off between battery longevity and size. Although a larger battery may be more costly, it has the potential to last longer due to a smaller percentage of its capacity being depleted. For certain lead acid batteries, considering a maximum depth of discharge of 50 percent, which can also be expressed as a factor of 0.5.

### 3.3.3.6. Battery sizing

- Lead Acid Option

A simple calculation is used to estimate its size.

$$Battery\ capacity = \frac{energy\ demand \times autonomy\ days \times temp.compensation\ factor}{Load\ subsystem\ efficiency \times DoD(\%) \times DC\ voltage}$$

Where,

Energy demand = 8100Wh
Autonomy days = 3days
Temperature compensation factor = 1.19
Depth of discharge = 0.5
Voltage = 24V
Load subsystem efficiency losses = 0.85

$$Battery\ capacity = \frac{8100Wh \times 3d \times 1.19}{0.85 \times 0.5 \times 24V} = 2835Ah$$

The lead acid battery equals a total usable battery capacity of 2835 Amp hour.

The determination of the quantity of batteries required for this application can be simply made, as battery capacities are commonly expressed in amp hours by manufacturers.

For this situation, we could choose a set of 12-volt 215-amp hour lead acid batteries. The aggregate battery capacity of 2835-amp hours is divided by the individual rated capacity of each battery, which is 215-amp hours.

This implies that approximately 14 of these batteries are required to supply power to all electrical loads with a backup duration of three days. However, this solution is somewhat costly, each cost $69.99 close to 24,500huf, that is a high price.

- Lithium-Ion Option
  - For Lithium-ion batteries, considering a maximum depth of discharge of 85 percent, which can also be expressed as a factor of 0.85.
  - Also, according to the wiring regulations AS/NZS 3000, it is recommended that there should be a maximum voltage loss of 5% to the highest point of a circuit. In this design, I am deliberately selecting the most unfavorable situation, a whole 5% decrease in this wiring system, so it is 0.95 for a voltage drop of 5%. Therefore, the load subsystem efficiency will be calculated as follows:

$$roundtrip\ efficiency \times wiring\ losses \times conversion\ efficiency = load\ sussystem\ efficiency$$

$$0.95 \times 0.95 \times 0.92 = 0.83$$

This shows the fact that around 17% of the energy is lost throughout the process of charging a battery and then discharging it through the transmission of energy across a cable, as well as the conversion from direct current (DC) to alternating current (AC).

- For the thermal losses in this option, assuming the battery is stored in a room having an average winter temperature of 40°F/4.4°C. This temperature corresponds to a temperature correlation factor of 1.30 from fig 3.4.6.

$$Battery\ capacity = \frac{energy\ demand \times autonomy\ days \times temp.compensation\ factor}{Load\ subsystem\ efficiency \times DoD(\%) \times DC\ voltage}$$

Where,

Energy demand = 8100Wh
Autonomy days = 3days
Temperature compensation factor = 1.30

Depth of discharge = 0.85
Voltage = 24V
Load subsystem efficiency losses = 0.83

$$Battery\ capacity = \frac{8100Wh \times 3d \times 1.30}{0.83 \times 0.85 \times 24V} = 1866Ah$$

The lithium-ion battery equals a total usable battery capacity of 1866 Amp hours, which will equal 5 pieces of a 400Ah battery.

But, instead of increasing the size of the battery bank, which is more costly than solar panels, it is recommended to increase the size of the photovoltaic (PV) system. This is because a larger PV system reduces the dependence on batteries. that is to add additional solar capacity to the system as opposed to adding battery capacity.

Also, reducing the battery capacity by having more renewables helps to rapidly recover with the low cost of solar panels. It's becoming much more achievable to oversized PV systems. The more PV you have in a way, the less reliance on the batteries.

## 3.4. Amount of energy produced.

The electricity output of solar systems is unpredictable, with higher production during sunny summer months and decreased production during gloomy winter months when household energy consumption tends to be higher. There are four primary factors that will determine the amount of energy that solar panels will generate:

- The amount of sunshine
- Features of the panel and the system altogether
- The house roof.
- The lifespans of the panel

The amount of sunshine is an important component of the power that is generated by a solar panel. The amount of electricity generated by the panel is directly proportional to the amount of sunshine it receives. For example, in Hungary, we have about 2.5 – 3hours of sunlight in winter and 9.48hours in summer (June) according to the world data record [50]. While a 400watt panel can generate 1kWh in a day during winter, it will generate 4kWh in summer.
Also, not all roofs are suitable for solar installations. To optimize solar production, it is advisable to place solar panels on rooftops that are not shaded and ensure that they are free from any debris. The most effective positioning for solar panels is on rooftops facing south, as this layout maximizes energy production.

In the case scenario and calculations above, a 400-watt solar panel was installed.

- During summer, Hungary have approximately 9.5 hours of sunlight per day. This implies that this panel would generate 3,800 watt-hours of power daily. Electricity is often quantified in kWh, so to get the value in kWh, dividing a total of 3,800 watt-hours by 1,000, resulting in 3.8kWh.

$$400 \times 9.5 = 3800Wh$$

$$3800 \div 1000 = 3.8kWh\ per\ day$$

$$3.8 \times 30days = 114kWh\ per\ month$$

$$3.8 \times 365days = 1387kWh\ per\ year$$

- In winter when there is approximately 2.5 – 3 hours of peak sunlight daily. The panel generates:

$$400 \times 3 = 1200Wh$$

$$1200 \div 1000 = 1.2kWh\ per\ day$$

$$1.2 \times 30days = 36kWh\ per\ month$$

$$1.2 \times 365days = 438kWh\ per\ year$$

This is a simplified method of determining how much electricity a solar panel generates. The actual amount will vary each day, even hourly, depending on all the factors stated above.

Consequently, during the winter, a normal household generates an insufficient or low amount of electricity to meet its needs, while during the summer, it creates excess. Under optimal conditions, any excess can be supplied to the national power grid, a process referred to as feed-in.

From the beginning of the year 2024, 93 percent of the circuits in Hungary will be able to be connected to the grid for the purpose of providing electricity to households or the small power plants that they operate [46].

For example, during summer, there will be more sunlight hours which in turn result in more solar power production, when an individual or company generates more power than they use, the extra energy can be put back into the grid. This opportunity is available to both individuals and businesses. There are rules or regulations in place in numerous markets that make it possible for residents or companies to receive compensation for the power that they input into the grid. This compensation is often provided at a predetermined rate that is referred to as the feed-in tariff.

# 4. CALCULATIONS OF POWER TO GAS STORAGE OPTION FOR MOBILE AND STATIONARY USES

A process called "power-to-gas" (P2G) turns electrical power into gaseous energy carriers like hydrogen or methane. This process has gotten a lot of attention because it could help with grid balance and energy storage, has the capacity to improve energy security and decrease operational expenses in connected energy center [51]. P2G technology offers several energy services, such as energy storage, extra support services for the electrical grid, and the production of hydrogen for industrial processes and transportation fuel. There are a lot of technical and economic issues to consider with this process, as well as possible uses in new electrical systems.

## 4.1. How it works?

The following steps explain the processes involved in power to gas technology.

- Electrolysis

During this stage, electricity is used to separate water ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$) via the process of electrolysis.

The electrolysis reaction can be represented by the equation: $2H_2O$ + electricity yields $2H_2 + O_2$.

- Hydrogen production:

The generated hydrogen can be utilized immediately or stored for future use.

Hydrogen is an environmentally friendly and flexible element that can be utilized in diverse sectors such as transportation, manufacturing, and electricity production.

- Methanation (Optional):

Methanation is a process used in certain Power-to-Gas systems where hydrogen and carbon dioxide ($CO_2$) are mixed to form methane ($CH_4$).

The chemical reaction is as follows:

$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$.

- Gas grid injection or storage:

If the produced hydrogen or methane is compatible with the existing infrastructure, it can be fed into the natural gas grid.

Alternatively, the gases might be stored for future utilization during periods of increased energy demand.

- Utilization of Hydrogen:

Hydrogen generated by Power-to-Gas can be utilized directly in diverse applications, including fuel cells for electricity production or in industrial operations.

- Means of conveyance:

Hydrogen generated can serve as a pristine fuel for hydrogen fuel cell automobiles, offering a sustainable transportation alternative.

- Carbon Capture and Utilization (CCU):

When carbon dioxide is captured from industrial operations, it can be chemically mixed with hydrogen to create synthetic fuels or chemicals using Carbon Capture and Utilization (CCU) methods.

Power-to-Gas technology is essential for incorporating renewable energy sources into the current energy infrastructure. It allows for the storage and utilization of excess energy during times of less demand.

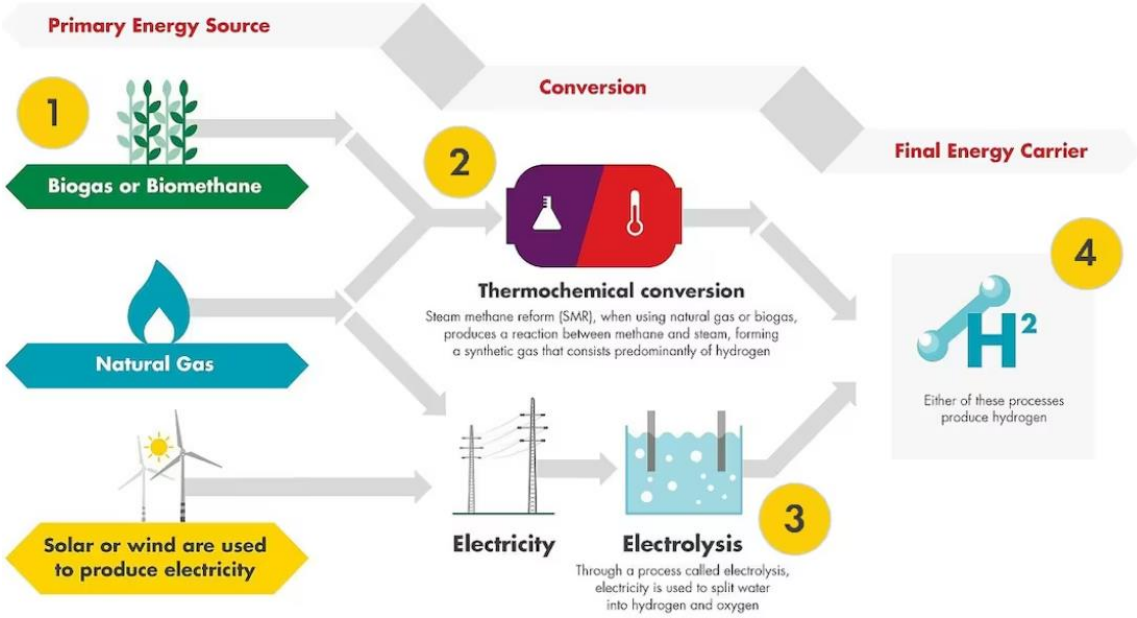



Fig. 4.1 How hydrogen is produced [52]

Hydrogen Fuel cells that use have attracted considerable interest for their ability to offer safe and effective energy options in various applications, whether mobile or fixed. Hydrogen fuel cells have a high mass-specific energy density, which makes them appropriate for buses, lorries, trains, forklifts, ships, and automobiles [53].

Mobile uses (Cars)

What is the power consumption of an average car user? A typical car uses an average of 40kWh and 30kWh for jets flight daily. Once we have obtained the conversion costs, we can perform basic arithmetic calculations:

$$energy\ used\ per\ day = \frac{distance\ traveled\ per\ day}{distance\ per\ unit\ of\ fuel} \times energy\ per\ unit\ of\ fuel$$

Designing a fuel-cell hydrogen system for a vehicle requires careful evaluation to achieve the best efficiency and effectiveness. The power output needed for the fuel cell technology is determined by parameters such the vehicle's size, required speed, distance travelled, and extra energy requirements such as cooling, lighting, and digital devices. The power produced by a fuel cell system for a passenger car usually falls between 50 to 150 kilowatts.

Hydrogen fuel is stored either in gaseous, liquid, or solid states. But the most used and preferable is storing using compressed gaseous state. To calculate and size the power to gas technology, below are the steps that must be taken.

## 4.2. Steps to Calculate Power-to-Gas technology:

- Calculate the electrical power input.
  - Determining the power supply to the electrolyzer, is an essential element in Power-to-Gas system.
  - Collect data on the electricity usage during the electrolysis procedure.

- Efficiency of the electrolysis process:
  - Calculate the electrolysis process efficiency by comparing the energy intensity in the gas output to its electrical energy source. This requires analyzing the electrolyzer's efficiency curve across various operating situations.

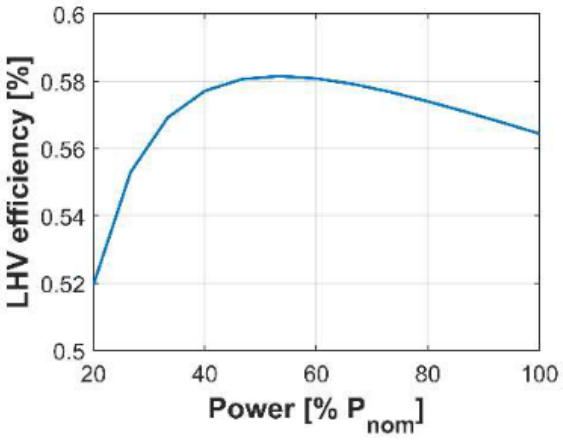



Fig. 4.2 Electrolyser efficiency as function of power input [54]

- Hydrogen or methane generation:

Determine the quantity of hydrogen or methane generated by the electrolyzer, considering parameters like reaction kinetics, efficiency, and gas composition. While also determining the energy component of the generated hydrogen or methane which involves considering the lower heating value (LHV) of the gases, which indicates the energy produced during combustion.

- Total Efficiency:

Determine the total efficiency of the Power-to-Gas process. This encompasses the electrolyzer's performance, compressed gas efficiency, and other system losses.

- Economic Evaluation:

Consider economic aspects including the price of electricity, the initial investment in the electrolyzer, as well as additional operating expenses by performing a cost-benefit study to evaluate the financial viability of the technology.

- Sustainability Consequences:

Assess the environmental consequences, including releases of greenhouse gases, if the power utilized in the operation is not sourced from renewable sources and examine safety concerns of hydrogen generation, storage, and use.

There are a few challenges involving hydrogen. Hydrogen is a less feasible energy storage option compared to other liquid fuels due to its large volume, whether stored as a highly compressed gas or as a state of liquid (which needs to be kept at a temperature of -253°C). At an operating pressure of 700 bar, which necessitates a robust pressure carrier, its energy density is 22% of gasoline's energy density. The cryogenic tank of the BMW Hydrogen 7 weighs 120 kg and can hold 8 kg of hydrogen [55].

# 5. CALCULATIONS OF PHYSICAL ENERGY STORAGE OPTIONS

Physical energy storage options include the use of flywheel, pumped hydro, and compressed air energy storage. Mechanical storage options are mostly used as stationary energy storage on a large scale and structures.

## 5.1. Operational techniques of a flywheel energy storage system

A flywheel energy storage system (FESS) is a form of mechanical technology for storage. Its primary feature is its lack of environmental contamination, high density of energy, and high efficiency in converting energy into electricity, making it a long-lasting energy source. The function of the FESS mainly involves the charging and discharging of electricity energy, as well as the upkeep of operational mode. When the gadget is charging, the motor will be active and can only supply current to the flywheel. The components of the flywheel are currently operating at a rapid speed Hence, the electrical energy generated by the solar cell is transformed into kinetic energy stored in the flywheel unit.

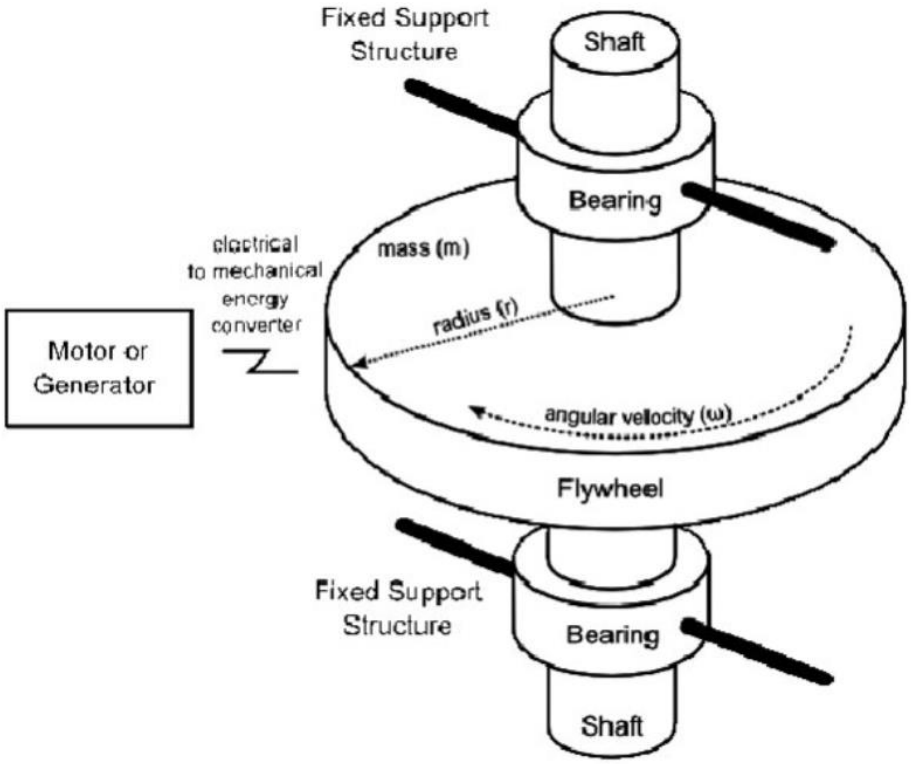



Fig. 5.1 components in an FESS [56]

When the FESS is in the electricity output state, the motor will make a transition to the electric energy output state. Currently, the FESS will achieve peak operational efficiency, causing the motor to begin rotating. Simultaneously, it will transition into braking mode. The kinetic energy stored in the flywheel will be converted into electrical energy.

## 5.2. Sizing a flywheel

Flywheels are growing into the preferred choice for energy storage systems compared to electrochemical cells in large scales [57] because they offer a greater capacity for energy, longer duration, predictable state of charge, and environmentally friendly operation. The mechanical efficiency of a flywheel is influenced by three main factors: material strength, mechanics, and rotational speed.

- Material strength

In flywheel energy storage devices, the material needs to be strong enough to handle the mechanical stresses and loads that happen during the energy storage and release cycles.
The materials used in flywheel energy storage systems must be very strong to make sure they are stable, reliable, and good at saving and releasing mechanical energy. To handle the centrifugal forces and high turning speeds that happen during operation, the material needs to be very strong.

- Mechanics

The design of the flywheel covers its shape, size, and distribution of force, Ensuring the flywheel is properly balanced and controlling vibrations are crucial for ensuring stability while on function, which can affect the energy storage capacity. It is crucial to optimize the basic structure to achieve desired energy storage capacity while ensuring stability.

- Rotational speed

The speed at which the flywheel rotates affects its ability to store energy. Greater rotational speeds result in larger energy storage capacity because of the increased kinetic energy of the spinning mass. It is crucial to weigh the benefits and drawbacks between rotational speed and the risk of higher wear caused by friction on the flywheel parts. It is essential to find the ideal balance to maximize energy storage efficiency.

The flywheel's potential to rapidly charge to its maximum and provide considerable energy quickly makes it ideal for applications that experience frequent fluctuations, such as compensating for differences in wind or solar energy. They have been utilized in experimental and grid applications to meet an unexpected demand for energy. The use of flywheel to supply power to the electrical start unit

of a ship. and its multiple benefits and variety of applications have been examined [11].

The flywheel spinning speed makes it possible to classify FESS into two categories, the low speed and high-speed flywheel.

*Table 6. characteristics of types of flywheel speed* [57]
Note: The values are mostly based on the design considerations

| Properties | High speed FESS | Low speed FESS |
|---|---|---|
| Rotational speed | Higher speeds because they are often constructed from composite, it can reach up to 700r/s based on design specification | Lower speeds, they are made from steel which ranges from 450-400r/s |
| Energy storage capacity | Higher capacity e.g a flywheel design that uses lightweight composite materials and has an energy storage capacity of 800 Wh at a rotational speed of 35,000 RPM [58]. | Lower capacity, it ranges from a few kWh to tens of kWh based on the size and design |
| Applications | Used in rapid storage applications like in aerospace industry | Suitable for moderate storage applications in power quality |
| Efficiency | Known for higher efficiency | May have lower efficiency |
| Design complexity | Require more sophisticated designs and materials | Generally simpler |
| Bearings | Mechanical or combined with magnetic | Magnetic |

The advantages of utilizing flywheel storage come from its efficient utilization and should be aligned with the specific utility needs it is meant to fulfill. For instance, if the sizing is to regulate the frequency, then it must be done with respect to the frequency fluctuation in the system because of the integration of renewable sources. If the generated power from the PV needs to be adjusted, an amount of energy is transmitted to the grid and the FESS handles the rest.

The size of a FESS can be categorized into power sizing and energy sizing. Power sizing is the maximum power output or charging capacities in watts needed from the FESS under any operational situation, while energy sizing is the watt-hour amount of energy that could be stored. The energy stored within the flywheel could

be affected by adjusting the flywheel's design. This is influenced by inertia and the rotational speed of the flywheel.

The retrievable kinetic energy stored in a flywheel can be calculated as:

$$\Delta E = \frac{1}{2} \times I \times (\omega^2 \max - \omega^2 min)$$

$$I = moment\ of\ inertia$$

$$\omega = angular\ velocity/speed$$

$$\omega^2 max = maximum\ flywheel\ speed$$

$$\omega^2 min = minimum\ flywheel\ speed$$

The flywheel, with moment of inertia I, rotates at an angular velocity ω, accumulating energy from its motion $\Delta E$. The moment of inertia is determined by the weight of the flywheel and its structure, which is the square of its radius. The electrical device converts kinetic energy into electricity and vice versa while moving the flywheel. If the spinning speed of the flywheel rises, then it generates electricity. The motor drives the flywheel, and it can sustain rapid acceleration only if the motor's spinning torque exceeds the device's frictional force, indicating the key role of the design of the rotor in the FESS.

*Table 7 Applications and advantages of using FESS* [45].

| Applications | Advantages |
|---|---|
| Uninterrupted power supply (UPS) | They may rapidly provide stored energy to bridge temporary shortages in case the primary source of energy malfunctions, making them well-suited for essential systems such as hospitals, information technology facilities, and factories. |
| Public Transportation system | In electric trains or trolleys, FESS can store the energy produced while braking and later use it for accelerated speed or other energy requirements, enhancing the system's efficiency, compared to battery storage which has a lower efficiency due to internal resistance and heat exchange. |
| Energy demand balance | FESS can store energy for use during off-peak hours and release it when demand is high. This can help businesses whose power needs are unpredictable by lowering their peak demand. |

| | |
|---|---|
| Applications requiring high power for limited time. | Manufacturing operations such as the use of electric arc furnaces or cutting using lasers might benefit from FESS since they effectively provide bursts of high power. |
| Frequency regulation | FESS can instantly release or absorb energy, which contributes to grid stability by keeping the frequency stable. |

Although, keeping a mass in motion at extremely high speed is a difficult and costly operation that calls for smart engineering and cutting-edge materials like E/S glass fiber/resin, Kevlar, Aluminum alloy etc. Additionally, FESS still has a decreased energy-to-weight ratio compared to other storage solutions, which makes it impractical for use in mobile applications.

## 5.3. CAES and PHS Sizing challenges

Designing a compressed air energy storage (CAES) system is difficult because it is both huge and stationary, as it is complicated to accurately determine the dimensions of volumetric compressors required for grid-scale uses. The lack of mobility in CAES systems adds complexity to their sizing, as these systems are fixed in place and necessitate specific geological formations for beneath the surface storage, which restricts their installation options and flexibility [59].

To tackle these obstacles and optimize the potential of CAES techniques for grid-scale applications. Extensive planning, design, and incorporation plans are required to subsidize the challenges involved in sizing CAES systems resulting from their large size and immobility.

Similarly, sizing pumped hydro is a complex process that requires consideration of technical, economic, geographical, and operational constraints. By thoroughly examining these parameters and using intricate simulators and modeling tools, it is feasible to address the challenges related to determining the appropriate size of these energy storage devices.

# 6. CALCULATIONS OF THE COMBINATIONS OF ENERGY STORAGE OPTIONS

Hybrid energy storage systems (HESS) provide a flexible solution to tackle the difficulties of energy storage by combining several storage technologies or renewable energy sources to achieve the most effective results and capacity in a range of applications. A popular approach is to combine a high-capacity energy storage device with a long reaction time, such as a battery, with a high-power storage device that has a quick response time, such as a supercapacitor.

The incorporation of diverse storage design offers a multitude of advantages and possibilities for a wide array of applications.

An important benefit of HESS is their capacity to integrate the advantages of several storage technologies. Battery-Supercapacitor HESS have been created to combine the high energy density of batteries with the high power density of supercapacitors, resulting in enhanced efficiency and productivity [60].

Moreover, the adaptability and a variety of uses of a hybrid system makes it appropriate for a range of applications. Hybrid energy storage solutions provide unique structures and control methods to fulfill the energy storage needs of many applications, ranging from distinct microgrids with DC to railway systems and electric-powered automobiles. To enhance energy storage qualities, these systems commonly incorporate batteries combined with supercapacitors, lead-acid batteries together with lithium-ion batteries, or alternative combinations.

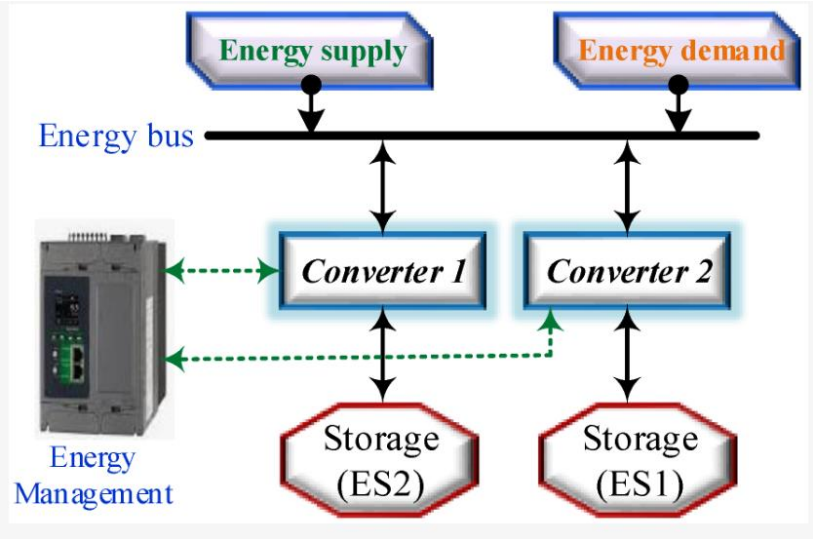



Fig. 6.0 The basic set-up of HESS [61]

It is vital to note that selecting proper HESS combinations depends on various criteria, including the integration aims of the storage, the expenses associated with the storage, the geographical location, and the extent of storage space, and also the control strategy for a HESS is more intricate compared to a single form of storage due to the necessity for a combined control system that considers the distinct features of various combined storage technologies. ESS technology can be high-power or high-energy. High-power storage systems supply energy quickly. Out of all ESS devices, SMES, supercapacitors, flywheels, and high-power batteries are included in this category. On the other hand, storage technologies provide energy for a greater duration. This technology includes pumped hydro, CAES, fuel cells and high-energy batteries. This classification classifies ESS technologies in Table 6. Battery has an extensive characteristic which qualifies to be used in both high power and high energy devices.

*Table 8 Classification based on high power and high energy.*

| High power devices (fast response) | High energy devices (slow response) |
|---|---|
| Supercapacitor | Pumped hydro |
| Flywheel | CAES |
| SMES | Battery |
| Battery | Fuel cell |

The high-power device is designed to fulfil short-term power requirements, while the high-energy device was created to respond to long-term energy needs.

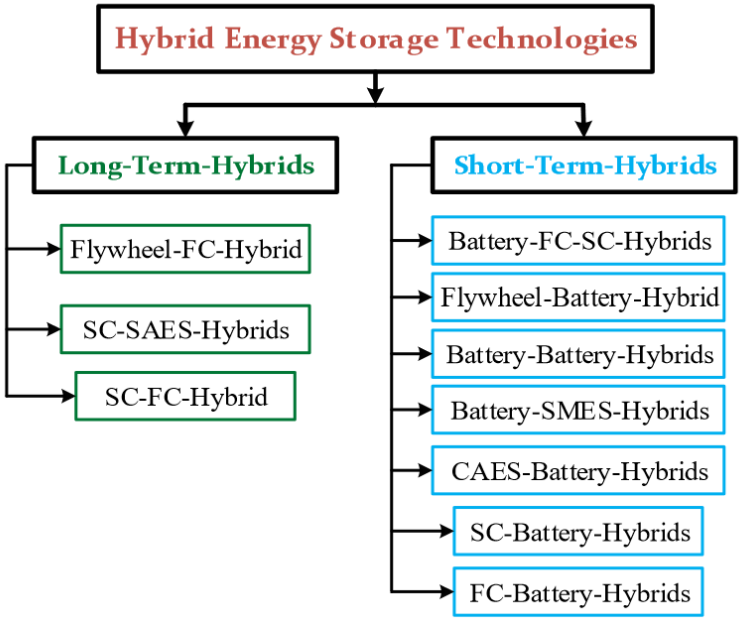



Fig. 6.1 Potential combinations of HESS [62]

The time axis, ranging from t = 0 to 1 year, is depicted on an exponential scale that spans from 1 to 7.5. Supercapacitors and flywheels, which are short-term storage devices, typically have a discharge time ranging from a few milliseconds to a few minutes. The mid-term storage, or batteries, typically have a discharge time that can range from a few minutes to several hours. The discharge rates, also known as C-rates, for lead acid batteries typically range from 10 hours (0.1C), while lithium batteries can discharge at an average pace of two hours (0.5C). Long-term storage devices, such as flow batteries or fuel cell hydrogen systems, possess a high energy density and are capable of discharging over a range of several hours to many days.

The requirement for sizing a hybrid system includes:

- Energy usage profile: Recognize the energy demand characteristics of the utilization, which includes the maximum power needs, the lifespan of storage devices, and frequency of cycles.
- Capacity for storing energy: Calculate the necessary energy storage required to satisfy the energy requirements of the usage during demand peak or when sources of sustainable energy are not accessible.
- Electrical power output: The system's power output requirements encompass the maximum power output and the rate at which energy is dissipated.

- Time of response: To determine the necessary response time for the storage system to effectively supply power or use surplus energy in line with fluctuations in demand or the supply of renewable energy.
- Limitations on space and weight: Consider any space or mass restrictions when implementing the energy storage system, particularly in mobile or space-limited scenarios.
- Financial limitations: Determine financial limitations and assess the efficiency of various energy storage methods and setups.

## 6.1. Summary of literature on sizing of storage systems cmbination

*Table 9 Research summary on storage options combinations.*

| Hybrid storage | Power supply | Application | Optimization approach | Ref. |
|---|---|---|---|---|
| Lithium-ion battery + supercapacitor | PV | EV, Grid, microgrid, | Dynamic programming | [63] [64] [65] |
| Pumped hydro + battery | PV, wind | | Genetic algorithm, grey wolf optimizer | [66] [67] |
| Battery + battery | PV, wind, biogas | EV | mixed integer linear programming | [68] |
| Battery + TES | | standalone multi-micro grids | Evolutionary PSO | [69] |
| lead acid + lithium polymer + flywheel + SC | | driving cycles | Mathematical algorithm | [70] |
| Battery (lead acid) + SMES | PV | Residential use | flexible design based on expected load | [71] |
| Battery + Ultracapacitor | 3-phase,4-wire PV | Smart grid | Smart energy management algorithm | [72] |

## 6.2. Battery and SMES hybrid storage technology

Considering battery and SMES combined technology, the electrochemical battery is considered the most prevalent energy storage technology because of its excellent combination of high-energy density, rapid response speed, and affordability. Nevertheless, if the battery is subjected to frequent and rapid charging/discharging cycles, together with high charging/discharging rates resulting in high-current peaks, it will experience a notable decline in its overall lifespan [73].

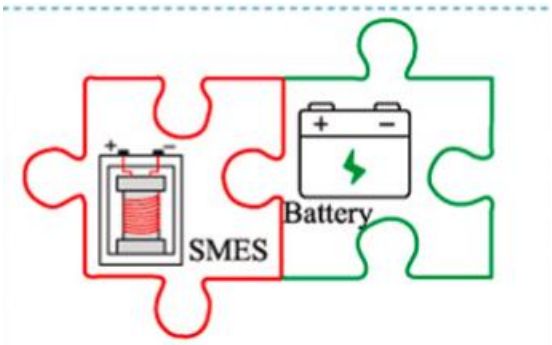



*Table 9 Pros and cons of the SMES and battery combination* [73]

| SMES | | BATTERY (lead acid) | |
|---|---|---|---|
| Pros | Cons | Pros | Cons |
| It offers rapid response times in the millisecond range. | It needs a refrigeration system that can be quite expensive. | Cost effective | Limited life cycle (1200-1800) |
| a high efficiency of over 95% | demand complex maintenance. | High energy density (30-50W/kg) | Big and bulky |
| delivers high power (multi-MW) range. | Developing a large-scale is technically challenging | Perfect for extended periods and high energy demands | Eco unfriendly |
| a long cycle life and allows for four-quadrant control. | | | |

Due to the reduced lifespan, the expenses for maintenance and replacement are elevated. On the other hand, the SMES is a developing Energy Storage Technology that relies on the phenomenon of superconductivity in certain materials. It has attracted interest because of its distinctive characteristics.

When comparing these two technologies, it's important to note that SMES offers a high-power density, making it ideal for delivering immediate and substantial power. On the other hand, batteries have a relatively high energy density, making them well-suited for applications that require sustained and significant energy over a longer period. The SMES regulates frequent and immediate power changes, while the battery is designed to manage long-term changes. One can maximize power and energy performance by fully harnessing these benefits.

A model of a wind powered grid connected with an SMES + battery HESS [74] is presented in fig. 6.3 below:

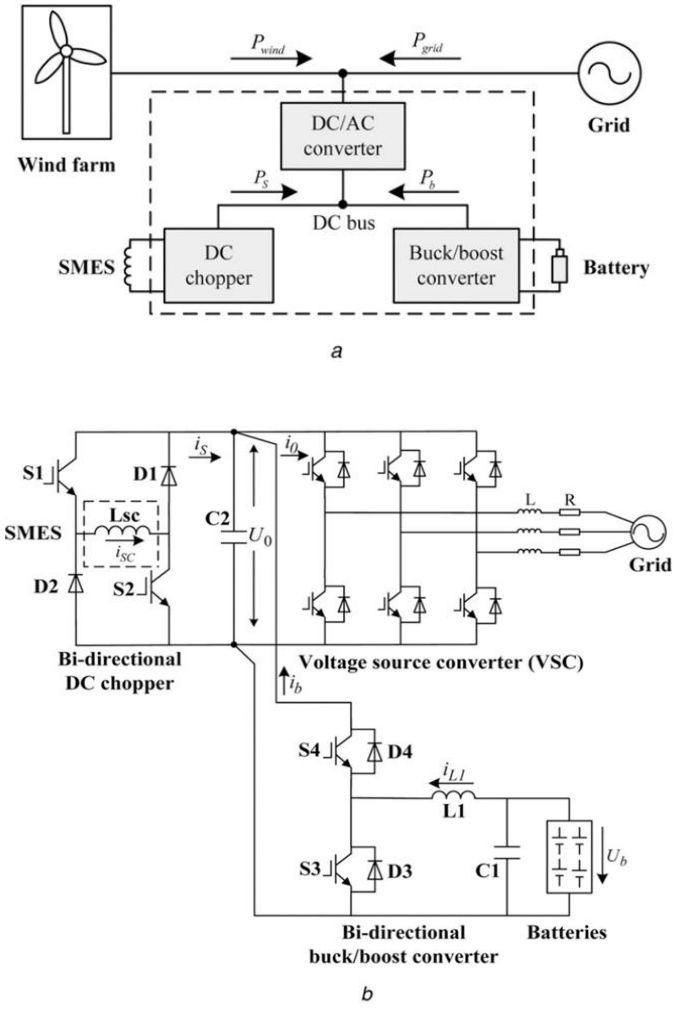



Fig 6.3 Flow direction model [74]

According to the directions in a, the dynamic power balance can be expressed as

$$P_{source} + P_S + P_B + P_{grid} = 0$$

Where, $P_{source}$ is the source power output, $P_s$ and $P_b$ is the power transfer from both the SMES and battery pack.

DC/AC converters have two main types: voltage source converter (VSC) and current source converter. VSC is frequently used for energy balancing and voltage or stability of frequency because it provides continuous voltage control. The VSC is used as a grid-side DC/AC converter to control power transfer swiftly and effectively in each quadrant. SMES coil voltage is regulated by a DC chopper because it is a DC source. Since the battery has a fixed voltage, a boost converter regulates its current. VSC and two DC/DC converters get voltage from the DC link capacitor. This setup has the benefit of the SMES DC chopper and battery buck/boost converter working standalone on their power commands (PS and Pb) from the system-level control plan, making the control approach feasible. This setup greatly separates ES devices from the power system and saves them from power disruptions.

An important parameter in calculating the energy output is the state of charge (SoC) because an appropriate charge and discharge strategy can boost cycle efficiency and lifespan.

It is calculated every time by [74]

$$S_OC = \frac{E_{ini} + \int_0^t \left(\eta_{ch} P_{ch} - \frac{P_{dis}}{\eta_{dis}}\right) dt}{E_{max}}$$

Where $E_{ini}$ is the initial stored capacity, $E_{max}$ is the maximum storage capacity, $P_{ch}$ and $P_{dis}$ are the charge and discharge power values, $\eta_{ch}$ and $\eta_{dis}$ are the charge and discharge value of efficiency of each of the storage.

Using generic algorithms and fuzzy logic control with different optimization points of both energy storage the simulations were carried out and the SoC result shows:

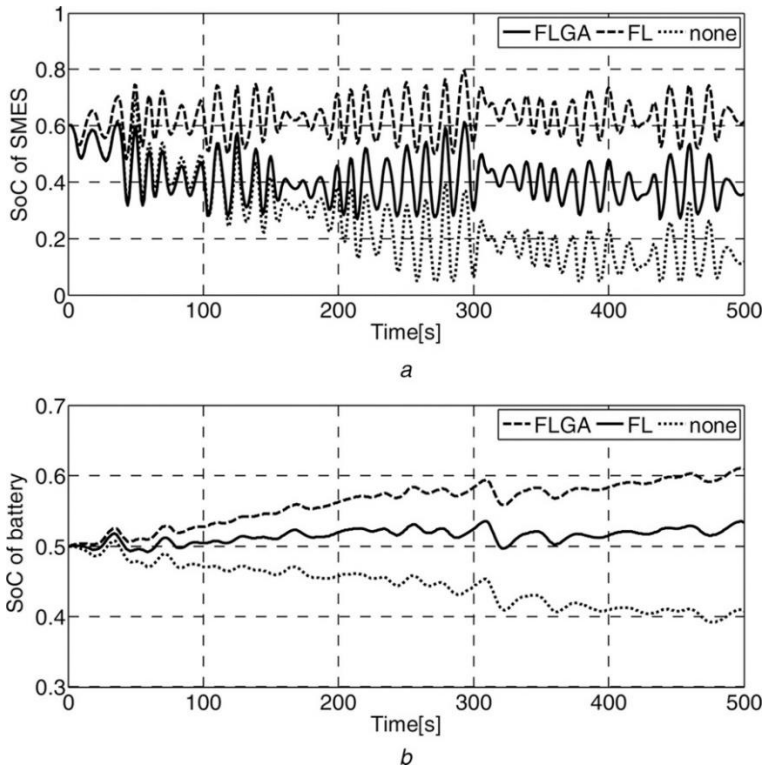



Fig. 6.4 Simulation results of both storage SoC [74]

The State of charge (SoC) results of SMES and batteries are compared separately. Firstly, SMES prioritizes power compensation for high-frequency components instead of using batteries. Consequently, the HESS may effectively safeguard the battery by minimizing frequent charging and discharging, thereby prolonging its cycle life. From the final line in Figure 6.4, it is evident that the SoC of the SMES system occasionally drops to the minimum threshold of 0.05. The results indicate that without a control system, it is essential to reach the operational limits of ES devices. However, with the use of a controller, both SMES and batteries can function effectively. Furthermore, utilizing a collection of fuzzy rules, the SoC of Energy Storage devices can rapidly be restored to an optimal condition, allowing the system to effectively mitigate power fluctuations in the immediate future.

## 6.3 Sizing Battery, supercapacitor, and hydrogen storage (Using Pinch analysis)

Battery (valve regulated lead acid), supercapacitor and hydrogen storage technologies can be useful in balancing a micro/macro grid system. In this case study, Pinch analysis was used, it is a methodical approach used to identify the places in a heat exchanger network where the smallest amount of energy is required. The use of pinch analysis and design space technique to determine the appropriate size of battery storage systems in isolated power systems was proposed by [75].

A standardized approach, utilizing pinch analysis and design space. Pinch analysis employs a time series simulation of the system in which the generation should consistently surpass the load.

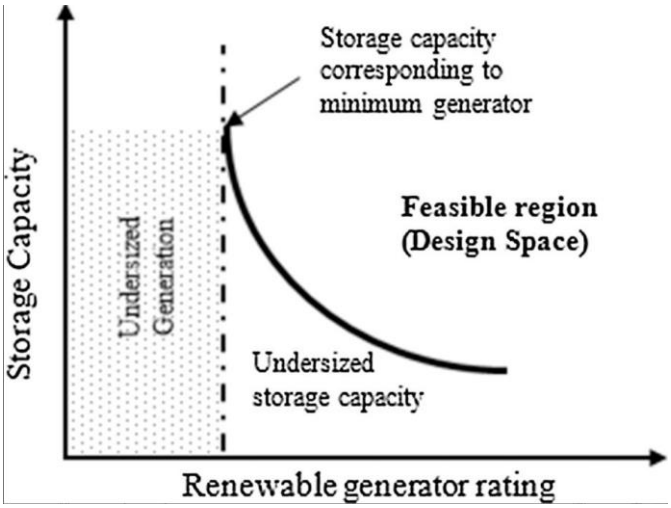



Fig. 6.5 Generic curve for sizing storage device [75]

The minimum storage capacity is calculated by:

$$C = \frac{\max\left[Q_S(t)\right]}{DoD}$$

Where DoD is the depth of discharge of the different storage devices, $Q_s$ is the energy to be stored, and t is the time step. The rate of energy storage change across the device is determined by the power difference between the energy source and load, considering their power conversion efficiency, as described:

$$\frac{dQ_s}{dt} = (G(t) - D(t))\eta_{st}$$

D(t) is the load demand power, G(t) is the power generated from renewable sources.

| Components | Charging efficiency (%) | Discharging efficiency (%) | Depth of discharge (%) |
|---|---|---|---|
| Hydrogen storage | 50 (Fuel cell efficiency) | 80 (Electrolyser efficiency) | 100 |
| VRLA battery | 84 | 84 | 80 |
| Supercapacitor | 90 | 90 | 80 |

Fig. 6.6 The storage technical parameters [62]

The power produced by the PV array can calculated using: $P(t) = \eta A I(t)$, where η is the PV array efficiency, A is the total area of the PV array, and I(t) is the insolation at that instant.

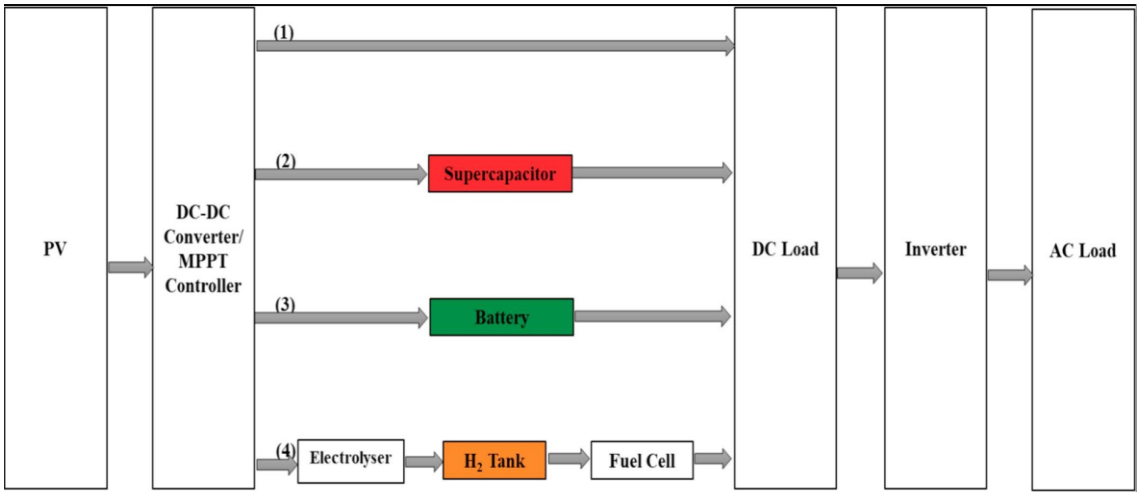



Fig. 6.7 The energy flow route[62]

Power is transferred to the load via route 1 when solar PV is available. When generation exceeds load, supercapacitor charges via route 2. The battery charges through route 3 when the supercapacitor is full. When the battery is fully charged ($SoC = SoC_{max}$), extra energy is diverted to route 4, where the electrolyser stores hydrogen.

b. When PV generation falls below load, battery drain occurs via route 3 and 1. The supercapacitor is depleted through route 2 if the load current exceeds the stated battery voltage by three times. Route 4 uses fuel cell-hydrogen storage to meet the load if battery charge is low.

# 7. CONCLUSION

This thesis extensively examines several energy storage technologies, including battery systems, power-to-gas conversion, flywheel energy storage, and hybrid energy storage solutions. By thoroughly analyzing sizing approaches and computations, we have acquired significant knowledge about the design, optimization, and integration of these technologies in the changing energy environment.

Battery technologies have emphasized their crucial role in facilitating grid stability, integrating renewable energy, and electrifying many sectors. Through meticulous sizing calculations, we have clarified the relationship between capacity, power, efficiency, and lifetime factors especially with the recently implemented Solar Plusz Program (Napenergia'24). This enables well-informed decision-making when it comes to deploying and managing batteries.

The investigation into power-to-gas conversion has uncovered its capacity to connect the disparity between renewable energy production and fluctuations in demand. By conducting thorough evaluations of energy conversion efficiencies, gas storage capacities, and system economics, we have discovered the adaptability of power-to-gas technologies in enabling energy storage, grid balancing, and the production of renewable fuel.

Flywheel energy storage has revealed its capacity to provide quick and powerful performance, as well as its smooth integration with current grid infrastructure. Through the clarification of the fundamental concepts of kinetic energy storage, rotor dynamics, and efficiency enhancements, we have proven that flywheel systems are practical, dependable, and environmentally friendly options for storing energy.

The incorporation of hybrid energy storage systems has arisen as a viable method to effectively integrate the advantages of several storage technologies. By using advanced sizing methods and performance evaluations, how hybrid systems may effectively meet the changing energy storage needs of modern power systems has been demonstrated.
Achieving a sustainable energy future depends on successfully implementing and incorporating various storage systems. By utilizing the knowledge obtained from our research, governments, industry stakeholders, and researchers can together plan a path towards energy systems that are resilient, adaptable, and free from carbon emissions.

Finally, this thesis demonstrates the significant capacity of energy storage technologies to profoundly influence the path of the energy sector in the years to come. As we deal with the challenges of transitioning to new energy sources, let us stay determined in our dedication to creativity, environmental responsibility, and working together, to guarantee a more promising and robust energy future for future generations.

# List of references/Bibliography

[1] A. A. Solomon, D. M. Kammen, and D. Callaway, "The role of large-scale energy storage design and dispatch in the power grid: A study of very high grid penetration of variable renewable resources," *Appl. Energy*, vol. 134, pp. 75–89, Dec. 2014, doi: 10.1016/j.apenergy.2014.07.095.

[2] Z. Hradílek, P. Moldřik, and R. Chválek, "Solar energy storage using hydrogen technology," in *2010 9th International Conference on Environment and Electrical Engineering*, May 2010, pp. 110–113. doi: 10.1109/EEEIC.2010.5489998.

[3] Joey, "Integrated Energy Storage: An Answer to Addressing the 'Duck Curve'?," Sunverge. Accessed: Dec. 13, 2023. [Online]. Available: https://www.sunverge.com/integrated-energy-storage-an-answer-to-addressing-the-duck-curve

[4] B. Sørensen, "Chapter 1 - Introduction and Overview," in *Solar Energy Storage*, B. Sørensen, Ed., Boston: Academic Press, 2015, pp. 1–4. doi: 10.1016/B978-0-12-409540-3.00001-3.

[5] M. T. Arif, A. M. T. Oo, A. B. M. S. Ali, and G. M. Shafiullah, "Significance of Storage on Solar Photovoltaic System—A Residential Load Case Study in Australia," *Smart Grid Renew. Energy*, vol. 4, no. 2, Art. no. 2, May 2013, doi: 10.4236/sgre.2013.42021.

[6] P. Sharma, S. R. Salkuti, and S.-C. Kim, "Advancements in energy storage technologies for smart grid development," *Int. J. Electr. Comput. Eng. IJECE*, vol. 12, no. 4, 2022, doi: 10.11591/ijece.v12i4.pp3421-3429.

[7] R. Kandari, N. Neeraj, and A. Micallef, "Review on Recent Strategies for Integrating Energy Storage Systems in Microgrids," *Energies*, vol. 16, no. 1, Art. no. 1, Jan. 2023, doi: 10.3390/en16010317.

[8] R. Peña-Alzola, R. Sebastián, J. Quesada, and A. Colmenar, "Review of flywheel based energy storage systems," in *2011 International Conference on Power Engineering, Energy and Electrical Drives*, May 2011, pp. 1–6. doi: 10.1109/PowerEng.2011.6036455.

[9] T. Santos, "Overview of energy storage technologies for PV systems," 2015. Accessed: Dec. 14, 2023. [Online]. Available: https://www.semanticscholar.org/paper/Overview-of-energy-storage-technologies-for-PV-Santos/b054e45e6bbfda87696745ed63709296ff213c15

[10] B. Schweber, "Is it again time for the flywheel-based energy storage systems?," EDN. Accessed: Dec. 14, 2023. [Online]. Available: https://www.edn.com/is-it-again-time-for-the-flywheel-based-energy-storage-systems/

[11] J. McGroarty, J. Schmeller, R. Hockney, and M. Polimeno, "Flywheel energy storage system for electric start and an all-electric ship," *IEEE Electr. Ship Technol. Symp. 2005*, pp. 400–406, 2005, doi: 10.1109/ESTS.2005.1524706.

[12] A. G. Ter-Gazarian, *Energy storage for power systems, 2nd edition*. 2011, p. 277.

[13] J. Cropley, "Closed-Loop Hydro's Climate Impact Found Less Than Batteries," RTO Insider. Accessed: Feb. 27, 2024. [Online]. Available: //www.rtoinsider.com/53822-closed-loop-hydro-climate-impact-less-batteries/
[14] Y.-M. Kim, J.-H. Lee, S.-J. Kim, and D. Favrat, "Potential and Evolution of Compressed Air Energy Storage: Energy and Exergy Analyses," *Entropy*, vol. 14, no. 8, pp. 1501–1521, Aug. 2012, doi: 10.3390/e14081501.
[15] X. Chen, T. Zhang, X. Xue, L. Chen, Q. Li, and S. Mei, "A Solar–Thermal-Assisted Adiabatic Compressed Air Energy Storage System and Its Efficiency Analysis," *Appl. Sci.*, vol. 8, no. 8, p. 1390, Aug. 2018, doi: 10.3390/app8081390.
[16] POWER, "Revived Energy Storage Technology Offers Major Grid Benefits," POWER Magazine. Accessed: Apr. 22, 2024. [Online]. Available: https://www.powermag.com/revived-energy-storage-technology-offers-major-grid-benefits/
[17] "Electrochemical Energy Storage for Green Grid | Chemical Reviews." Accessed: Dec. 16, 2023. [Online]. Available: https://pubs.acs.org/doi/epdf/10.1021/cr100290v#
[18] S. Yoomak and A. Ngaopitakkul, "Feasibility Analysis of Different Energy Storage Systems for Solar Road Lighting Systems," *IEEE Access*, vol. PP, pp. 1–1, Jul. 2019, doi: 10.1109/ACCESS.2019.2926105.
[19] B. V. Rajanna and M. K. Kumar, "Comparison study of lead-acid and lithium-ıon batteries for solar photovoltaic applications," *Int. J. Power Electron. Drive Syst. IJPEDS*, vol. 12, no. 2, Art. no. 2, Jun. 2021, doi: 10.11591/ijpeds.v12.i2.pp1069-1082.
[20] B. Yang, L. Hoober, F. Wang, G. Prakash, and S. Narayan, "An Inexpensive Aqueous Flow Battery for Large-Scale Electrical Energy Storage Based on Water-Soluble Organic Redox Couples," *J Electrochem Soc*, vol. 161, pp. A1371–A1380, Jun. 2014, doi: 10.1149/2.1001409jes.
[21] B. Dunn, H. Kamath, and J.-M. Tarascon, "Electrical Energy Storage for the Grid: A Battery of Choices," *Science*, vol. 334, no. 6058, pp. 928–935, Nov. 2011, doi: 10.1126/science.1212741.
[22] X. Zhang, Z. Li, L. Luo, Y. Fan, and Z. Du, "A review on thermal management of lithium-ion batteries for electric vehicles," *Energy*, vol. 238, p. 121652, Jan. 2022, doi: 10.1016/j.energy.2021.121652.
[23] M. M. Biswas, M. S. Azim, T. K. Saha, U. Zobayer, and M. C. Urmi, "Towards Implementation of Smart Grid: An Updated Review on Electrical Energy Storage Systems," *Smart Grid Renew. Energy*, vol. 04, no. 01, pp. 122–132, 2013, doi: 10.4236/sgre.2013.41015.
[24] "Batteries | Free Full-Text | Recent Advances in Hybrid Energy Storage System Integrated Renewable Power Generation: Configuration, Control, Applications, and Future Directions." Accessed: Apr. 09, 2024. [Online]. Available: https://www.mdpi.com/2313-0105/9/1/29
[25] B. V. Rajanna and M. Kumar, "Comparison study of lead-acid and lithium-ıon batteries for solar photovoltaic applications," *Int. J. Power Electron. Drive*

*Syst. IJPEDS*, vol. 12, p. 1069, Jun. 2021, doi: 10.11591/ijpeds.v12.i2.pp1069-1082.

[26] "Redox flow batteries: a sustainable technology." Accessed: Apr. 27, 2024. [Online]. Available: https://cicenergigune.com/en/blog/redox-flow-batteries-sustainable-technology

[27] D. P. Dubal, N. R. Chodankar, D.-H. Kim, and P. Gomez-Romero, "Towards flexible solid-state supercapacitors for smart and wearable electronics," *Chem. Soc. Rev.*, vol. 47, no. 6, pp. 2065–2129, Mar. 2018, doi: 10.1039/C7CS00505A.

[28] N. Kurra and Q. Jiang, "18 - Supercapacitors," in *Storing Energy (Second Edition)*, T. M. Letcher, Ed., Elsevier, 2022, pp. 383–417. doi: 10.1016/B978-0-12-824510-1.00017-9.

[29] M. G. Molina and P. E. Mercado, "Power Flow Stabilization and Control of Microgrid with Wind Generation by Superconducting Magnetic Energy Storage," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 910–922, Mar. 2011, doi: 10.1109/TPEL.2010.2097609.

[30] D. S. Padimiti and B. H. Chowdhury, "Superconducting Magnetic Energy Storage System (SMES) for Improved Dynamic System Performance," in *2007 IEEE Power Engineering Society General Meeting*, Jun. 2007, pp. 1–6. doi: 10.1109/PES.2007.385739.

[31] A. K. Worku *et al.*, "Energy Storage Technologies; Recent Advances, Challenges, and Prospectives," in *Planning of Hybrid Renewable Energy Systems, Electric Vehicles and Microgrid: Modeling, Control and Optimization*, A. K. Bohre, P. Chaturvedi, M. L. Kolhe, and S. N. Singh, Eds., Singapore: Springer Nature, 2022, pp. 125–150. doi: 10.1007/978-981-19-0979-5_7.

[32] J. Vandewalle, K. Bruninx, and W. D'haeseleer, "Effects of large-scale power to gas conversion on the power, gas and carbon sectors and their interactions," *Energy Convers. Manag.*, vol. 94, pp. 28–39, Apr. 2015, doi: 10.1016/j.enconman.2015.01.038.

[33] A. Perna, L. Moretti, G. Ficco, G. Spazzafumo, L. Canale, and M. Dell'Isola, "SNG Generation via Power to Gas Technology: Plant Design and Annual Performance Assessment," *Appl. Sci.*, vol. 10, no. 23, Art. no. 23, Jan. 2020, doi: 10.3390/app10238443.

[34] "Power-to-Gas Plant for Long Term Energy Storage." Accessed: Apr. 22, 2024. [Online]. Available: https://www.boldbusiness.com/energy/power-to-gas-plant/

[35] "Fuel Cell Systems Explained | Wiley Online Books." Accessed: Dec. 18, 2023. [Online]. Available: https://onlinelibrary.wiley.com/doi/book/10.1002/9781118706992

[36] "Fuel Cell & Hydrogen Energy Basics," Fuel Cell & Hydrogen Energy Association. Accessed: Apr. 22, 2024. [Online]. Available: https://www.fchea.org/h2-day-2019-events-activities/2019/8/1/fuel-cell-amp-hydrogen-energy-basics

[37] C. Pasten and J. Carlos Santamarina, "Energy geo-storage — analysis and geomechanical implications," *KSCE J. Civ. Eng.*, vol. 15, no. 4, pp. 655–667, Apr. 2011, doi: 10.1007/s12205-011-0006-6.
[38] D. Barlev, R. Vidu, and P. Stroeve, "Innovation in concentrated solar power," *Sol. Energy Mater. Sol. Cells*, vol. 95, no. 10, pp. 2703–2725, Oct. 2011, doi: 10.1016/j.solmat.2011.05.020.
[39] M. M. Farid, A. M. Khudhair, S. A. K. Razack, and S. Al-Hallaj, "A review on phase change energy storage: materials and applications," *Energy Convers. Manag.*, vol. 45, no. 9, pp. 1597–1615, Jun. 2004, doi: 10.1016/j.enconman.2003.09.015.
[40] F. Alnaimat and Y. Rashid, "Thermal Energy Storage in Solar Power Plants: A Review of the Materials, Associated Limitations, and Proposed Solutions," *Energies*, vol. 12, no. 21, Art. no. 21, Jan. 2019, doi: 10.3390/en12214164.
[41] A. J. Carrillo, J. González-Aguilar, M. Romero, and J. M. Coronado, "Solar Energy on Demand: A Review on High Temperature Thermochemical Heat Storage Systems and Materials," *Chem. Rev.*, vol. 119, no. 7, pp. 4777–4816, Apr. 2019, doi: 10.1021/acs.chemrev.8b00315.
[42] "Thermochemical Energy Storage: The next generation thermal batteries? - #SINTEFblog." Accessed: Apr. 22, 2024. [Online]. Available: https://blog.sintef.com/sintefenergy/thermochemical-energy-storage-the-next-generation-thermal-batteries/
[43] C. Chukwuka and K. Folly, "Overview of Concentrated Solar Power," *J. Energy Power Eng.*, vol. 7, Jul. 2013, doi: 10.17265/1934-8975/2013.12.010.
[44] "E17IR ThEnergy Stor_AH_Jan2013_final_GSOK.pdf." Accessed: May 01, 2024. [Online]. Available: https://iea-etsap.org/E-TechDS/PDF/E17IR%20ThEnergy%20Stor_AH_Jan2013_final_GSOK.pdf
[45] P. C. Nikolaos, F. Marios, and K. Dimitris, "A Review of Pumped Hydro Storage Systems," *Energies*, vol. 16, no. 11, p. 4516, Jun. 2023, doi: 10.3390/en16114516.
[46] "Napenergia Plusz Program 2024 - E.ON." Accessed: Jan. 27, 2024. [Online]. Available: https://www.eon.hu/hu/lakossagi/termekek/solar/hirek/napenergia-plusz-program.html
[47] "Estimating Hungarian Household Energy Consumption Using Artificial Neural Networks," *Acta Polytech. Hung.*, vol. 11, no. 4, Apr. 2014, doi: 10.12700/APH.25.04.2014.04.10.
[48] "Battery Voltage | PVEducation." Accessed: Feb. 25, 2024. [Online]. Available: https://www.pveducation.org/pvcdrom/battery-characteristics/battery-voltage
[49] "IEEE Guide for the Characterization and Evaluation of Lithium-Based Batteries in Stationary Applications," *IEEE Std 16791-2017*, pp. 1–47, Jan. 2018, doi: 10.1109/IEEESTD.2018.8262521.
[50] "This is how long the sun shines in Hungary! Up to 16 hours of daylight a day.," Worlddata.info. Accessed: Feb. 12, 2024. [Online]. Available: https://www.worlddata.info/europe/hungary/sunset.php

[51] N. Gholizadeh, M. J. Vahid-Pakdel, and B. Mohammadi-ivatloo, "Enhancement of demand supply's security using power to gas technology in networked energy hubs," *Int. J. Electr. Power Energy Syst.*, vol. 109, pp. 83–94, Jul. 2019, doi: 10.1016/j.ijepes.2019.01.047.
[52] "Hydrogen - What Is It? | Hydrogen Fuel & Projects | Shell Global." Accessed: Feb. 27, 2024. [Online]. Available: https://www.shell.com/energy-and-innovation/new-energies/hydrogen.html
[53] Y. Yang, G. Wang, S. Zhang, L. Zhang, and L. Lin, "Review of Hydrogen Standards for China," *E3S Web Conf.*, vol. 118, p. 03032, 2019, doi: 10.1051/e3sconf/201911803032.
[54] A. Liponi, A. Baccioli, L. Ferrari, and U. Desideri, "Techno-economic analysis of hydrogen production from PV plants," *E3S Web Conf.*, vol. 334, p. 01001, Jan. 2022, doi: 10.1051/e3sconf/202233401001.
[55] "David MacKay FRS: : Contents." Accessed: Feb. 27, 2024. [Online]. Available: https://www.withouthotair.com/
[56] S. Sabihuddin, A. Kiprakis, and M. Mueller, *A diamagnetically stabilized magnetically levitated flywheel battery*. 2013, p. 5. doi: 10.1109/EVER.2013.6521621.
[57] E. Dragoni, "Mechanical design of flywheels for energy storage: A review with state-of-the-art developments," *Proc. Inst. Mech. Eng. Part J. Mater. Des. Appl.*, vol. 233, no. 5, pp. 995–1004, May 2019, doi: 10.1177/1464420717729415.
[58] A. Kailasan, T. Dimond, P. Allaire, and D. Sheffler, "Design and Analysis of a Unique Energy Storage Flywheel System—An Integrated Flywheel, Motor/Generator, and Magnetic Bearing Configuration," *J. Eng. Gas Turbines Power*, vol. 137, no. 4, p. 042505, Apr. 2015, doi: 10.1115/1.4028575.
[59] G. L. Guizzi, M. Manno, L. M. Tolomei, and R. M. Vitali, "Thermodynamic analysis of a liquid air energy storage system," *Energy*, vol. 93, 2015, doi: 10.1016/j.energy.2015.10.030.
[60] W. Jing, C. H. Lai, S. H. W. Wong, and M. L. D. Wong, "Battery-supercapacitor hybrid energy storage system in standalone DC microgrids: areview," *IET Renew. Power Gener.*, vol. 11, no. 4, 2017, doi: 10.1049/iet-rpg.2016.0500.
[61] I. E. Atawi, A. Q. Al-Shetwi, A. M. Magableh, and O. H. Albalawi, "Recent Advances in Hybrid Energy Storage System Integrated Renewable Power Generation: Configuration, Control, Applications, and Future Directions," *Batteries*, vol. 9, no. 1, Art. no. 1, Jan. 2023, doi: 10.3390/batteries9010029.
[62] A. S. Jacob, R. Banerjee, and P. C. Ghosh, "Sizing of hybrid energy storage system for a PV based microgrid through design space approach," *Appl. Energy*, vol. 212, pp. 640–653, Feb. 2018, doi: 10.1016/j.apenergy.2017.12.040.
[63] X. Wu, Z. Tang, and T. Kerekes, "Sizing of Hybrid Energy Storage System for Residential PV Applications," in *2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe)*, Sep. 2022, pp. 1–6. Accessed: Apr. 07, 2024. [Online]. Available: https://ieeexplore.ieee.org/document/9907265?denied=

[64] X. Wu, Z. Tang, and T. Kerekes, "Sizing of Hybrid Energy Storage System for Residential PV Applications," in *2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe)*, Sep. 2022, pp. 1–6. Accessed: Apr. 07, 2024. [Online]. Available: https://ieeexplore.ieee.org/document/9907265

[65] S. Hajiaghasi, M. M. Hosseini Ahmadi, P. Goleij, A. Salemnia, and M. Hamzeh, "Hybrid energy storage sizing based on discrete Fourier transform and particle swarm optimization for microgrid applications," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 12, p. e13156, 2021, doi: 10.1002/2050-7038.13156.

[66] A. M. Abdelshafy, J. Jurasz, H. Hassan, and A. M. Mohamed, "Optimized energy management strategy for grid connected double storage (pumped storage-battery) system powered by renewable energy resources," *Energy*, vol. 192, p. 116615, Feb. 2020, doi: 10.1016/j.energy.2019.116615.

[67] D. N. Luta and A. K. Raji, "Decision-making between a grid extension and a rural renewable off-grid system with hydrogen generation," *Int. J. Hydrog. Energy*, vol. 43, no. 20, pp. 9535–9548, May 2018, doi: 10.1016/j.ijhydene.2018.04.032.

[68] Y. Jiang, L. Kang, and Y. Liu, "A unified model to optimize configuration of battery energy storage systems with multiple types of batteries," *Energy*, vol. 176, pp. 552–560, Jun. 2019, doi: 10.1016/j.energy.2019.04.018.

[69] A. Lorestani, G. B. Gharehpetian, and M. H. Nazari, "Optimal sizing and techno-economic analysis of energy- and cost-efficient standalone multi-carrier microgrid," *Energy*, vol. 178, pp. 751–764, Jul. 2019, doi: 10.1016/j.energy.2019.04.152.

[70] S. Günther, A. Bensmann, and R. Hanke-Rauschenbach, "Theoretical dimensioning and sizing limits of hybrid energy storage systems," *Appl. Energy*, vol. 210, pp. 127–137, Jan. 2018, doi: 10.1016/j.apenergy.2017.10.116.

[71] S. Bae, S. U. Jeon, and J.-W. Park, "A Study on Optimal Sizing and Control for Hybrid Energy Storage System with SMES and Battery*," *IFAC-Pap.*, vol. 48, no. 30, pp. 507–511, Jan. 2015, doi: 10.1016/j.ifacol.2015.12.430.

[72] A. Aktas, K. Erhan, S. Ozdemir, and E. Ozdemir, "Experimental investigation of a new smart energy management algorithm for a hybrid energy storage system in smart grid applications," *Electr. Power Syst. Res.*, vol. 144, pp. 185–196, Mar. 2017, doi: 10.1016/j.epsr.2016.11.022.

[73] P. G. Papageorgiou, K. O. Oureilidis, and G. C. Christoforidis, "A systematic review of hybrid superconducting magnetic/battery energy storage systems: Applications, control strategies, benefits, limitations and future prospects," *Renew. Sustain. Energy Rev.*, vol. 183, p. 113436, Sep. 2023, doi: 10.1016/j.rser.2023.113436.

[74] S. Wang *et al.*, "Design and advanced control strategies of a hybrid energy storage system for the grid integration of wind power generations," *IET Renew. Power Gener.*, vol. 9, no. 2, pp. 89–98, 2015, doi: 10.1049/iet-rpg.2013.0340.

[75] S. Bandyopadhyay, “Design and optimization of isolated energy systems through pinch analysis,” *Asia-Pac. J. Chem. Eng.*, vol. 6, no. 3, pp. 518–526, 2011, doi: 10.1002/apj.551.