MALLA REDDY COLLEGE
OF ENGINEERING & TECHNOLOGY
(AUTONOMOUS INSTITUTION - UGC, GOVT. OF INDIA)
Affiliated to JNTUH; Approved by AICTE, NBA-Tier 1 & NAAC with A-GRADE | ISO 9001:2015

DEPARTMENT OF

ELECTRICAL AND ELECTRONICS
ENGINEERING

DIGITAL NOTES

ON

ENERGY STORAGE SYSTEM

2023 - 2024

III B. Tech I Semester

By
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MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY

III YEAR B. Tech EEE – I SEM L/T/P/C 3/-/-/3

(PROFESSIONAL ELECTIVE-II) (R20A0218)

ENERGYSTORAGESYSTEMS

COURSE OBJECTIVES:

The objectives of this course is to acquire knowledge on

• Need of energy storage and different types of energy storage.

• Thermal, magnetic, electrical and electrochemical energy storage systems.

• Emerging needs for EES pertaining to Renewable energy

• Types of electrical energy storage systems • Sign and Applications of Electrical Energy Storage

UNIT - I: Introduction:

Necessity of energy storage, different types of energy storage, mechanical, chemical, electrical, electrochemical, biological, magnetic, electromagnetic, thermal, comparison of energy storage technologies

UNIT - II: Energy Storage Systems:

Thermal Energy storage-sensible and latent heat, phase change materials, Energy and exergy analysis of thermal energy storage, Electrical Energy storage-super-capacitors, Magnetic Energy storage Superconducting systems, Mechanical-Pumped hydro, flywheels and pressurized air energy storage, Chemical-Hydrogen production and storage, Principle of direct energy conversion using fuel cells, thermodynamics of fuel cells, Types of fuel cells, Fuel cell performance, Electrochemical Energy Storage Battery, primary, secondary and flow batteries.

UNIT - III Needs for Electrical Energy Storage:

Emerging needs for EES, more renewable energy-less fossil fuel, Smart Grid uses - the roles of electrical energy storage technologies-the roles from the viewpoint of a utility-the roles from the viewpoint of consumers-the roles from the viewpoint of generators of renewable energy.

UNIT - IV: Types of Electrical Energy Storage systems:

Electrical storage systems, Double-layer capacitors (DLC), Superconducting magnetic energy storage (SMES), super charging stations, Thermal storage systems, Standards for EES, Technical comparison of EES technologies.

UNIT - V: Design and Applications of Electrical Energy Storage:

Renewable energy storage-Battery sizing and stand-alone applications, stationary (Power Grid application), Small scale application-Portable storage systems and medical devices, Mobile storage Applications- Electric vehicles (EVs), types of EVs, batteries and fuel cells, future technologies, hybrid systems for energy storage.

Text Books:

• Energy Storage - Technologies and Applications by Ahmed Faheem Zobaa, InTech

• Fundamentals of Energy Storage by J. Jensen and B. Sorenson, Wiley-Interscalene, NewYork,

• Energy Storage: Fundamentals, Materials and Applications, by Huggins R. A., Springer.

Reference Books:

• Thermal energy storage: Systems and Applications by Dincer I. and Rosen M. A., Wileypub.

• Energy Storage: Fundamentals, Materials and Applications, by Huggins R. A., Springer.

• Electric & Hybrid Vehicles by G. Pistoia, Elsevier B. V.

• Fuel cell Fundamentals by R. O’ Hayre, S. Cha, W. Colella and F. B. Prinz, Wiley Pub.

Course Outcomes:

The students should be able to

• know the characteristics of electricity and need for continuous and flexible supply

• discuss about the role of electrical energy storage technologies

• Analyses feature of EES systems

• acquire knowledge on various types of EES systems

• apply EES systems to various applications such as smart micro grid, smart home etc.

UNIT-I

INTRODUCTION

1.1 Necessity of energy storage:

Energy Storage is the capture of energy produced at one time for use at a later time

A device that stores energy is generally called an accumulator or battery

Energy comes in multiple forms including radiation, chemical, gravitational potential, electrical potential electricity, elevated temperature, latent heat and kinetic

Energy storage involves converting energy from forms that are difficult to store to more conveniently or economically storable forms.

Some techniques provide short term energy storage, while others can endure for much longer.

Technologies-In Energy Storage

There are different methods for storing energy that has been developed so that the grid can meet everyday energy needs. These are: electrical, mechanical, electrochemical, thermal, and chemical. Tabulated data in Fig.1 below focuses on technologies that can currently provide large storage capacities (of at least 20 MW).

- *The Importance of Energy Storage in Future Energy Supply*

- Sustainability is a crucial factor for economic growth, and it will continue to be an important consideration in the future.
    - Demand for clean energy drives sustainable technology development that will impact future energy and the environment.
    - Stationary energy storage is essential in transitioning to a sustainable energy system with higher shares of renewable energy.
    - Energy storage has become a ubiquitous component of the electricity grid, leading to a boom in storage capacity worldwide as electricity is expected to make up half of the final energy consumption by 2050.

1.2. Different Types of Energy Storage System

The different types of energy storage

1. Batteries
2. Thermal
3. Mechanical
4. Pumped hydro
5. Hydrogen

Within these they can be broken down further in application scale to utility-scale or the bulk system, customer-sited and residential. In addition, with the electrification of transport, there is a further mobile application category.

1. Battery storage

Batteries, the oldest, most common and widely accessible form of storage, are an electrochemical technology comprised of one or more cells with a positive terminal named a cathode and negative terminal or anode.

Batteries encompass a range of chemistries. The best known and in widespread use in portable electronic devices and vehicles are lithium-ion and lead acid. Others solid battery types are nickel-cadmium and sodium-sulphur, while zinc-air is emerging.

Another category is flow batteries with liquid electrolyte solutions, including vanadium redox and iron-chromium and zinc-bromine chemistries.

Supercapacitors, although not a battery as such, also can be categorised as an electrochemical technology, with their application particularly for sub-minute level response.

2. Thermal storage

Thermal storage in essence involves the capture and release of heat or cold in a solid, liquid or air and potentially involving changes of state of the storage medium, e.g. from gas to liquid or solid to liquid and vice versa.

Technologies include energy storage with molten salt and liquid air or cryogenic storage. Molten salt has emerged as commercially viable with concentrated solar power but this and other heat storage options may be limited by the need for large underground storage caverns.

3. Mechanical storage

Mechanical storage systems are arguably the simplest, drawing on the kinetic forces of rotation or gravitation to store energy. But feasibility in today's grid applications requires the application of the latest technologies.

The main options are energy storage with flywheels and compressed air systems, while gravitational energy is an emerging technology with various options under development.

4. Pumped hydro

Energy storage with pumped hydro systems based on large water reservoirs has been widely implemented over much of the past century to become the most common form of utility-scale storage globally.

Such systems require water cycling between two reservoirs at different levels with the 'energy storage' in the water in the upper reservoir, which is released when the water is released to the lower reservoir.

5. Hydrogen

Energy storage with hydrogen, which is still emerging, would involve its conversion from electricity via electrolysis for storage in tanks. From there it can later undergo either re-electrification or supply to emerging applications such as transport, industry or residential as a supplement or replacement to gas.

Choosing the best energy storage option

So what is the best energy storage option? Each of the different energy storage technologies has applications for which it is best suited, which need to be considered in the implementation.

Key issues that must be assessed are the charge, discharge profiles and the storage capacity capability and potential scalability. In addition to the cost of the storage, the expected lifetime in terms of cycling frequency before degradation sets in also needs to be factored in a cost benefit analysis.

The figure shows that for the sub-minute level response supercapacitors are the main option.

The rapid cost declines that lithium-ion has seen and are expected to continue in the future make battery energy storage the main option currently for requirements up to a few hours and for small-scale residential and electric vehicle applications. But as the storage duration requirement increases, the options shift to either thermal, mechanical or pumped hydro and in the future hydrogen.

Storage in the zero carbon system of the future

All of the storage technologies are undergoing innovation to improve efficiencies and lower costs. New materials such as graphene and others based on nanoscale concepts offer the prospect for a new level of efficiency in supercapacitors and thermal storage, for example.

The integration of renewables such as floating solar and digitalisation are expected to improve the value and economics of pumped hydro.

Competition and economies of scale should be a further driver to cost reductions.

Looking ahead to a 2050 net zero energy system, the Energy Transitions Commission in its plan anticipates that three of the storage technologies could win out long term, although obviously not to the exclusion of other options, the optimal mix of which will depend on individual use cases and market and other circumstances.

These are lithium-ion for daily balancing and pumped hydro and hydrogen for the long term requirements.

The Commission states that by 2040 the balance of different energy storage technologies might include a very significant role for lithium-ion across a large spectrum, a limited role for flywheels for low duration, high discharge frequencies, a significant role for pumped hydro for the 16-60 hour range, a role for compressed air for longer durations and hydrogen in fuel cells playing the major role for the longest requirements.

1.3 Mechanical Storage Systems

Mechanical energy storage devices store received energy by utilizing kinetic or gravitational forces. These systems are useful in real-world applications due to quality materials, advanced computer control systems, and imaginative design. Mechanical energy storage operates in complicated systems that employ heat, water, or air in conjunction with compressors, turbines, and other machinery.

1.3.1 Pumped Hydro Storage (PHS)

Pumped hydro storage power plants provide for more than 95% of the world's current electrical storage capacity. In pumped hydro storage systems, two water reservoirs at different heights are utilized to pump water during off-peak hours (charging), and as needed, water flows downstream from the top pool to the lower reservoir, driving a turbine that produces electricity (discharging). The efficiency of the PHS plant ranges from 70% to 85%. The main benefits of this system are long life and almost unlimited cycle stability, while its drawbacks are its topography and heavy land use. The world's largest PHS plants have installed capacity of 3003 MW and 2400 MW (as of December 2021), respectively.

1.3.2 Compressed Air Energy Storage (CAES)

CAES has been used in a range of industrial applications since the eighteenth century. Electricity is used to compress air and store it in a subsurface construction or an above-ground system of containers or lines. Subsurface storage options include tunnels, aquifers, and abandoned mines. Diabatic technology is well proven; the plants are highly reliable and can operate without external power (shown in Figure 3). CAES has a large capacity, but it has drawbacks such as low round-trip performance (less than 50%) and geographical constraints.

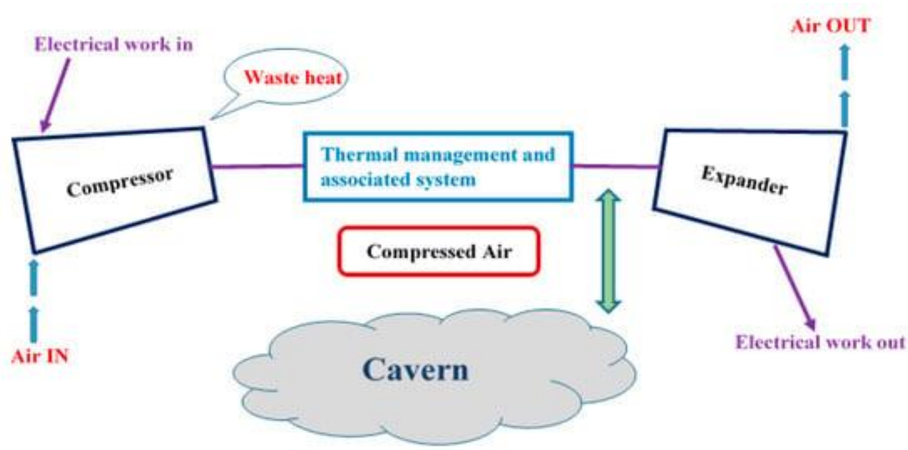


Figure 3. Compressed air energy storage system schematic.

1.3.3 Flywheel Energy Storage (FES)

In flywheel energy storage, kinetic energy is stored in an accelerated rotor which is a massive rotating cylinder. Electricity is supplied to the flywheel using a transmission mechanism and with rise in the speed, amount of stored energy increases. Flywheels are commonly utilized for power quality in industrial and other applications. Flywheels have advantages of exceptional cycle stability and long life, low maintenance, greater power density and the use of environmentally friendly materials. However, it has demerits such as high self-discharge and poor current efficiency. Efforts are focused on improving the management of flywheels as power storage devices for usage in cars and industries for long operation hours (shown in Figure 4).

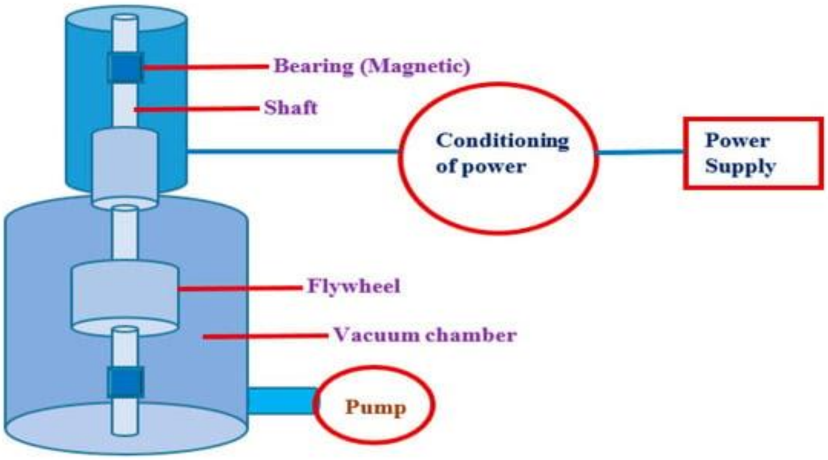


Figure 4. Flywheel energy storage system schematic.

1.4 Chemical Energy Storage

A chemical energy storage system is the only idea that allows for the long-term storage of significant amounts of energy, up to TWh, even as periodic accumulation. SNG and hydrogen may be used in a range of industries, including commuting, movement, heating, and the chemical industry. They have lesser overall efficiency than PHS and Li-ion storage technologies, but are more cost efficient and effective than ordinary batteries.

1.4.1 Hydrogen (H_2)

An electrolyzer is a type of electrochemical converter that splits water into hydrogen and oxygen using electricity. It is an endothermic reaction, which indicates that heat is required throughout the process. Hydrogen may be stored under pressure in gas bottles or tanks for nearly indefinite periods of time. Electrolysis releases oxygen into the environment rather than retaining it, and oxygen from the air is utilized to create electricity.

1.4.2 Synthetic Natural Gas (SNG)

Methane (synthetic natural gas or SNG) may be synthesized to store energy. SNG can be stored in pressure tanks, underground, or fed directly into the gas infrastructure. To prevent energy losses, CO2 and H2 transport to the methanation plant should be avoided. The fundamental drawback of SNG is its low efficiency as a result of conversion losses in electrolysis, methanation, storage, transport, and power production. The overall AC-AC efficiency of 35% is significantly lower than that of hydrogen.

1.5 Electrical Storage Systems

The classifications of EES are as follows:

1.5.1 Double-Layer Capacitors (DLC)

DLCs, also known as super-capacitors, are a 60-year-old electrochemical double-layer capacitor (DLC) technology. The extremely high capacitance values, on the order of thousands of farads, and the capability to charge and discharge very fast due to extremely low inner resistance are the two important properties. This technology offers a lot of space for advancement because it might result in substantially greater capacitance and energy density than standard capacitors, permitting for more compact designs. Durability, dependability, no maintenance, prolonged lifetime, and functioning across a wide temperature range are further benefits. With the exception of the chemical used in capacitors, which deteriorate in 5–6 years regardless of the number of cycles, the lifetime surpasses one million cycles without degradation. The efficiency is often more than 90%, with discharge times varying from seconds to hours. DLCs are not suitable for long-term energy storage due to their high self-discharge rate, low energy density, and hefty investment needs. As a UPS, a DLC is excellent for bridging small power disruptions. The electric automobile might be used in a unique way, as a buffer system for acceleration and regenerative braking.

1.5.2 *Superconducting Magnetic Energy Storage (SMES)*

SMES devices store magnetic energy in a magnetic field that is generated by a superconducting coil held less than its critical temperature. A temperature of around 4 °K was required at the early age but now materials with higher critical temperatures (about 100 °K) have been developed and are now accessible. Particle detectors for high-energy scientific experiments and nuclear fusion use large SMES systems with more than 10 MW of power. The main benefits of SMES are high overall round-trip efficiency (85–90%), the extremely high power output and the extremely fast reaction time: the required power is practically instantly accessible. The energy can be stored basically as long as the cooling system is running, but longer storage times are restricted by the refrigeration system's energy demand.

1.6 Electrochemical Storage Systems

Electrochemical energy storage devices have the ability to make a major contribution to the deployment of sustainable energy. Electrochemical energy storage is based on systems with high energy density (batteries) or power density (electrochemical capacitors). High energy and high power densities in the same material are increasingly required in current and near-future applications. These are categorized in two types: secondary batteries and flow batteries. The secondary batteries have again classified into following types: lead–acid, NiCd/NiMH, Li-ion, metal–air, sodium–sulfur and sodium–nickel chloride.

1.6.1 Secondary Batteries

A secondary battery, or charge accumulator, is a cell or set of cells with reversible cell processes. This implies that the original chemical conditions inside the cell can be restored by allowing current to flow into it, i.e., charging from outside [22].

1.6.2 *Lead–Acid Battery (LA)*

Lead–acid batteries are the most widely used form of battery in the world, dating back to roughly 1890. Service life is typically 6–15 years, with a service life of 1500 cycles at a % depth of discharge and a cycle efficiency of 80–90%. The downsides are lower energy density and the use of lead, a dangerous element that is prohibited or restricted in some locations. Advantages include a good cost/performance ratio, simple recyclability, and a simple charging method. The current focus of lead–acid battery development is to improve their efficiency for micro-hybrid electric vehicles.

1.6.3 *Nickel–Cadmium and Nickel–Metal Hydride Battery (NiCd, NiMH)*

Before the commercial launch of nickel–metal hydride (NiMH) batteries in 1995, nickel–cadmium (NiCd) batteries had been in use since around 1915. NiMH batteries contain all of the advantages of NiCd batteries, such as greater power density, marginally better energy density, and a larger number of cycles, with the exception of a 10-fold lower maximum nominal capacity. They are far more robust and secure than lithium-ion batteries. However, due to the toxicity of cadmium, they have been limited for consumer use since 2006. NiMH batteries are currently about the same cost as Li-ion battery packs.

1.6.3 *Lithium-Ion Battery (Li-Ion)*

Lithium-ion batteries have been the most important form of storage in portable and mobile applications since about the year 2000. With a cell voltage of only 1.2 Volts, one lithium-ion cell may substitute three NiCd or NiMH batteries. The most significant impediment is the high cost of the unique packaging and incorporated overload protection circuits. Safety is a serious problem in lithium-ion battery technology. Most metal oxide electrodes are thermally unstable and can melt at high temperatures. Lithium-ion batteries feature a monitoring device that prevents overcharging and discharging to lessen this risk. A voltage regulation circuit is often provided to monitor and avoid voltage changes in each individual cell. Lithium-ion battery technology is constantly improving, with plenty of possibilities for advancement. The evolution of cathode materials is being studied. The construction of typical Li-ion battery module is depicted in Figure 5.

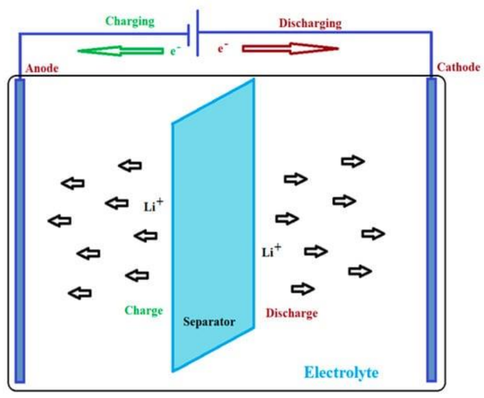


Figure 5. Typical Li-ion battery module.

1.6.5 *Metal–Air Battery*

A metal–air electrochemical cell's anode is made of pure metal, while the cathode is connected to an infinite supply of air. In the electrochemical process, only oxygen from the air is used. Because of its greater specific energy excluding oxygen (theoretically 11.14 kWh/kg), the lithium air battery is the most enticing of the several metal–air battery chemical couples. Due to lithium's high reactivity to air and humidity, it can catch fire, creating a serious safety risk. Only a zinc–air battery with a theoretical specific energy of 1.35 kWh/kg (without oxygen) is theoretically practical at the moment. It is difficult to design rechargeable zinc–air cells since zinc precipitation from the water-based electrolyte must be properly handled. Although a viable, electrically rechargeable metal–air system could offer low material costs and high specific energy, none has yet attained marketability.

1.6.6 *Sodium–Sulphur Battery (NaS)*

In sodium–sulfur batteries, a solid beta-alumina ceramic electrolyte isolates the active constituents (molten sulfur at the anode and molten sodium at the cathode). NaS batteries have a discharge time of 6.0 to 7.2 h and a standard life cycle of around 4500. They are both effective and quick to respond (round-trip efficiency based on AC is around 75%). Over 200 places in Japan have tested the NaS battery technology, largely for peak shaving. Many countries employ NaS batteries as well. Although the lack of a heat source is a significant drawback, with correctly sized insulation, the heat developed in the battery may be managed in frequent use by its own reaction heat. These batteries are suited for high-frequency cycling applications. The construction of typical NaS battery module is depicts in Figure 6.

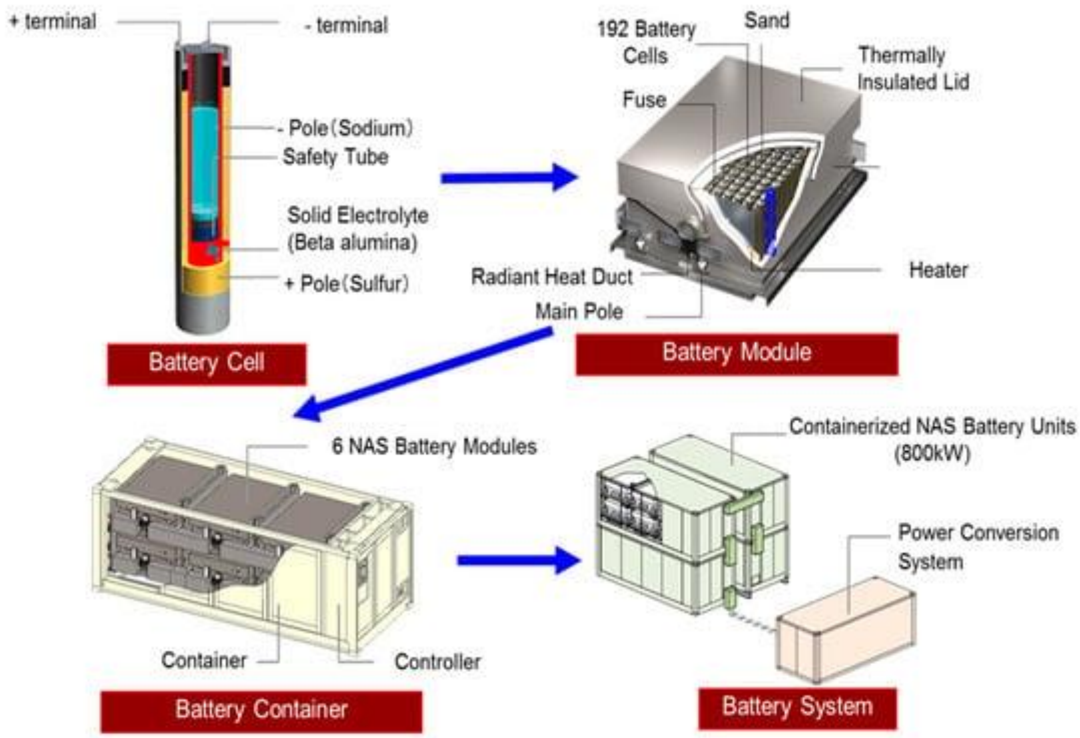


Figure 6. NaS battery system.

1.6.7 *Sodium–Nickel Chloride Battery (NaNiCl)*

The sodium–nickel chloride (NaNiCl) battery, also known as the ZEBRA battery is a high-temperature (HT) battery that, like the NaS battery, has been available on the market since approximately 1995. NaNiCl batteries outperform NaS batteries in terms of safety and cell voltage, and they can withstand limited overload and discharge. These batteries have been employed effectively in a variety of electric vehicle designs, and they are a viable alternative for fleet applications. Upgraded variants of the ZEBRA battery with greater power density values for hybrid electric vehicles, as well as high-energy versions for conserving renewable power for load-leveling and industrial purposes, are presently being developed.

1.6.8 *Flow Batteries*

NASA invented flow batteries in the early 1970s as an EES for long-term space flights [25]. They have the potential to store energy for hours or days and have a power of many megawatts. Flow batteries are of two types: redox flow batteries and hybrid flow batteries.

1.6.9 Redox Flow Battery (RFB)

The electrolytes present at the negative and positive electrodes of a redox flow battery are anolyte and catholyte. During discharge, electrodes are continually provided with dissolved active masses from the tanks; once converted, the product is returned to the tank. During the charge exchange, a current flows between the electrodes, which may be used by a battery-powered device. Redox flow batteries are being studied for use in electric vehicles; however, electrolyte energy density has proved too low thus far. An RFB may potentially be “refilled” in minutes by draining out the emptied electrolyte and replacing it with recharged electrolyte. In RFBs today, many redox couples, such as a Fe-Ti system or a poly S-Br system, have been investigated and tested (shown in Figure 7).

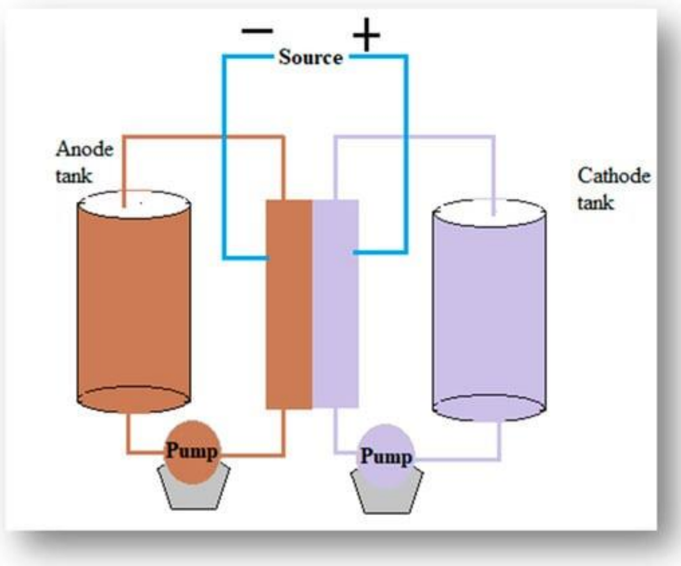


Figure 7. Schematic of redox flow battery.

1.6.10 Hybrid Flow Battery (HFB)

One active mass in a hybrid flow battery (HFB) is kept within the electrochemical cell, while the other is kept externally. The benefits of classic secondary batteries and RFBs are combined in HFBs. HFBs include the Zn-Ce and Zn-Br systems. The anolyte is a Zn2+ ion-acid solution, and the electrodes are primarily carbon-plastic composites. Exxon pioneered the Zn-Br hybrid flow battery in the early 1970s, and it is now being commercialized by a variety of companies. In addition, 5 kW/20 kWh community energy storage devices are also being developed.

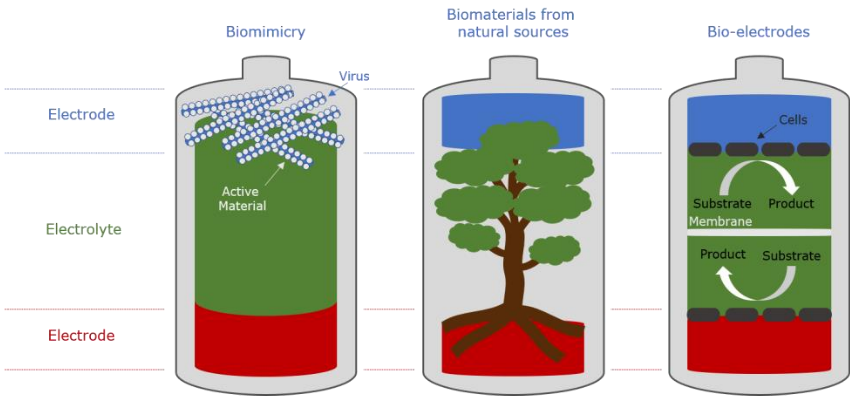
1.7 Biological Energy Storage

The use of bio-electrochemical devices or bio-batteries based on biological systems will represent a breakthrough for the electronics industry in developing greener and more sustainable energy storage systems for portable devices.

The widespread use of cell phones, tablets and smart watches or bracelets has many advantages, such as immediate access to a large amount of information and better communication between people (regardless of distance). However, the acquisition of materials needed for manufacturing some device components has devastating effects on the planet.

Although many biological systems are able to store energy, currently, the insertion of biomolecules in energy storage systems (batteries or supercapacitors) is very unusual due to their harsh working conditions, that often, cause the denaturalization of the biological molecules present in the system. However, the gap between these two fields is getting narrower, and biotechnology and bioengineering could be one of the key players in the development of next generation batteries and supercapacitors with higher energy and power densities.

Bio-electrochemical devices or bio-batteries are defined as energy storage systems in which a bio-based element has been included in its design. This can be done (i) by mimicking solutions already existing in the nature, (ii) by modifying and incorporating biological components obtained from natural sources (biomaterials) or (iii) by using biomolecules that can convert substrates into products.



The imitation of solutions that already exist in nature is known as biomimetics. This solution is based on the observation and exploration of strategies established by nature during species evolution to apply them to human design problems. One example is the use of bio templates in which viruses or other biological molecules are used as scaffolds to synthesize materials at the nanoscale. This solution has made possible the use of sustainable and efficient methods to manufacture supercapacitor electrodes with larger surface areas.

The second strategy consist in using materials from natural sources (biomaterials) to integrate them into energy storage systems. This can be done by extracting materials from natural sources. Polysaccharides are the best-known example of this group and can be extracted from plants, bacteria or fungi. In particular, cellulose has been present as separator from the initial battery design, and its role as a binder and as a precursor for carbon electrodes is, nowadays, well known.

In this second group, we can also find examples of other biomolecules such as proteins or fatty acids. For example, reduced graphene sheets functionalized with BSA protein provided nanopores that served as nanochannels for shuttling ions to conductive graphene interlayers of supercapacitor electrodes. Although the use of fatty acids for energy storage is less widespread, their combination with light-sensitive organic compounds resulted in hybrid materials that can store thermal energy for longer periods and release it when a optical trigger is activated.

Finally, some systems employ bioelectrodes for collecting the electrons and protons released by the conversion of a substrate into a product. These types of devices are known as biofuel cells. They can employ cells or enzymes combined with small molecules obtained from biomass such as quinones, flavins, or porphyrins known for their functions in the electron-transport chain of mitochondria and chloroplasts.

Batteries and capacitors are mature technologies used in a large number of commercial applications. However, they still present some limitation to integrate them into flexible and lightweight devices. The addition of biomolecules as materials for cathodes, anodes or electrolytes could allow for manufacturing flexible and implantable biomedical devices with applications in fields such as diagnosis, monitoring or treatment. In addition, the Internet of Things, that will allow the interconnection of these devices with external databases, demand energy storage devices, such as supercapacitors and batteries, to power the biomedical devices attached or implanted into the body in energy storage, is committed to preserve our environment, and for that reason, among other alternatives, supports research activities on bio-electrochemical devices or bio-batteries, whose components are fully sustainable, environmentally friendly and biocompatible.

1.8 Electromagnetic Energy Storage

Electromagnetic energy can be stored in the form of an electric field or a magnetic field, the latter typically generated by a current-carrying coil. Practical electrical energy storage technologies include electrical double-layer capacitors (EDLCs or ultracapacitors) and superconducting magnetic energy storage (SMES).

1.9 Thermal Storage Systems

Thermal storage systems capture heat from a wide range of sources and preserve it in an insulated storage for later use in industrial and residential applications. Thermal storage systems are used to act as an intermediary between thermal energy demand and supply, making them crucial for the integration of renewable energy sources.

There are three forms of thermal storage: sensible heat storage, latent heat storage and thermo chemical adsorption and absorption storage. A storage medium can be a liquid or a solid. Thermal energy can only be stored by varying the temperature of the storage medium. A storage system's capacity is determined by the specific heat capacity and mass of the medium used. For latent heat storage, phase change materials (PCMs) are utilized as storage media. Organic (paraffins) and inorganic PCMs (salt hydrates) are also viable options for such storage systems. Latent heat is the energy transmitted during a phase transition, e.g., ice melting. It is also referred to as "hidden" heat since there is no temperature difference during energy transmission. The most well-known latent heat—or cold—storage method is the ice cooler, which uses ice in an insulated container or chamber to keep food cool on hot days. The solid–liquid phase shift is used in the majority of PCMs currently in operation, such as molten salts as a thermal storage device for concentrated solar power (CSP) plants.

1.11 Classifications and overview of energy storage technologies

Energy storage system incorporates a method by which electricity imported from a power grid, is changed over into a form that could be stored at off- peak demand, when energy cost is generally low or amid surplus production, and changed over back to electricity at peak demand or when required. There are several technologies available for storing energy. These technologies are often classified per the aim that the energy is hold on. Different approach exists for categorising energy storage technologies with the form of energy storage and the time of discharge being the most common.

1.11.1. Based on discharge duration

Energy storage technologies depending on discharge period are divided as short-term (a few seconds or minutes), medium-term (minutes or hours) and long-term (several h to few days).

1.11.1.1. Short term response energy storage technology

This category consists of energy storage technologies which have high power density (MW/m3) and capable respond for short spans. Power quality improvement, predominantly to maintain the voltage stability during transients (few seconds or minutes) is main applications of such energy storage technologies.

1.11.1.2. Medium term response energy storage technology

These energy storage technologies are capable to hold and supply electrical energy from few minutes to hours. They are mainly used in power system applications and contribute in frequency regulation, grid congestion management, and energy management.

1.11.1.3. Real long term response energy storage technology

These technologies are capable of withholding and supplying energy for real long-term (days, weeks, or months). They are typically applied to fullfil demand and supply gap over a day or longer.

1.11.2. Based on form of energy stored

The form of converted energy widely determines the classification of energy storage technologies. They may be divided into five major categories such as mechanical, electrochemical, chemical, electrical, and thermal energy storage as shown in Fig. 5. These technologies first convert energy into other form for storing and converting them back to useful form as required.

1.12 Comparative Study of EES Systems

Energy storage technologies and comparison Every energy storage technology has various features and characteristics, with some exceptional characteristics making them different from each other. With the help of these character- istics and features, it is possible to select most suitable energy storage technology for a given conditions. This segment concen-trates on the comparison of the technical features of selected energy storage technologies.

1.12.1. Energy and power density

The power density of any Energy Storage(ES) technology is characterized as the rated power yield divided by the volume of the device. Its unit is W/kg or W/l. This is marginally not the same as the energy density which is characterized as energy stored divided by the volume of the storage device (Wh/kg or Wh/l) [13]. Fig. 13, and moreover gives a quick comparison.

1.12.2. Storage Capacity/Duration

The overall energy available or stored in the energy storage device after charging refers to the storage capacity. It is measured in Watthour (Wh). Storage duration of any energy store device acts as a crucial property as well. It refers to the stored energy which can be supplied by an energy storage device over a period of time. PHES and CAES have large storage capacity which makes them appropriate for grid scale energy storage application.

1.12.3. Power rating

Power rating comparison of various energy storage devices is shown in Fig.14 and gives quick these technologies ranging from few watts to thousands of megawatts providing information about the installed capacity of the system.

1.12.4. Discharge time and self-discharge

Discharge time is the entire time in which maximum power of an energy storage device is released (maximum-power discharge duration). The portion of the energy in storage device, stored initially after charging and has dissipated over a certain amount of non-use time refers to the self-discharge of the storage device.

1.12.5. Round-trip efficiency

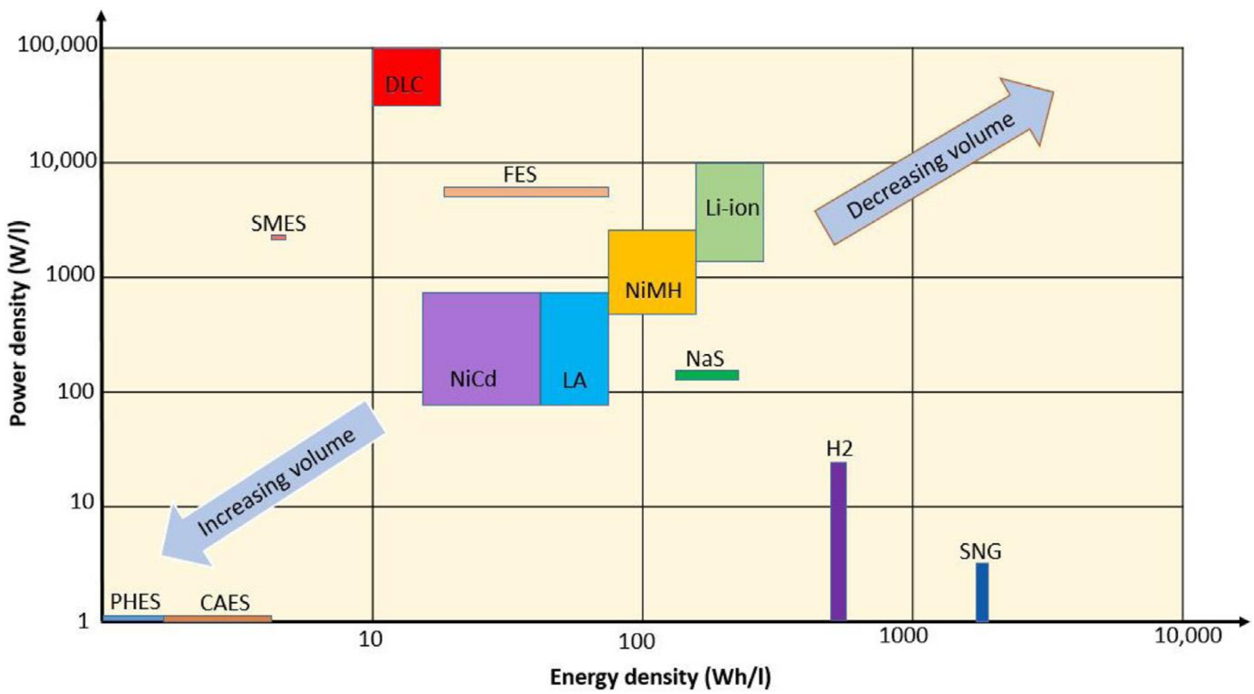
Round-trip efficiency or cycle efficiency is the ratio of the electricity output to the electricity input. Thus, SMES, Super- capacitors, Flywheel and Li-ion battery with very high cycle efficiency of >90% are at the top amongst energy storage devices. PHES, CAES, Batteries and Flow batteries hold high cycle efficiency in the range of 60–90%. But Hydrogen energy storage and Thermal energy storage exhibits cycle efficiency lower than 60%.

1.12.6. Technology maturity

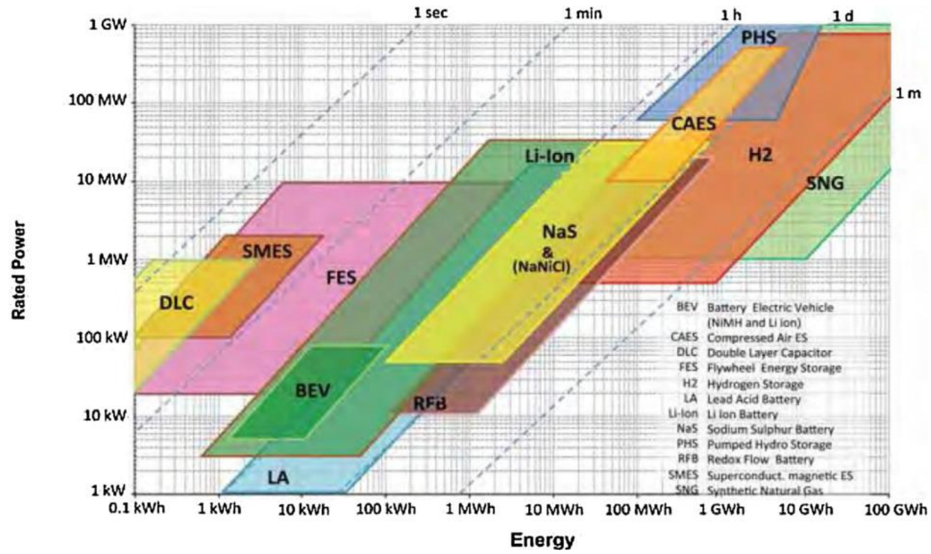
It plays an important role while selecting any energy storage technology. A matured technology is preferred owing to more expertise in the field. As technology becomes more mature, there is reduction in the investment required. Maturity level is shown in Fig. 15.

1.12.7. Capital cost

For widespread use of any energy storage technology, capital cost is an imperative factor. As shown in Table 1, it is expressed in cost per kWh and per kW. The supplementary parts utilized by



Comparison of Power density and Energy density (in relation to volume) of ES technologies



Comparison of Rated power, Energy content and Discharge time of different ES technologies

some energy storage technology add to the aggregate capital cost of the system.

1.12.8. Response time

Response time of any energy storage technology basically refers to, how swiftly an energy storage device releases its stored energy to fulfil the required demand. Flywheel, SMES and Supercapacitors offers very swift response time in milliseconds, Batteries response time in seconds and PHES, CAES in minutes. This is shown in.

1.12.9. Impact on environment

In present global world, sustainable development, emissions and climate change have become major point of concern. As a result, impact of energy storage technologies on environment has become an important aspect in their selection for any application. Influence of various energy storage technologies on environment.

SUMMARY

- Reliable and affordable energy storage is a prerequisite for using renewable energy.
- Energy storage therefore has a pivotal role in the future.
- Energy storage is the most promising technology currently available to meet the ever increasing demand for energy.
- Overall Savings in Money –Overall incorporation of storage is beneficial to all end-users as it saves costs to society by enabling storage of low-cost energy and retrieving it later when electricity prices are low.

Question 1: Define energy storage.
Answer:
The technique by which we store the energy that was generated all at once is known as energy storage. The act of converting energy into a form that can be retained economically for later use can also be referred to as energy storage. These storages can be of any sort depending on the energy's shelf-life, meaning some storages can hold energy for a long period while others can just for a short time. Energy storage can take several forms, including batteries, flywheels, solar panels, etc.

Question 2: What are the different types of energy storage.
Answer:
There are five types of energy storage:

Thermal energy

Mechanical energy

Chemical energy

Electrochemical energy

Solar energy storage

Question 3: Explain briefly about solar energy storage and mention the name of any five types of solar energy systems.
Answer:

Solar energy storage is the process of storing solar energy for later use. Simply using sunlight will enable you to complete the task. It is electricity-free. It just makes use of natural resources to power a wide range of machines, automobiles, and other things.

Names of any 5 types of solar energy storage:

- *Off-Grid Solar Storage System*
- *On-Grid Solar Storage System*
- *Hybrid Solar Storage Systems*
- *Solar Fuels*
- *Stratified Solar Energy Storage Systems*

Question 4: Explain about Carnot battery.
Answer:
A Carnot battery uses thermal energy storage to store electrical energy first, then, during charging, electrical energy is converted into heat, and then it is stored as heat. Afterward, when the battery is discharged, the previously stored heat will be converted back into electricity.

Uses for a Carnot battery

- *Since these Carnot batteries store excess energy from diverse renewable sources only to create power for later use, they may be employed as grid energy storage.*
- *A few Carnot battery systems can store heat or cold for later use. District heating and data center cooling are two examples.*

Question 5: Write the name of the batteries that are used for electrochemical storage.
Answer:
Batteries that are used as electrochemical storage:

- *Lithium-ion*
- *Lead acid*
- *Flow*
- *Sodium*

Unit-II

ENERGY STORAGE SYSTEM

2.1 Thermal Energy Storage-Sensible and Latent Heat

The remainder of this chapter provides thermal storage technologies, which can include sensible, latent, and thermo chemical systems. Sensible storage relies on a temperature difference within the storage medium to enable useful work to be performed, such as using hot molten salt to heat water and generate steam to spin a turbine for electricity production. Latent storage involves storing heat in a phase-change material that utilizes the large latent heat of phase change, for example, during isothermal melting of a solid to a liquid, which requires heat, and subsequent freezing of the liquid to a solid, which releases heat, isothermally. Thermo chemical energy storage (TCES) reversibly converts heat into chemical bonds using a reactive storage medium. When the energy is needed, a reverse reaction combines the reactants, releasing energy. Table 1 summarizes the different thermal storage technologies and key attributes.

	Sensible Heat Storage	Latent Heat Storage
Storage mechanism	Energy stored as temperature difference in solid (e.g., concrete, rock, sand) or liquid media (molten salt)	Energy stored using phase change materials (e.g., salts, metals, organics)
Energy Density	~200 – 500 kJ/kg (for ~200 – 400 °C temperature differential)	~100 – 200 kJ/kg for nitrate salts; ~200 – 500 kJ/kg for metals; ~1000 kJ/kg for fluoride salts
Advantages	Demonstrated large energy capacity (~GWh) • Inexpensive	Good for isothermal or low T applications • Can provide large

	media • Solid media does not freeze and can achieve >1000°C	energy density with combined sensible and latent heat storage
Challenges	• Requires insulation to mitigate heat losses • Lower energy density requires larger volumes • Molten salts freeze at ~200 °C.	• Potential for corrosion • For larger T, may need cascaded systems (adds costs and complexity) • Low maturity
Maturity	High	Low
Cost	• ~$1/kg for molten salts and ceramic particles • ~$0.1/kg for rock and sands • ~$1/MJ – $10/MJ (system capital cost)	• ~$4/kg – $300/kg • ~$10/MJ – $100/MJ (system capital cost)

2.2. A Phase-Change Material (PCM):

Is a substance which releases/absorbs sufficient energy at phase transition to provide useful heat or cooling. Generally the transition will be from one of the first two fundamental states of matter - solid and liquid - to the other. The phase transition may also be between non-classical states of matter, such as the conformity of crystals, where the material goes from conforming to one crystalline structure to conforming to another, which may be a higher or lower energy state.

The energy released/absorbed by phase transition from solid to liquid, or vice versa, the heat of fusion is generally much higher than the sensible heat. Ice, for example, requires 333.55 J/g to melt, but then water will rise one degree further with the addition of just 4.18 J/g.

Water/ice is therefore a very useful phase change material and has been used to store winter cold to cool buildings in summer since at least the time of the Achaemenid Empire.

By melting and solidifying at the phase-change temperature (PCT), a PCM is capable of storing and releasing large amounts of energy compared to sensible heat storage. Heat is absorbed or released when the material changes from solid to liquid and vice versa or when the internal structure of the material changes; PCMs are accordingly referred to as latent heat storage (LHS) materials.

There are two principal classes of phase-change material: organic (carbon-containing) materials derived either from petroleum, from plants or from animals; and salt hydrates, which generally either use natural salts from the sea or from mineral deposits or are by-products of other processes. A third class is solid to solid phase change.

PCMs are used in many different commercial applications where energy storage and/or stable temperatures are required, including, among others, heating pads, cooling for telephone switching boxes, and clothing.

2.3 Energy and Exergy Analysis of Thermal Energy Storage

Energy Analysis

Energy and exergy analysis was performed for the Blocks Part of CHP plant Siekierki in Warsaw. CHP Plant Siekierki is the largest CHP plant in Poland and the second largest in Europe. The heating capacity of this plant is 2078 MW_{th} whereas electrical capacity is 622 MW_{el}. CHP plant Siekierki was launched in 1961.

It consists of:

- Collector Part—the boilers supply a common steam collector from which the steam is directed to the turbines (number of boilers—4, number of turbines—5, electrical capacity—170 MW_{el}).
- Blocks Part—each block consists of its own boiler and its own turbine (number of blocks—3, electrical capacity—110 MW_{el} each, heating capacity—175 MW_{th} each).
- Condensing turbine with steam extraction (electrical capacity—125 MW_e).

- Water boilers (number of boilers—6, total heating capacity—884 MW_{th}).

The Blocks Part of the Siekierki Combined Heat and Power Plant consists of base load units. During the heating season, all blocks work as basic units in continuous mode. Only one heating block is in operation in summer. This is due to the much lower heat demand. Heat is only needed to provide domestic hot water. When the ambient temperature drops below zero, the collector part is introduced to operation. When the temperature drops below −15 °C, the water boilers are started. They are considered as a peak load boilers. Some cogeneration units are also put into operation when heat demand is low or does not exist. This takes place when the electricity demand is high or electricity prices are profitable. The decisive factor here is the economic calculation.

Figure shows a simplified layout of CHP plant Siekierki. The CHP plant is connected to the DHS. The main piping lines indicated in the Figure as O, C, L, and U are responsible for supplying hot water to the DHS (top of the figure) and collecting cold water coming back (return) from DHS (bottom of the figure). The pumps responsible for return water are indicated as RP, pumps supplying water to the DHS are indicated as SP, water boilers B, and network water heaters XB or XC.

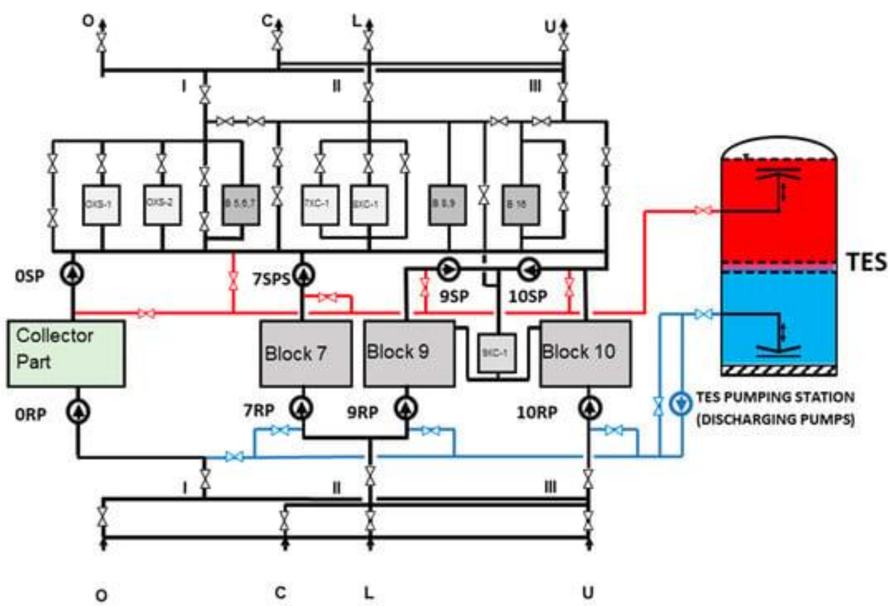


Figure. Simplified layout of the analyzed plant—combined heat and power plant (CHP) plant Siekierki.

TES at the Siekierki CHP plant was put into operation in March 2009. Its design process started in 2007 and it was built in 2008. Its design is pressure-free tank. The TES was integrated with the DHS system by Discharging Pumps (DP). A steam cushion system has been used to prevent oxygen absorption by the water in the reservoir.

The TES tank is shown in Figure

Figure. View of the TES tank in Warsaw CHP plant Siekierki.

Materials and Methods

Energy and exergy analysis was undertaken for three different operation variants for the Blocks Part of the CHP plant:

- Operation without TES,
- Operation with TES—charging process,
- Operation with TES—discharging process.

For all three operation variants the calculations for three representative values of outside temperatures were provided, i.e., $T_{ex} = -20$ °C—calculated temperature for the District Heating

System in this region of Poland, T_{ex} = 1 °C—temperature close to the average temperature for the heating season, T_{ex} = 15 °C—average temperature during the summer season.

The efficiency levels of the pumps in the system are set as below:

- Return Pumps—η_{RP} = 80%,
- Supply Pumps—η_{SP} = 82%,
- Discharging Pumps (TES pumps)—η_{DP} = 90%.

As input data for the calculations, operating parameters were collected from the existing plant (CHP plant Siekierki Warsaw). The data are hourly average taken from the DCS system for the period of 2 years before the TES installation and for 2 years after the installation. Data were measured and collected from characteristic CHP plant points which are indicated as numbers 1–7 presented in Figures. The parameters that were measured are as follows: temperatures, flows, and pressures (return and supply water). The remaining quantities necessary for energy and exergy analysis were calculated.

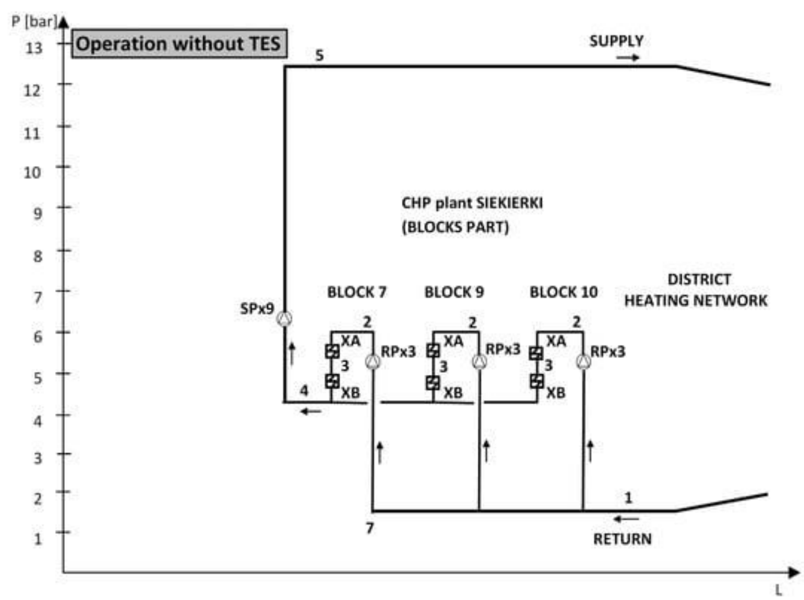


Figure. Pressures diagram for the Blocks Part of CHP plant Siekierki (operation without TES).

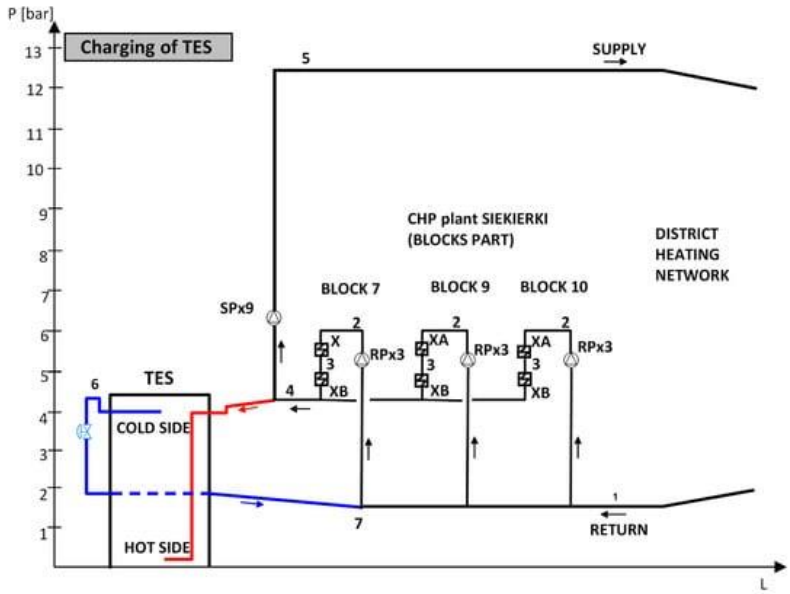


Figure. Pressures diagram for the Blocks Part of CHP plant Siekierki during charging of TES.

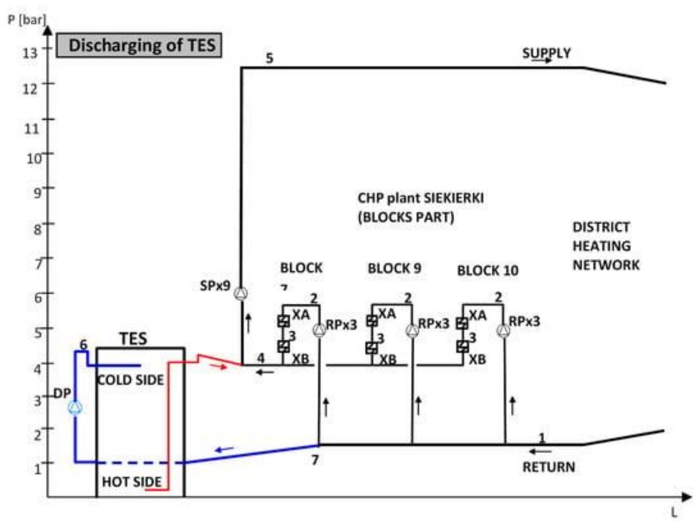


Figure. Pressures diagram for the Blocks Part of CHP plant Siekierki during discharging of TES.

Energy Analysis

CHP Plant Operation without TES

The pressures diagram for the Blocks Part of the CHP plant Siekierki during operation of the plant without TES is shown in Figure. The thermodynamic parameters of water at five points of the system for block numbers 7, 9, and 10 were calculated on the basis of collected operational data of CHP plant (1—before RP pumps, 2—after RP pumps and before XA heat exchanger, 3—after XA and before XB heat exchangers, 4—after XB heat exchanger and before SP pumps, 5—after SP pumps).

The power of the pumps RP and SP and heating capacities of the heat exchangers XA and XB were calculated from following equations for various external air temperatures: $T_{ex} = -20$ °C, $T_{ex} = +1$ °C, and $T_{ex} = +15$ °C:

Power for RP pumps (η = 0.8; three devices) is calculated as:

$$W_{RP} = \dot{m} \cdot (h_2 - h_1) / \eta_{RP}$$

Heating capacity for XA heat exchanger is expressed as:

$$\dot{Q}_{XA} = \dot{m} \cdot (h_3 - h_2)$$

Heating capacity for XB heat exchanger is stated as:

$$\dot{Q}_{XB} = \dot{m} \cdot (h_4 - h_3)$$

Power of SP pumps (η = 0.82; three devices) is described as:

$$W_{SP} = \dot{m} \cdot (h_5 - h_4) / \eta_{SP}$$

Charging Process of TES

Figure shows a pressures diagram for the Blocks Part of CHP plant Siekierki during operation of the plant with TES in the course of the charging process of the TES. The thermodynamic parameters of the water at seven points of the system for block numbers 7, 9, and 10 were calculated on the basis of operational data of the CHP plant collected during the charging process of the TES (1—before RP pumps, 2—after RP pumps and before XA heat exchanger, 3—after XA and before XB heat exchangers, 4—after XB heat exchanger and before SP pumps, 5—after SP pumps, 6—cold side of TES before control valve, 7—cold side of TES after control valve).

The power of the pumps RP and SP and heating capacities of the heat exchangers XA and XB were calculated from the same Equations (1)–(4) as for operation of the plant without TES and also for various external air temperatures: $T_{ex} = -20$ °C, $T_{ex} = 1$ °C, and $T_{ex} = 15$ °C

3.1.3. CHP Plant Operation with TES—Discharging Process of TES

Figure 5 shows the pressures diagram for the Blocks Part of CHP plant Siekierki during operation of the plant with TES in the course of the discharging process of the TES. The thermodynamic parameters of the water at seven points of the system for block numbers 7, 9, and 10 were calculated on the basis of operational data of the CHP plant collected during the discharging process of the TES (1—before RP pumps, 2—after RP pumps and before XA heat exchanger, 3—after XA and before XB heat exchangers, 4—after XB heat exchanger and before SP pumps, 5—after SP pumps, 6—cold side of TES after DP pump, 7—cold side of TES before DP pump).

The power of the pumps RP and SP and heating capacities of the heat exchangers XA and XB were calculated from the same Equations (1)–(4) as for operation of the plant without TES. The power of the DP pumps was calculated from Equation (5). As in previous cases all calculations were performed for various external air temperatures: $T_{ex} = -20$ °C, $T_{ex} = 1$ °C, and $T_{ex} = 15$ °C.

Exergy Analysis

Exergy is defined as the maximum amount of work that a thermodynamically open system can do in a given environment by going into equilibrium with the environment. The environment is treated as a reservoir of useless energy and matter at a constant temperature. Maximum energy is obtained in a reversible process. Exergy analysis can be recognized as one of the most important methods for performance evaluations and design calculations of TES systems. It is considered as more powerful than energy analysis.

In this paper exergy analysis is simplified and neglects exergy destruction for the storing period of the TES. This is related to the fact that the analyzed TES in Warsaw CHP plant has the following construction and operation characteristics:

- The tank insulation is 500 mm thick (glass wool), therefore heat losses to ambient air are very low,
- The storing periods are short, not usually more than a few hours,
- Stratification and thermocline are observed as good and very stable.

The heat losses from the TES tank depend mainly on the thickness of insulation, insulation conductivity, and the heat transfer coefficient [36]. For sensible water TES with a short-term storage period, 500 mm thickness of insulation is commonly applied. Presently, as insulation material, usually glass wool is preferred due to its low density and thermal conductivity. In case of such insulated water tank, heat losses do not exceed 1–3% of the total heat stored in the tank as was observed during start-up and commissioning of the TES in the last few years in Poland.

Results of analyses presented in indicate that for properly designed TES, the storing period is characterized by relatively high exergy efficiencies in excess of 80%.

In order to integrate the heat accumulator into the existing hydraulic system of the CHP plant, new pipelines were added. The length of new pipelines does not exceed 5% of the length of existing pipelines. Exergy losses in pipelines should be considered as an important element of the balance of losses for the entire system, however, due to a slight change in the existing hydraulic system, it was decided to omit these calculations in this study.

As was presented in, the three-zone temperature-distribution models for the TES tank appear to provide sufficient calculation accuracy for exergy contents of vertically stratified TES. Additionally, in this paper, a stepped (two-zones) temperature-distribution model was analyzed and the results were compared with a basic three-zone temperature-distribution model. The equivalent temperature of a mixed TES that has the same exergy as the stratified TES was calculated for both of the above-mentioned models. The difference between temperatures computed for those models was less than 1%, therefore for further calculation of exergy destruction for the TES tank, a stepped two-zones model was applied, for reasons of greater simplicity.

3.2.1. CHP Plant Operation without TES

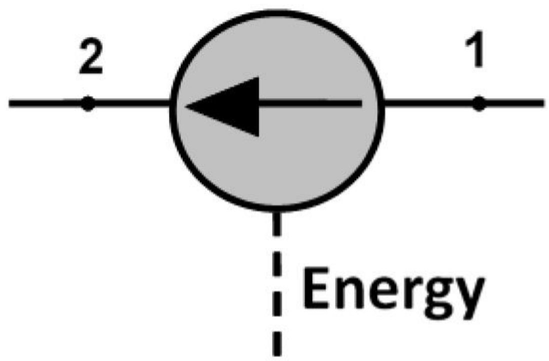
For the scheme presented in Figure 3 thermodynamic parameters at specified points of the system for block numbers 7, 9, and 10 were calculated on the basis of collected operational data of the CHP plant without TES. Water and steam parameters were calculated using IF-97 formulas.

In pumps, exergy destruction is described by following equation (Gouy–Stodola Theorem) [41]. Due to the fact that the heat transfer in this process is assumed to be zero, the equation takes the form as below:

$$\dot{I}I_P = T_o\Delta\dot{S}_P$$

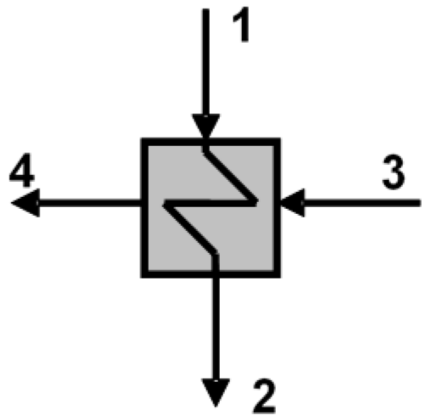
The Gouy–Stodola Theorem states that the rate of exergy destruction is proportional to the rate of entropy generation. This destruction is caused by irreversibility and is equal to the ambient temperature multiplied by the sum of the increases in entropy of all components participating in the thermodynamic transformation. The exergy losses calculated according to this equation are additive. The exergy loss described by the Gouy–Stodola Theorem is completely irreversible and cannot even be partially recovered.

Exergy destruction in RP pumps (three devices):



$$\dot{I}I_{RP} = T_o\Delta\dot{S} = T_o \cdot \dot{m} \cdot (s_2 - s_1)$$

Exergy destruction in XA heat exchanger (necessary parameters of medium, i.e., steam, condensate, and water, were calculated for the points shown in the sketch) was calculated as per the procedure shown below.



Power of XA heat exchanger:

$\dot{Q}_{XA}$—given from operational data

Steam/condensate mass flow:

$$\dot{m}_{s/c} = \dot{Q}_{XA} / \left(h_1'' - h_2'\right)$$

Water mass flow:

$\dot{m}_w$—was given from operational data

Entropy change:

$$\Delta\dot{S}_{XA} = \left(\dot{m}_{s/c} \cdot s_2 + \dot{m}_w \cdot s_4\right) - \left(\dot{m}_{s/c} \cdot s_1 + \dot{m}_w \cdot s_3\right)$$

Exergy destruction:

$$\dot{\Pi}_{XA} = T_o \Delta\dot{S}_{XA}$$

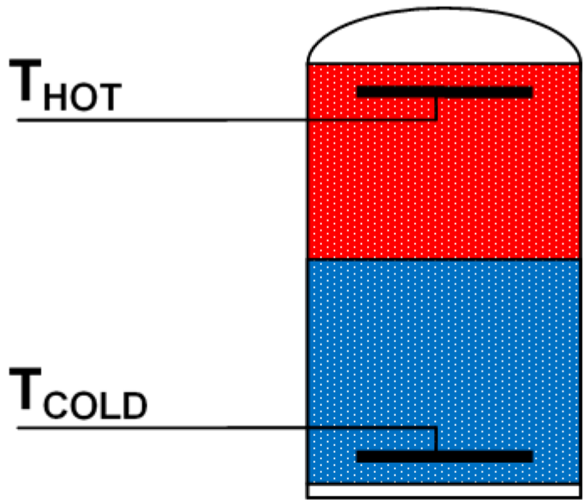
Exergy destruction in XB heat exchanger is calculated in a similar way as for heat exchanger XA: power of XB heat exchanger:

3.2.2. CHP Plant Operation with TES—Charging Process of TES

Throttling losses during the charging process:

$$\dot{I}I_{thr} = T_o \Delta \dot{S} = T_o \cdot \dot{m} \cdot (s_1 - s_7)$$

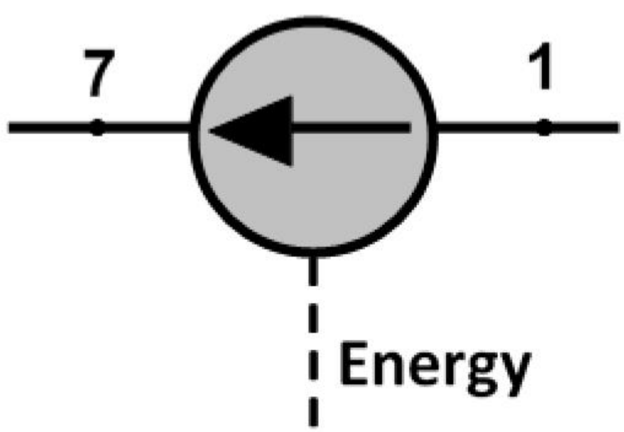
Exergy destruction for TES during the charging process:



$$\dot{I}I_{TES} = T_o \Delta \dot{S} = T_o \cdot \dot{m} \cdot c_p \ln (T_{HOT} / T_{COLD})$$

3.2.3. CHP Plant Operation with TES—Discharging Process of TES

Exergy destruction in TES Discharging Pumps (DP pumps):



$$\dot{I}I_{DP} = T_o \Delta \dot{S} = T_o \cdot \dot{m} \cdot (s_7 - s_1)$$

Exergy destruction for TES during the discharging process could also be calculated from Equation (20).

2.4 Thermal Storage

Thermal storage can be defined as the process of storing thermal energy storage. The process of storing thermal energy is to continuously heat and cool down the container (in which we are storing thermal energy). And further, we can use this thermal energy later on from this container. It creates a balance between the demand for energy in daytime and nighttime, winter and summer, etc.

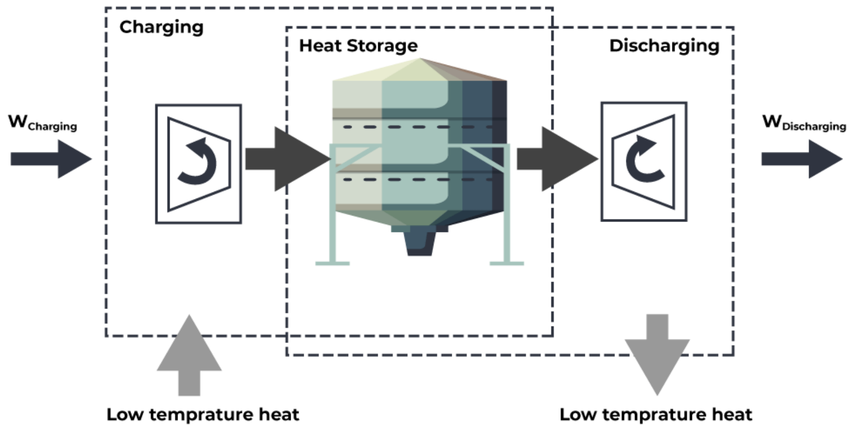
Thermal Energy is used for the following purposes:

- Water heating
- Cooking
- Thermal power plants
- Automobiles
- Thermal processing of various metals.

Examples of Thermal Energy Storage

Some common examples of Thermal Energy Storage are given below in the article:

Carnot Battery

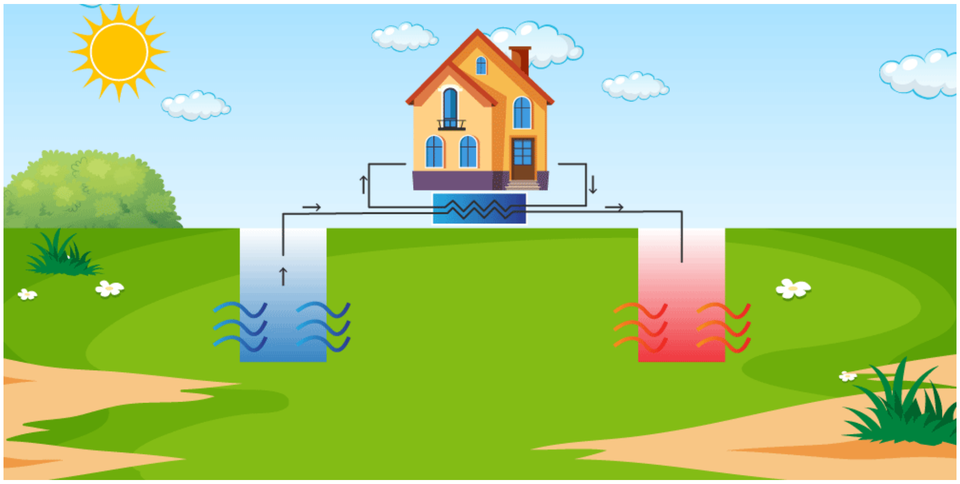


A Carnot battery first uses thermal energy storage to store electrical energy. And then, during charging of this battery electrical energy is converted into heat and then it is stored as heat. Now, upon discharge, the heat that was previously stored will be converted back into electricity. This is how a Carnot battery works as thermal energy storage.

Applications of Carnot Battery

- These Carnot batteries can be used as grid energy storage as they store extra energy from various renewable sources just to generate electricity for later use.
- Some Carnot battery systems can store heat or cold for later use. For example, district heating and data center cooling.
- In coal-fired power plants, the coal-fueled boiler should be replaced with Carnot batteries as they can transfer to a generation system without using fossil fuels.

2.4.1 STES Energy System:



This is seasonal thermal energy storage. Also, can be referred to as inter seasonal thermal energy storage. This type of energy storage stores heat or cold over a long period. When this stores the energy, we can use it when we need it.

Application of Seasonal Thermal Energy Storage

Application of Seasonal Thermal Energy Storage systems are

- Greenhouse Heating
- Aquifers use this type of storage

2.5 Mechanical Storage

They are the most common energy storage used devices. These types of energy storage usually use kinetic energy to store energy. Here kinetic energy is of two types: gravitational and rotational. These storages work in a complex system that uses air, water, or heat with turbines, compressors, and other machinery. It provides a robust alternative to an electrochemical battery.

Where is Mechanical Energy used?

Mechanical Energy is used in,

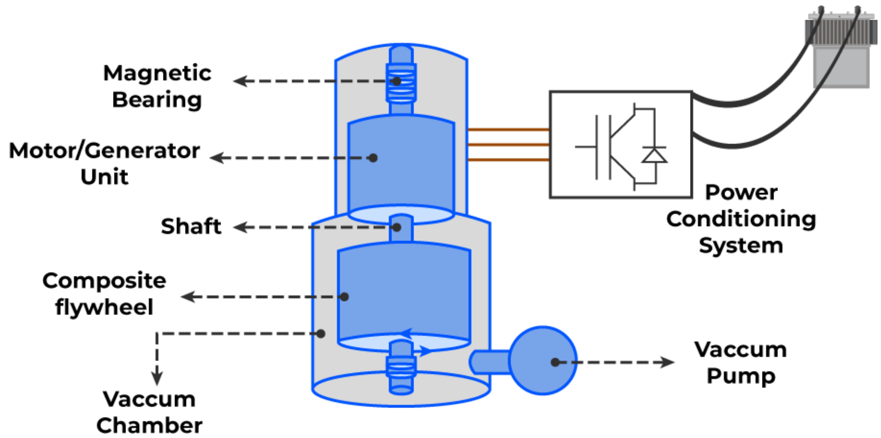
- Generator
- Steam engines

- Electric motors
- Hydroelectric power plants

Examples of Mechanical Energy

Examples of Mechanical Energy storage include:

2.5.1 Flywheels



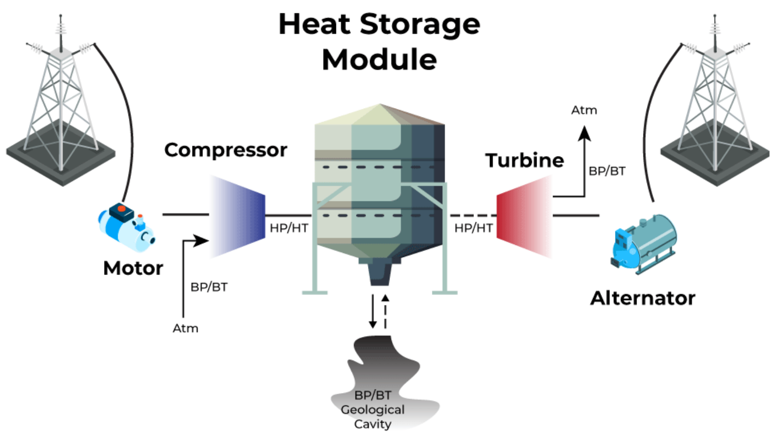
These energy storages use mechanical energy to store energy. In these flywheels, electricity is converted into kinetic energy in the form of a spinning wheel, which can store grid energy. In these flywheels, we can prevent energy loss by creating a magnetic field that will maintain the wheel in a frictionless vacuum. When we need power, the spinning wheel can be slowed down in a way that generates electricity.

Application of Flywheels

There are various applications of flywheels some of the most common are:

- A motorized generator uses a flywheel to store energy.
- Used to increase the speed of electric vehicles
- It prevents obstructions in major power systems
- It helps in the maintenance of the gyroscope and mechanical system adjustments.

2.5.2 Compressed Air Systems Storage



These systems use compressed air to store energy for later use. This storage can be of any type: Diabatic, adiabatic, or isothermal. These storages fulfill the demand of consumers by meeting their demands efficiently.

Application of Compressed Air Systems

The most common application of compressed air systems are:

- Drills
- Atomize paints systems
- Operating air cylinders in automation systems
- Cryogenics system

2.5.3 Pumped Hydro Storage

This type of storage generally helps in storing grid energy. These are used in the balancing of loads by electric power systems. This energy is stored in the form of the gravitational potential energy of water. When electricity demand is low then the extra generation capacity is used to pump water into a higher reservoir from a lower source. When the demand increases, water can be reversed back into the lower source from the higher reservoir by using turbines, generating electricity.

Application of Pumped Hydro Storage

Some important applications of Pumped Hydro Storage include:

- An electricity storage medium for various renewable energy storage.
- Ancillary grid services
- Storing Electricity for other purposes

2.6 Chemical Storage:

Chemical storage can be defined as storing chemicals for later use. These chemicals can be stored in chemical stores, cabinets, or other storage. These chemicals can be hazardous or non-hazardous. For the current energy generation system, these storages will be in the form of biomass, coal, and gas. Energy stored chemically can be used in various sectors such as transporting, heating, and producing electricity.

Where is Chemical Energy used?

Chemical storage is used for,

- Power plants

- Electric vehicles
- Mobiles

Examples of Chemical Energy Storage

There are various examples of chemical energy storage some of the most common are:

2.6.1 Hydrogen Storage

Storing hydrogen for later consumption is known as hydrogen storage This can be done by using chemical energy storage. These storages can include various mechanical techniques including low temperatures, high pressures, or using chemical compounds that release hydrogen only when necessary. It is most widely used in the manufacturing site, especially in the synthesis of ammonia.

Application of Hydrogen Storage

Some of the important applications of Hydrogen Storage systems are in

- Transportation sector as fuel
- Industrial sector for power supply
- Residential sector for heating

1.2.7 Bio-fuels

Bio-fuel storage stores energy from waste. It can be created by plants, and home, commercial and agricultural wastes. Bio-fuel storage stores renewable energy that can be utilized to produce both heat and power.

Application of Bio-fuels

Some of the important applications of Bio-fuels are,

- Water cleaning
- As a lubricant
- Electrical energy generation
- Charging of electrical equipment.

2.7 Electrochemical Storage

Electrochemistry is the production of electricity through chemicals. Electrochemical storage refers to the storing of electrochemical energy for later use. This energy storage is used to view high density and power density. The energy in the storage can be used over a long period.

Where is Electrochemical Storage?

- Mobiles
- Computers
- Music players
- Electric vehicles
- Wind-based electricity generation

Examples of Electrochemical Storage

Some Examples of Electrochemical Storage include,

Battery

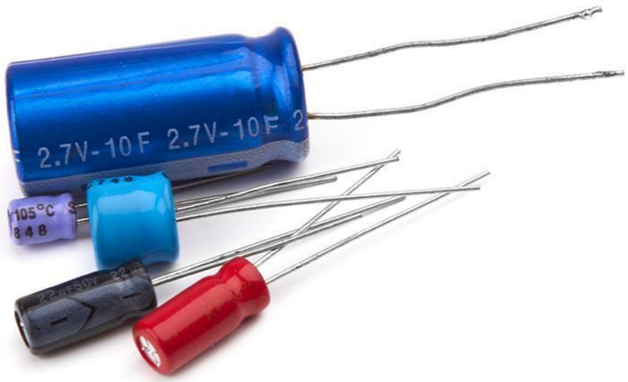
It consists of a cathode (positive terminal) and anode (negative terminal). Used in portable electronics and automobiles. There are various forms of battery, for example, lithium-ion, lead-acid, nickel-cadmium, etc. Some flow batteries included liquid electrolyte solutions, for example, iron-chromium, zinc-bromine, and vanadium redox.

Application of Battery

Some of the common examples application of batteries includes,

- Invertors
- Micro-grids
- Integrated Sensors

Super capacitor



They are also known as ultra capacitors or electric double-layer capacitors. They come in the category of electrochemical capacitors that lack normal solid dielectrics. These super capacitors fill the void between the regular capacitor and the rechargeable battery. They have a high energy density of all capacitors. Its charge or discharge cycle is shorter as compared to other capacitors.

Application of Super capacitor

Some examples of the application of Super capacitor includes,

- Static random-access memory backup (SRAM)
- Elevators
- Cranes
- Buses
- Trains
- Automobiles

1.2.9 Solar Energy Storage

Storing solar energy for later use is known as solar energy storage. It can be done easily just by using sunlight. It uses no electricity. It just uses the natural source to operate various appliances, vehicles, and many more.

Where is Solar Energy Used?

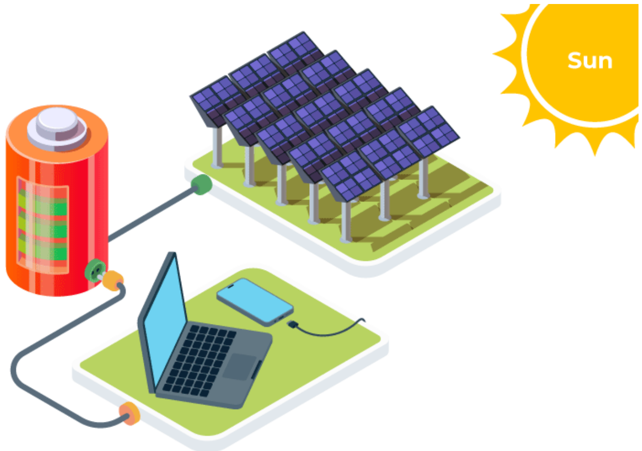
Solar Energy is mainly used in,

- Batteries
- Cooking Appliances
- Electrical appliances
- Fuels

Examples of Solar Energy Storage

Some of the common examples of Solar Energy Storage system includes,

Solar Fuel Cell



It can be produced through,

- Solar panel electricity (Electrochemistry)
- Artificial photosynthesis (Photobiology)
- Concentrated solar thermal energy (Thermo chemistry)
- Photons (Photo chemically)

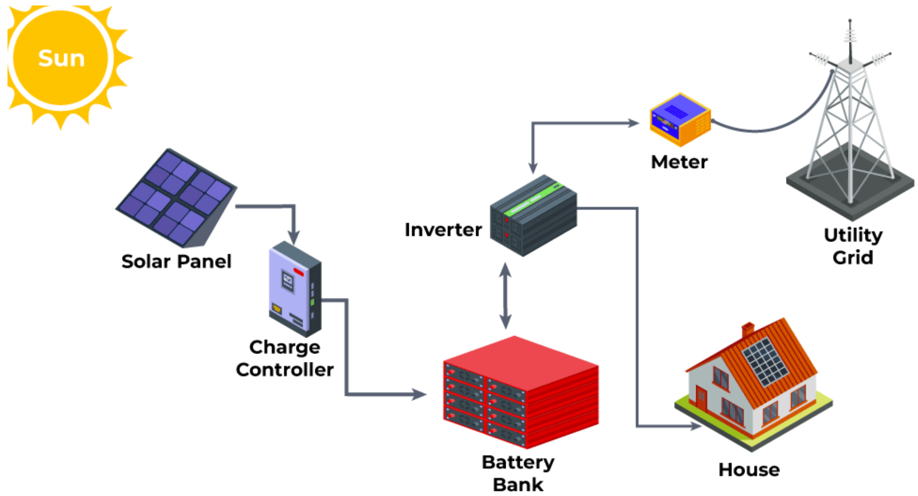
Solar fuels can be manufactured and stored in synthetic compounds ammonia, hydrogen, and hydrazine when there is no sunlight. They are portable or transportable and can be used over a long period.

Application of Solar Fuels

The important application of Solar fuel cell includes,

- Separating water into hydrogen and oxygen.
- For Cooking Food
- Used for the Creation of Clean and Efficient Energy.

1.2.10 Hybrid Solar Storage Systems



This solar storage system stores solar energy for public access. These energy storage systems store energy produced by one or more energy systems. They can be solar or wind turbines to generate energy.

Application of Hybrid Solar Storage Systems

Hybrid Solar Storage Systems are mostly used in,

- Battery
- Inventor
- Smart meter

1.3 Chemical Energy Storage

New substance capable of holding potential energy for later use can be created through suitable chemical reactions. They include: methane, hydrogen, hydrocarbons, synthetic natural gas, methanol, butanol and ethanol. Hydrogen is regarded as chemical compound which can be easily produced from electricity amongst the above listed compounds [13,37].1.3.1 Hydrogen energy Storage (HES).

A normal hydrogen storage system comprises of an electrolyzer, a hydrogen storage tank and a fuel cell. An electrolyzer is a converter which parts water with the assistance of electricity into hydrogen and oxygen electrochemically. To create power, both gasses flow into the fuel cell where an electrochemical reaction which is opposite to the water splitting happens: hydrogen and oxygen react and deliver water, heat is discharged producing electricity [44,46]. Off peak power is utilized to electrolyse water to create hydrogen for energy storage application [13]. Storing hydrogen in different forms as compressed gas, liquefied gas, metal hydrides or carbon nanostructures is also possible. In fixed applications, gaseous storage under high compression is the most prevalent decision. Smaller measures of hydrogen can be stored in over the ground tanks or bottles at pressure up to 900 bar [44]. One noteworthy disadvantage is the considerable energy loss amid a single cycle (from hydrogen production to electricity generation from fuel cell) in utilizing hydrogen for energy storage.

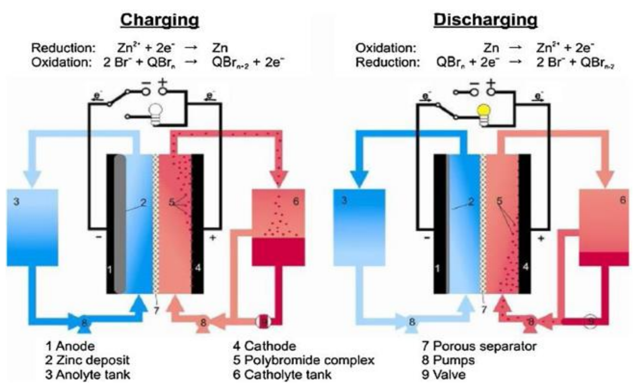
1.3.2. Synthesis Natural Gas (SNG).

Methane synthesis (likewise called engineered common gas, SNG) is the second alternative for storing electricity in chemical form. After water splitting by an electrolyzer, another step is required in which hydrogen and carbon dioxide react to methane in a methanation reactor. Just like the case for hydrogen, the SNG produced can be put away in pressure tanks, underground, or encouraged straight forwardly into the gas grid. Several CO2 sources are available for the methane synthesis process, for example, fossil-fuelled power stations, industrial establishments or biogas plants. The creation of SNG is ideal at areas where CO2 and excess electricity are both accessible. Specifically, the utilization of CO2 from biogas generation procedures is promising as it is a broadly utilized technology [44]. Comparatively low efficiency of SNG owing to the conversion losses in methanation, electrolysis, storage, transport and the subsequent power generation are the key disadvantage. It has an overall AC–AC efficiency <35%, even lower than hydrogen. Fig. 8, underneath shows a comprehensive diagram of the consolidated utilization of hydrogen and SNG as chemical energy storage.

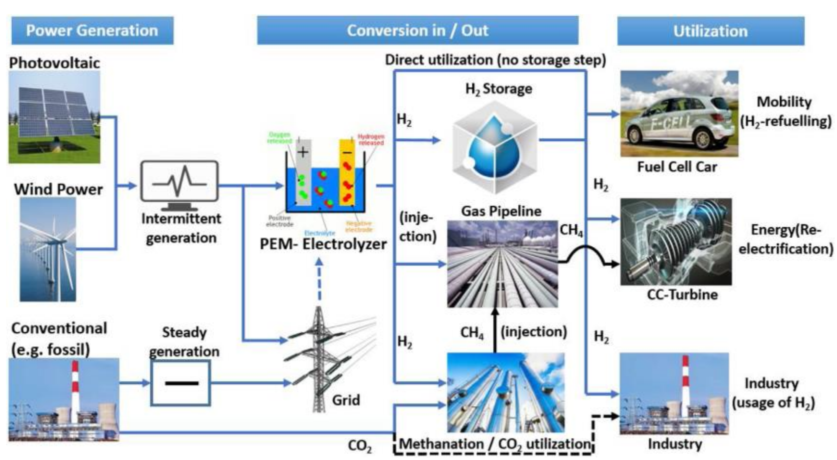
2.8 Electrical energy storage

Double layer capacitors (Super capacitors).

Electrochemical double Layer Capacitors (DLC), otherwise called Supercapacitors, are energy storage devices which follow same basic equations as traditional capacitors but uses thinner dielectrics and often porous carbon or higher surface area electrodes for accumulating large amount of charge carriers and capacitances (up to 5000F). As a result of the minimum distance between the plates(less than 1 nm) and larger surface area of activated carbons up to 2000 m2 per gram, provides capability for supercapacitors to have extensive



Working of Hybrid Flow Battery



Overall concept for the use of Hydrogen and SNG as energy carriers energy storage and capacitances. Fig , shows supercapacitor and its working principle. Benefits include, enormously high capacitance qualities, of the order of numerous thousand farads, long cycle life, low inner resistance, quick charging and discharge, great reversibility, incredible low temperature execution, no destructive substance, lower cost per cycle, high cycle efficiency (up to 95%), no moving parts, modular design, perfect with existing source-voltage inverter, can give VAR(reactive power) and kW (active power) support. Giga Capacitor Hyderabad Test Project (IL) in Hyderabad India, is Super capacitor based facility with rated power of 15,000kW.

Superconducting Magnetic Energy Storage

(SMES). Superconducting Magnetic Energy Storage (SMES) system is based on an electrodynamics principle. The flow of direct current in a superconducting coil cryogenically cooled at very low temperature creates magnetic field in which energy is stored. Ordinarily, the conductor is made of niobium-titanium, and the coolant can be fluid helium at 4.2 K, or super liquid helium at 1.8 K. The SMES system with three noteworthy parts, is shown in Fig. 10. The energy stored in the SMES coil can be figured by E = 0.5LI2, where L is the coil inductance and I is the current circulating in it. The essential benefits of SMES are the swift response time: the demanded power is accessible promptly. Additionally, the framework is described by its high general round- trip efficiency (85%–90%) and the powerful yield which can be supplied for a brief timeframe. However, the over-all reliability depends immediately on the refrigeration framework. The significant issues going up against the usage of SMES units are the high cost and ecological issues connected with solid magnetic field.

Impact on environment

In present global world, sustainable development, emissions and climate change have become major point of concern. As a result, impact of energy storage technologies on environment has become an important aspect in their selection for any application [47,58]. Influence of various energy storage technologies on environment is shown in Table 2.

UNIT-III

NEEDS FOR ELECTRICAL ENERGY STORAGE

UNIT - III Needs for Electrical Energy Storage:

Emerging needs for EES, more renewable energy-less fossil fuel, Smart Grid uses - the roles of electrical energy storage technologies-the roles from the viewpoint of a utility-the roles from the viewpoint of consumers-the roles from the viewpoint of generators of renewable energy.

3.1 Introduction

Two characteristics of electricity lead to issues in its use, and by the same token generate the market needs for EES. First, electricity is consumed at the same time as it is generated. The proper amount of electricity must always be provided to meet the varying demand. An imbalance between supply and demand will damage the stability and quality (voltage and frequency) of the power supply even when it does not lead to totally unsatisfied demand. The second characteristic is that the places where electricity is generated are usually located far from the locations where it is consumed 1. Generators and consumers are connected through power grids and form a power system. In function of the locations and the quantities of power supply and demand, much power flow may happen to be concentrated into a specific transmission line and this may cause congestion. Since power lines are always needed, if a failure on a line occurs (because of congestion or any other reason) the supply of electricity will be interrupted; also because lines are always needed, supplying electricity to mobile applications is difficult. The following sections outline the issues caused by these characteristics and the consequent roles of EES.

3.1.1 Electricity and the roles of EES

Power demand varies from time to time (see Figure 1-1), and the price of electricity changes accordingly. The price for electricity at peak demand periods is higher and at off-peak periods lowers. This is caused by differences in the cost of generation in each period. During peak periods when electricity consumption is higher than average, power suppliers must complement the base-load power plants (such as coal-fired and nuclear) with less cost-effective but more flexible forms of generation, such as oil and gas-fired generators.

During the off-peak period when less electricity is consumed, costly types of generation can be stopped. This is a chance for owners of EES systems to benefit financially. From the utilities' viewpoint there is a huge potential to reduce total generation costs by eliminating the costlier methods, through storage of electricity generated by low-cost power plants during the night being reinserted into the power grid during peak periods. With high PV and wind penetration in some regions, cost-free surplus energy is sometimes available. This surplus can be stored in EES and used to reduce generation costs. Conversely, from the consumers' point of view, EES can lower electricity costs since it can store electricity bought at low off-peak prices and they can use it during peak periods in the place of expensive power. Consumers who charge batteries during off-peak hours may also sell the electricity to utilities or to other consumers during peak hours.

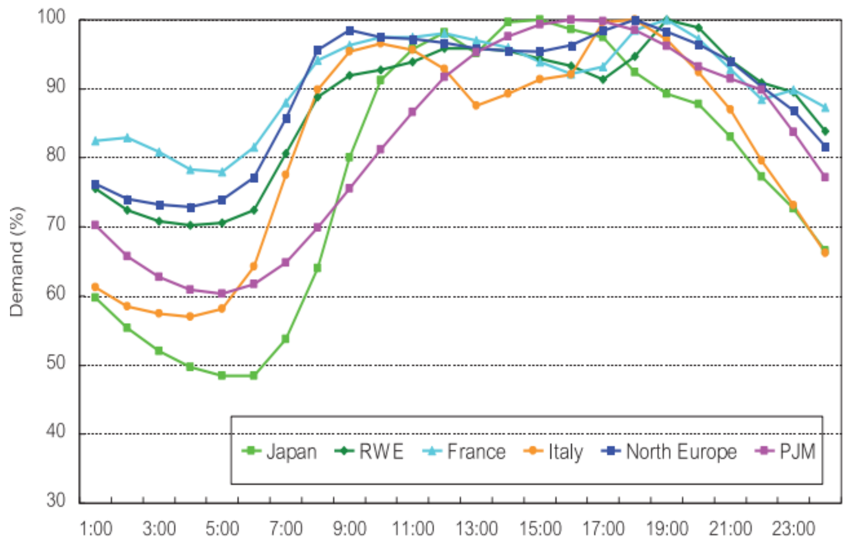


Figure.3.1 Comparison of daily load curves

3.1.2 Need for continuous and flexible supply

A fundamental characteristic of electricity leads to the utilities' second issue, maintaining a continuous and flexible power supply for consumers. If the proper amount of electricity cannot be provided at the time when consumers need it, the power quality will deteriorate and at worst this may lead to a service interruption. To meet changing power consumption appropriate amounts of electricity should be generated continuously, relying on an accurate forecast of the variations in demand. Power generators therefore need two essential functions in addition to the basic generating function. First, generating plants are required to be equipped with a "kilowatt function", to generate sufficient power (kW) when necessary. Secondly, some generating facilities must possess a frequency control function, fine-tuning the output so as to follow minute-by-minute and second-by-second fluctuations in demand, using the extra power from the "kilowatt function" if necessary. Renewable energy facilities such as solar and wind do not possess both a kW function and a frequency control function unless they are suitably modified. Such a modification may be a negative power margin (i.e. decreasing power) or a phase shift inverter 2. EES is expected to be able to compensate for such difficulties with a kW function and a frequency control function. Pumped hydro has been widely used to provide a large amount of power when generated electricity is in short supply. Stationary batteries have also been utilized to support renewable energy output with their quick response capability.

3.1.3 Long distance between generation and consumption

Consumers' locations are often far from power generating facilities, and this sometimes leads to higher chances of an interruption in the power supply. Network failures due to natural disasters (e.g. lightning, hurricanes) and artificial causes (e.g. overload, operational accidents) stop electricity supply and potentially influence wide areas. EES will help users when power network failures occur by continuing to supply power to consumers. One of the representative industries utilizing EES is semi-conductor and LCD manufacturing, where voltage sag lasting for even a few milliseconds impacts the quality of the products. A UPS system, built on EES and located at a customer's site, can keep supplying electricity to critical loads even when voltage sag occurs due to, for example, a direct lightning strike on distribution lines. A portable battery may also serve as an emergency resource to provide power to electrical appliances.

3.1.4 Congestion in power grids

This issue is a consequence of the previous problem, a long distance between generation and consumption. The power flow in transmission grids is determined by the supply and demand of electricity. In the process of balancing supply and demand power congestion can occur. Utility companies try to predict future congestion and avoid overloads, for example by dispatching generators' outputs or ultimately by building new transmission routes. EES established at appropriate sites such as substations at the ends of heavily-loaded lines can mitigate congestion, by storing electricity while transmission lines maintain enough capacity and by using it when lines are not available due to congestion. This approach also helps utilities to postpone or suspend the reinforcement of power networks.

3.1.5 Transmission by cable

Electricity always needs cables for transmission, and supplying electricity to mobile applications and to isolated areas presents difficulties. EES systems such as batteries can solve this problem with their mobile and charge/discharge capabilities. In remote places without a power grid connection recharging an electric vehicle may present a challenge, but EES can help realize an environmentally friendly transport system without using conventional combustion engines.

3.2 Emerging needs for EES

Electrical Energy Storage has to play three main roles. First, EES reduces electricity costs by storing electricity obtained at off-peak times when its price is lower, for use at peak times instead of electricity bought then at higher prices. Secondly, in order to improve the reliability of the power supply and their third role is to maintain and improve power quality, frequency and voltage. Regarding emerging market needs, in on-grid areas, EES is expected to solve problems such as excessive power fluctuation and undependable power supply which are associated with the use of large amounts of renewable energy. In the off-grid domain, electric vehicles with batteries are the most promising technology to replace fossil fuels by electricity from mostly renewable sources.

There are two major emerging market needs for EES as a key technology:

i) To utilize more renewable energy and less fossil fuel and

ii) The future Smart Grid.

3.3. More renewable energy, less fossil fuel

3.3.1. On-grid areas

In on-grid areas, the increased ratio of renewable generation may cause several issues in the power grid (see Figure 1-2). First, in power grid operation, the fluctuation in the output of renewable generation makes system frequency control difficult, and if the frequency deviation becomes too wide system operation can deteriorate. Conventionally, frequency control is mostly managed by the output change capability of thermal generators. When used for this purpose thermal generators are not operated at full capacity, but with some positive and negative output margin (i.e. increases and decreases in output) which is used to adjust frequency, and this implies inefficient operation. With greater penetration of renewable generation this output margin needs to be increased, which decreases the efficiency of thermal generation even more. Renewable generation units themselves in most cases only supply a negative margin 3. If EES can mitigate the output fluctuation, the margins of thermal generators can be reduced and they can be operated at a higher efficiency. Secondly, renewable energy output is undependable since it is affected by weather conditions. Some measures are available to cope with this. One is to increase the amount of renewable generation installed, i.e. provide overcapacity, so that even with undependability enough power can be secured. Another is to spread the installations of renewable generators over a wide area, to take advantage of weather conditions changing from place to place and of smoothing effects expected from the complementarily of wind and solar generators. These measures are possible only with large numbers of installations and extension of transmission networks. Considering the cost of extra renewable generation and the difficulty of constructing new transmission facilities, EES is a promising alternative measure.

3.3.2 Off-grid areas

In off-grid areas where a considerable amount of energy is consumed, particularly in the transport sector, fossil energy should be replaced with less or non-fossil energy in such products as plugin hybrid electric vehicles (PHEVs) or electric vehicles (EVs) (see Figure 1-2). More precisely, fossil fuels should be replaced by low-carbon electricity produced mainly by renewable generation. The most promising solution is to replace petrol or diesel-driven cars by electric ones with batteries. In spite of remaining issues (short driving distance and long charging time) EES is the key technology for electric vehicles.

3.3.3 Smart Grid uses

EES is expected to play an essential role in the future Smart Grid. Some relevant applications of EES are described below. First, EES installed in customer-side substations can control power flow and mitigate congestion, or maintain voltage in the appropriate range. Secondly, EES can support the electrification of existing equipment so as to integrate it into the Smart Grid. Electric vehicles (EVs) are a good example since they have been deployed in several regions, and some argue for the potential of EVs as a mobile, distributed energy resource to provide a load shifting function in a smart grid. EVs are expected to be not only a new load for electricity but also a possible storage medium that could supply power to utilities when the electricity price is high. A third role expected for EES is as the energy storage medium for Energy Management Systems (EMS) in homes and buildings. With a Home Energy Management System, for example, residential customers will become actively involved in modifying their energy spending patterns by monitoring their actual consumption in real time. EMSs in general will need EES, for example to store electricity from local generation.

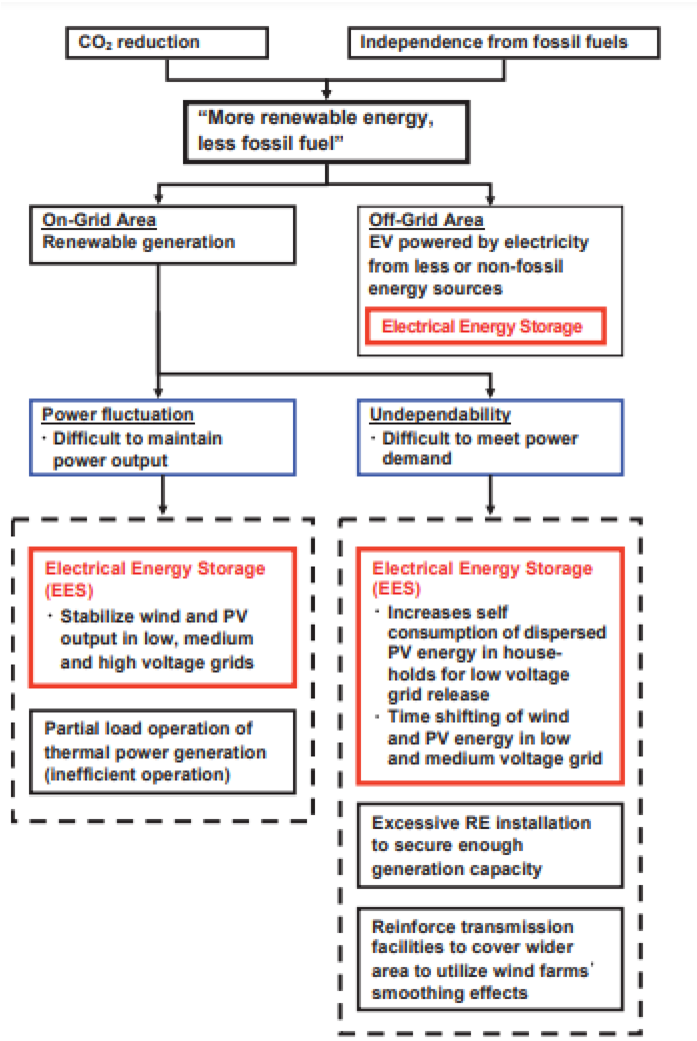


Figure.3.2. Problems in renewable energy installation and possible solutions

When it is not needed and discharges it when necessary, thus allowing the EMS to function optimally with less power needed from the grid.

3.4 The roles of electrical energy storage technologies

Generally the roles for on-grid EES systems can be described by the number of uses (cycles) and the duration of the operation, as shown in Figure 1-3. For the maintenance of voltage quality (e.g. compensation of reactive power), EES with high cycle stability and short duration at high power output is required; for time shifting on the other hand longer storage duration and fewer cycles are needed. The following sections describe the roles in detail.

3.4.1 The roles from the viewpoint of a utility

1) Time shifting

Utilities constantly need to prepare supply capacity and transmission/distribution lines to cope with annually increasing peak demand, and consequently develop generation stations that produce electricity from primary energy. For some utilities generation cost can be reduced by storing electricity at off-peak times, for example at night, and discharging it at peak times. If the gap in demand between peak and off-peak is large, the benefit of storing electricity becomes even larger. Using storage to decrease the gap between daytime and night-time may allow generation output to become flatter, which leads to an improvement in operating efficiency and cost reduction in fuel. For these reasons many utilities have constructed pumped hydro, and have recently begun installing large-scale batteries at substations.

2) Power quality

A basic service that must be provided by power utilities is to keep supply power voltage and frequency within tolerance, which they can do by adjusting supply to changing demand. Frequency is controlled by adjusting the output of power generators; EES can provide frequency control functions. Voltage is generally controlled by taps of transformers, and reactive power with phase modifiers. EES located at the end of a heavily loaded line may improve voltage drops by discharging electricity and reduce voltage rises by charging electricity.

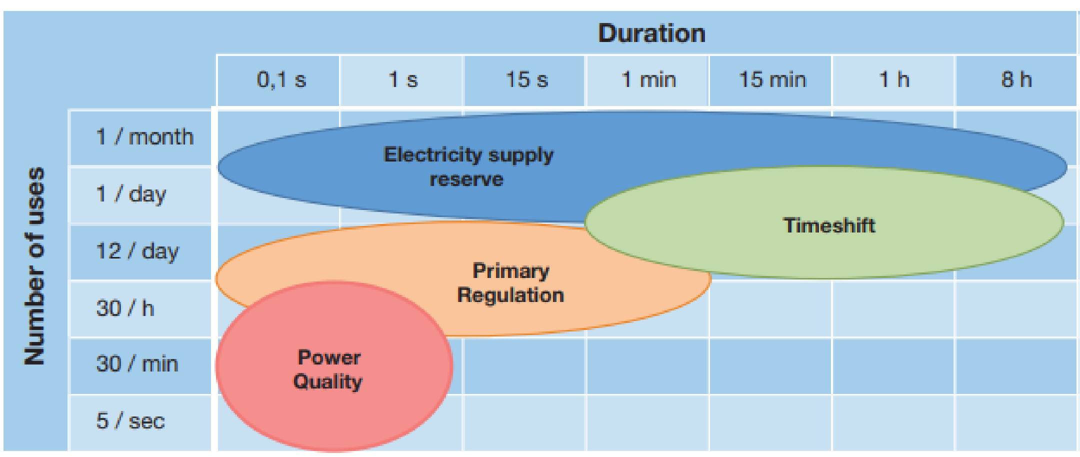


Figure 3.3.Different uses of electrical energy storage in grids, depending on the frequency and duration of use

3) Making more efficient use of the network

In a power network, congestion may occur when transmission/distribution lines cannot be reinforced in time to meet increasing power demand. In this case, large-scale batteries installed at appropriate substations may mitigate the congestion and thus help utilities to postpone or suspend the reinforcement of the network.

4) Isolated grids

Where a utility company supplies electricity within a small, isolated power network, for example on an island, the power output from small-capacity generators such as diesel and renewable energy must match the power demand. By installing EES the utility can supply stable power to consumers.

5) Emergency power supply for protection and control equipment

A reliable power supply for protection and control is very important in power utilities. Many batteries are used as an emergency power supply in case of outage.

3.4.2 The roles from the viewpoint of consumers

1) Time shifting/cost savings

Power utilities may set time-varying electricity prices, a lower price at night and a higher one during the day, to give consumers an incentive to flatten electricity load. Consumers may then reduce their electricity costs by using EES to reduce peak power needed from the grid during the day and to buy the needed electricity at off-peak times.

2) Emergency power supply

Consumers may possess appliances needing continuity of supply, such as fire sprinklers and security equipment. EES is sometimes installed as a substitute for emergency generators to operate during an outage. Semiconductor and liquid-crystal manufacturers are greatly affected by even a momentary outage (e.g. due to lightning) in maintaining the quality of their products. In these cases, EES technology such as large-scale batteries, double-layer capacitors and SMES can be installed to avoid the effects of a momentary outage by instantly switching the load off the network to the EES supply. A portable battery may also serve in an emergency to provide power to electrical appliances.

3) Electric vehicles and mobile appliances

Electric vehicles (EVs) are being promoted for CO2 reduction. High-performance batteries such as nickel cadmium, nickel metal hydride and lithium ion batteries are mounted on EVs and used as power sources. EV batteries are also expected to be used to power in-house appliances in combination with solar power and fuel cells; at the same time, studies are being carried out to see whether they can usefully be connected to power networks. These possibilities are often abbreviated as “V2H” (vehicle to home) and “V2G” (vehicle to grid).

3.4.3 The roles from the viewpoint of generators of renewable energy

1) Time shifting

Renewable energy such as solar and wind power is subject to weather, and any surplus power may be thrown away when not needed on the demand side. Therefore valuable energy can be effectively used by storing surplus electricity in EES and using it when necessary; it can also be sold when the price is high.

2) Effective connection to grid

The output of solar and wind power generation varies greatly depending on the weather and wind speeds, which can make connecting them to the grid difficult. EES used for time shift can absorb this fluctuation more cost-effectively than other, single-purpose mitigation measures (e.g. a phase shifter).

Summary

1) The potential market for EES in the future is much larger than the existing market, mainly driven by the extended use of renewable energy sources and the transformation of the energy sector, including new applications such as electric mobility. The market volume is relatedto the (future) renewable energy ratio and varies among regions. 2) If further cost reductions and technology improvement can be achieved, EES systems will be widely deployed, for example, to shift the demand, smooth renewable energy output and improve the effi ciency of existing power

generation. 3) European studies indicate huge expectations for EES technologies to compensate for the fluctuation of renewable energy power output. Large installations of wind turbines and Pvs may require numerous EES systems, capable of discharging electricity for periods from two hours up to one day. Hence the market for conventional large-scale EES is attractive. 4) The extensive introduction of electrochemical EES such as NaS, Li-ion and RFB in the MW -MWh range is expected, for discharge times of hours to days. 5) Long-term energy storage is essential to achieving very high renewable energy ratios. The IEA report shows that further installation of renewable energy will lead to an insufficiency of thermal power generators for power control, and cause short-time output fluctuations. This scenario may be expected in Western Europe and China which have both set high renewable-energy-penetration targets. 6) To cover longer discharge times of days to months hydrogen and SNG technology have to be developed. The well established natural gas grid and underground storage in regions such s Europe can be (partly) used for H 2 and SNG storage. 7) Smart Grid technology using many small, dispersed batteries, such as EV batteries, is attractive for many applications. But even if all EV batteries are used for this purpose they will be insufficient to cover future demand for EES.

Unit-IV

TYPES OF ELECTRICAL ENERGY STORAGE SYSTEMS

Electrical storage systems, Double-layer capacitors (DLC), Superconducting magnetic energy storage (SMES), super charging stations, Thermal storage systems, Standards for EES, Technical comparison of EES technologies.

4.1 Introduction

In this section the types of EES system and their features are listed. A brief classification is followed by a description of the various EES types with their advantages and disadvantages. Finally the main technical features are summarized.

4.2 Classification of EES systems

A widely-used approach for classifying EES systems is the determination according to the form of energy used. In Figure 2-1 EES systems are classified into mechanical, electrochemical, chemical, electrical and thermal energy storage systems. Hydrogen and synthetic natural gas (SNG) are secondary energy carriers and can be used to store electrical energy via electrolysis of water to produce hydrogen and, in an additional step, methane if required. In fuel cells electricity is generated by oxidizing hydrogen or methane. This combined electrolysis-fuel cell process is an electrochemical EES. However, both gases are multi-purpose energy carriers. For example, electricity can be generated in a gas or steam turbine. Consequently, they are classified as chemical energy storage systems. In Figure 2-1 thermal energy storage systems are included as well, although in most cases electricity is not the direct input to such storage systems. But with the help of thermal energy storage the energy from renewable energy sources can be buffered and thus electricity can be produced on demand. Examples are hot molten salts in concentrated solar power plants and the storage of heat in compressed air plants using an adiabatic process to gain efficiency.

4.2 Mechanical storage systems

The most common mechanical storage systems are pumped hydroelectric power plants (pumped hydro storage, PHS), compressed air energy storage (CAES) and flywheel energy storage (FES).

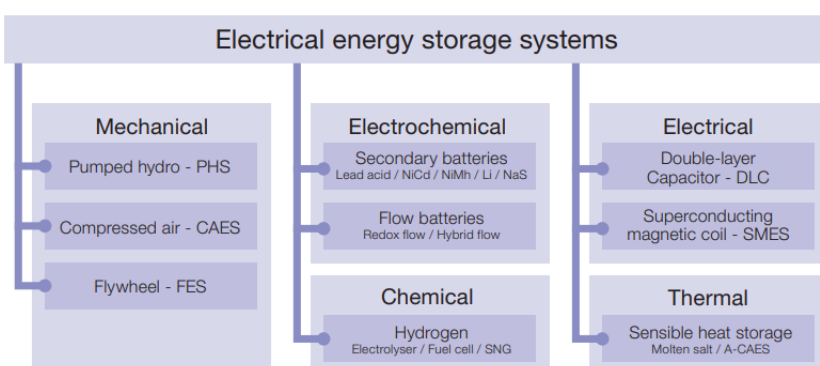


Figure.4.1 Classification of electrical energy storage systems according to energy form

4.3 Pumped hydro storage (PHS)

With over 120 GW, pumped hydro storage power plants (Figure 2-2) represent nearly 99 % of world-wide installed electrical storage capacity [doe07], which is about 3 % of global generation capacity 4 . Conventional pumped hydro storage systems use two water reservoirs at different elevations to pump water during off-peak hours from the lower to the upper reservoir (charging). When required, the water flows back from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging). There are different options for the upper and lower reservoirs, e.g. high dams can be used as pumped hydro storage plants. For the lower reservoir flooded mine shafts, other underground cavities and the open sea are also technically possible. Seawater pumped hydro plant was first built in Japan in 1999 (Yanbaru, 30 MW). PHS has existed for a long time – the first pumped hydro storage plants were used in Italy and Switzerland in the 1890s. By 1933 reversible pump-turbines with motor generators were available 5. Typical discharge times range from several hours to a few days. The efficiency of PHS plants is in the range of 70 % to 85 %. Advantages are the very long lifetime and practically unlimited cycle stability of the installation. Main drawbacks are the dependence on topographical conditions and large land use. The main applications are for energy management via time shift, namely non spinning reserve and supply reserve.

Figure.4.2 Pumped Hydro Storage

4.4 Compressed air energy storage (CAES)

Compressed air (compressed gas) energy storage (Figure 4.3) is a technology known and used since the 19th century for different industrial applications including mobile ones. Air is used as storage medium due to its availability. Electricity is used to compress air and store it in either an underground structure or an above-ground system of vessels or pipes. When needed the compressed air is mixed with natural gas, burned and expanded in a modified gas turbine. Typical underground storage options are caverns, aquifers or abandoned mines. If the heat released during compression is dissipated by cooling and not stored, the air must be reheated prior to expansion in the turbine. This process is called diabatic CAES and results in low round-trip efficiencies of less than 50 %. Diabatic technology is well proven; the plants have a high reliability and are capable of starting without extraneous power 6. The advantage of

CAES is its large capacity; disadvantages are low round-trip efficiency and geographic limitation of locations [nak07].

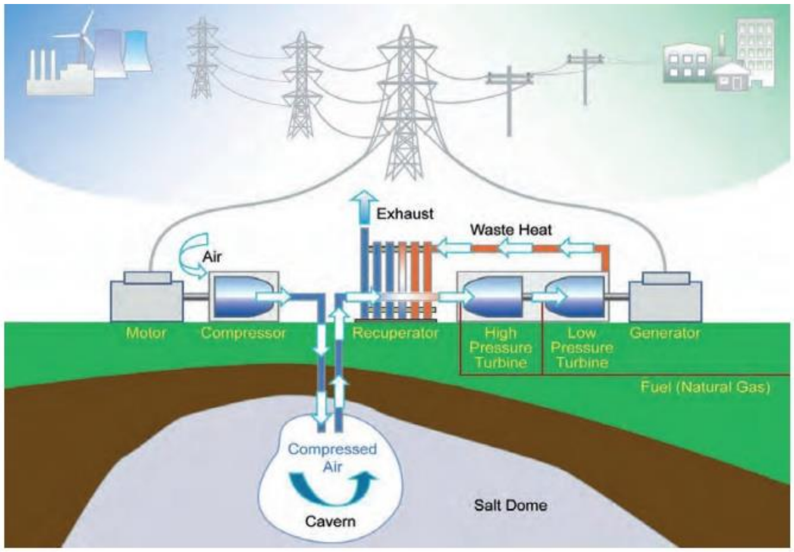


Figure.4.3 Underground CAES

4.5 Flywheel energy storage (FES)

In flywheel energy storage (Figure 4.4) rotational energy is stored in an accelerated rotor, a massive rotating cylinder. The main components of a flywheel are the rotating body/cylinder (comprised of a rim attached to a shaft) in a compartment, the bearings and the transmission device (motor/generator mounted onto the stator 7). The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy stored. To accelerate the flywheel electricity is supplied by a transmission device. If the flywheel's rotational speed is reduced electricity may be extracted from the system by the same transmission device. Flywheels of the first generation, which have been available since about 1970, use a large steel rotating body on mechanical bearings. Advanced FES systems have rotors made of high-strength carbon filaments, suspended by magnetic bearings, and spinning at speeds from 20 000 to over 50 000 rpm in a vacuum enclosure. The main features of flywheels are the excellent cycle stability and a long life, little maintenance, high power density and the use of environmentally inert material. However, flywheels have a high level of self-discharge due to air resistance and bearing losses and suffer from low current efficiency. Today flywheels are commercially deployed for power quality in industrial and UPS applications, mainly in a hybrid configuration. Efforts are being made to optimize flywheels for long-duration operation (up to several hours) as power storage devices for use in vehicles and power plants.

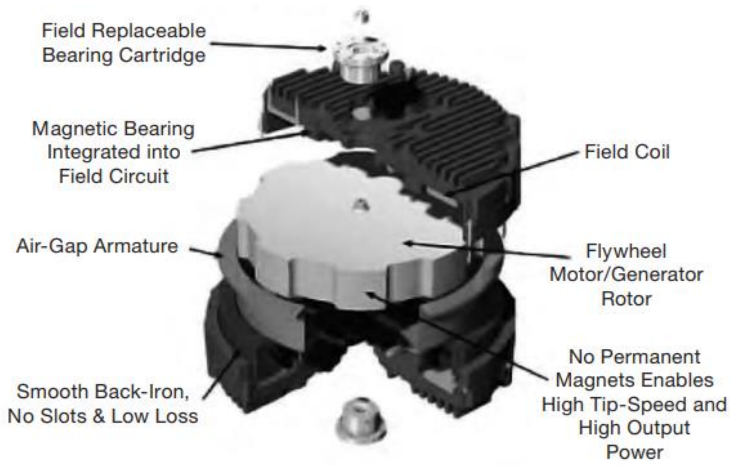


Figure.4.5 Flywheel energy storage

4.6 Electrochemical storage systems

In this section various types of batteries are described. Most of them are technologically mature for practical use. First, six secondary battery types are listed: lead acid, NiCd/NiMH, Li-ion, metal air, sodium sulphur and sodium nickel chloride; then follow two sorts of flow battery.

4.6.1 Secondary batteries

Lead acid battery (LA)

Lead acid batteries are the worlds most widely used battery type and have been commercially deployed since about 1890. Lead acid battery systems are used in both mobile and stationary applications. Their typical applications are emergency power supply systems, stand-alone systems with PV, battery systems for mitigation of output fluctuations from wind power and as starter batteries in vehicles. In the past, early in the “electrification age” (1910 to 1945), many lead acid batteries were used for storage in grids. Stationary lead acid batteries have to meet far higher product quality standards than starter batteries. Typical service life is 6 to 15 years with a cycle life of 1 500 cycles at 80 % depth of discharge, and they achieve cycle efficiency levels of around 80 % to 90 %. Lead acid batteries offer a mature and well-researched technology at low cost. There are many types of lead acid batteries available, e.g. vented and sealed housing versions (called valve-regulated lead acid batteries, VRLA). Costs for stationary batteries are currently far higher than for starter batteries. Mass production of lead acid batteries for stationary systems may lead to a price reduction. One disadvantage of lead acid batteries is usable capacity decrease when high power is discharged. For example, if a battery is discharged in one hour, only about 50 % to 70 % of the rated capacity is available. Other drawbacks are lower energy density and the use of lead, a hazardous material prohibited or restricted in various jurisdictions. Advantages are a favorable cost/performance ratio, easy recyclability and a simple charging technology. Current R&D on lead acid batteries is trying to improve their behavior for micro-hybrid electric vehicles.

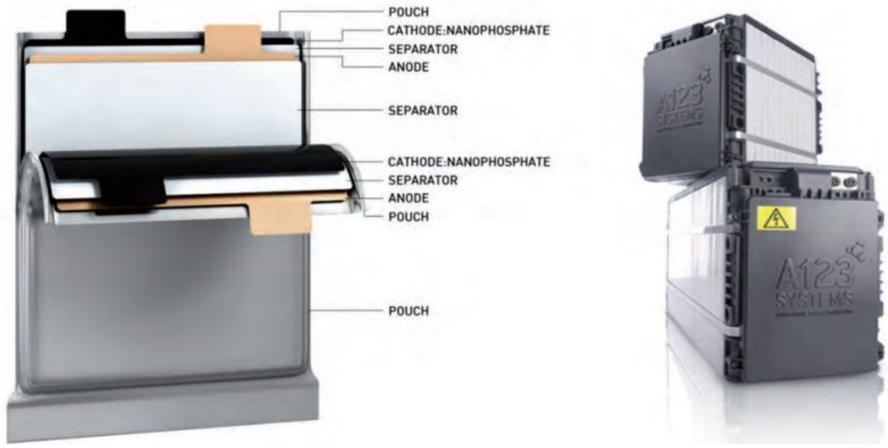
Nickel cadmium and nickel metal hydride battery (NiCd, NiMH)

Before the commercial introduction of nickel metal hydride (NiMH) batteries around 1995, nickel cadmium (NiCd) batteries had been in commercial use since about 1915. Compared to lead acid batteries, nickel-based batteries have a higher power density, a slightly greater energy density and the number of cycles is higher; many sealed construction types are available. From a technical point of view, NiCd batteries are a very successful battery product; in particular, these are the only batteries capable of performing well even at low temperatures in the range from -20 °C to -40 °C. Large battery systems using vented NiCd batteries operate on a scale similar to lead acid batteries. However, because of the toxicity of cadmium, these batteries are presently used only for stationary applications in Europe. Since 2006 they have been prohibited for consumer use. NiMH batteries were developed initially to replace NiCd batteries. Indeed, NiMH batteries have all the positive properties of NiCd batteries, with the exception of the maximal nominal capacity which is still ten times less when compared to NiCd and lead acid. Furthermore, NiMH batteries have much higher energy densities (weight for weight). In portable and mobile applications sealed NiMH batteries have been extensively replaced by lithium ion batteries. On the other hand, hybrid vehicles available on today's market operate almost exclusively with sealed NiMH batteries, as these are robust and far safer than lithium ion batteries. NiMH batteries currently cost about the same as lithium ion batteries.

Lithium ion battery (Li-ion)

Lithium ion batteries (Figure 2-5) have become the most important storage technology in the areas of portable and mobile applications (e.g. laptop, cell phone, electric bicycle, and electric car) since around 2000. High cell voltage levels of up to 3.7 nominal Volts mean that the number of cells in series with the associated connections and electronics can be reduced to obtain the target voltage. For example, one lithium ion cell can replace three NiCd or NiMH cells which have a cell voltage of only 1.2 Volts. Another advantage of Li-ion batteries is their high gravimetric energy density, and the prospect of large cost reductions through mass production. Although Li-ion batteries have a share of over 50 % in the small portable devices market, there are still some challenges for developing larger-scale Li-ion batteries. The main obstacle is the high cost of more than USD 600/kWh due to special packaging and internal overcharge protection circuits. Lithium ion batteries generally have a very high efficiency, typically in the range of 95 % - 98 %. Nearly any discharge time from seconds to weeks can be realized, which makes them a very flexible and universal storage technology.

Standard cells with 5000 full cycles can be obtained on the market at short notice, but even higher cycle rates are possible after further development, mainly depending on the materials used for the electrodes. Since lithium ion batteries are currently still expensive, they can only compete with lead acid batteries in those applications which require short discharge times (e.g. as primary control backup). Safety is a serious issue in lithium ion battery technology. Most of the metal oxide electrodes are thermally unstable and can decompose at elevated temperatures, releasing oxygen which can lead to a thermal runaway. To minimize this risk, lithium ion batteries are equipped with a monitoring unit to avoid over-charging and over-discharging. Usually a voltage balance circuit is also installed to monitor the voltage level of each individual cell and prevent voltage deviations among them. Lithium ion battery technology is still developing, and there is considerable potential for further progress. Research is focused on the development of cathode materials.



Typical Li-ion prismatic cell design and battery modules

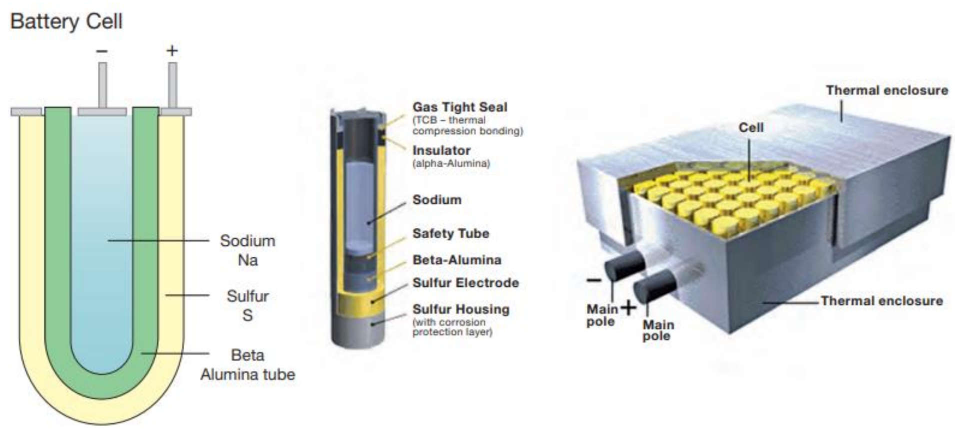
Metal air battery (Me-air)

A metal air electrochemical cell consists of the anode made from pure metal and the cathode connected to an inexhaustible supply of air. For the electrochemical reaction only the oxygen in the air is used. Among the various metal air battery chemical couples, the lithium air battery is most attractive since its theoretical specific energy excluding oxygen (oxygen is not stored in the battery) is 11.14 kWh/kg, corresponding to about 100 times more than other battery types and even greater than petrol (10.15 kWh/kg). However, the high reactivity of lithium with air and humidity can cause fire, which is a high safety risk. Currently only a zinc air battery with a theoretical specific energy excluding oxygen of 1.35 kWh/kg is technically feasible. Zinc air batteries have some properties of fuel cells and conventional batteries: the zinc is the fuel, the reaction rate can be controlled by varying air flow, and oxidized zinc/electrolyte paste can be replaced with fresh paste. In the 1970s, the development of thin electrodes based on fuel-cell research made small button prismatic primary cells possible for hearing aids, pagers and medical devices, especially cardiac telemetry. Rechargeable zinc air cells have a difficulty in design since zinc precipitation from the water based electrolyte must be closely controlled. A satisfactory, electrically rechargeable metal air system potentially offers low materials cost and high specific energy, but none has reached marketability yet.

Sodium sulphur battery (NaS)

Sodium sulphur batteries (Figure 2-6) consist of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode; the active materials are separated by a solid beta alumina ceramic electrolyte. The battery temperature is kept between 300 °C and 350 °C to keep the electrodes molten. NaS batteries reach typical life cycles of around 4 500 cycles and have a discharge time of 6.0 hours to 7.2 hours. They are efficient (AC-based round-trip efficiency is about 75 %) and have fast response. These attributes enable NaS batteries to be economically used in combined power quality and time shift applications with high energy density.

The NaS battery technology has been demonstrated at around 200 sites in Japan, mainly for peak shaving, and Germany, France, USA and UAE also have NaS batteries in operation. The main drawback is that to maintain operating temperatures a heat source is required, which uses the battery's own stored energy, partially reducing the battery performance. In daily use the temperature of the battery can almost be maintained by just its own reaction heat, with appropriately dimensioned insulation. Since around 1990 NaS batteries have been manufactured by one company in Japan, with a minimum module size of 50 kW and with typically 300 kWh to 360 kWh. It is not practical for the present to use only one isolated module. Because 20 modules are combined into one battery the minimal commercial power and energy range is on the order of 1 MW, and 6.0 MWh to 7.2 MWh. These batteries are suitable for applications with daily cycling. As the response time is in the range of milliseconds and NaS batteries meet the requirements for grid stabilization, this technology could be very interesting for utilities and large consumers.



NaS Battery: Cell design and 50 kW module

Sodium nickel chloride battery (NaNiCl)

The sodium nickel chloride (NaNiCl) battery, better known as the ZEBRA (Zero Emission Battery Research) battery, is – like the NaS battery – a high-temperature (HT) battery, and has been commercially available since about 1995. Its operating temperature is around 270 °C, and it uses nickel chloride instead of sulphur for the positive electrode. NaNiCl batteries can withstand limited overcharge and discharge and have potentially better safety characteristics and a higher cell voltage than NaS batteries. They tend to develop low resistance when faults occur and this is why cell faults in serial connections only result in the loss of the voltage from one cell, instead of premature failure of the complete system. These batteries have been successfully implemented in several electric vehicle designs (Think City, Smart EV) and are an interesting opportunity for fleet applications. Present research is in developing advanced versions of the ZEBRA battery with higher power densities for hybrid electric vehicles, and also high-energy versions for storing renewable energy for load-leveling and industrial applications [esp11].

4.7 Flow batteries

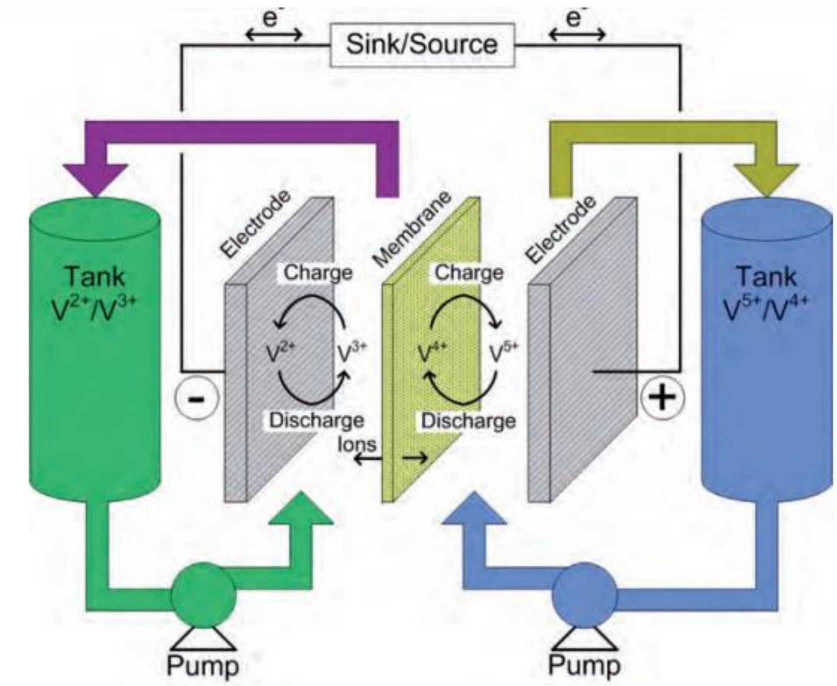
In conventional secondary batteries, the energy is charged and discharged in the active masses of the electrodes. A flow battery is also a rechargeable battery, but the energy is stored in one or more electro active species which are dissolved in liquid electrolytes. The electrolytes are stored externally in tanks and pumped through the electrochemical cell that converts chemical energy directly to electricity and vice versa. The power is defined by the size and design of the electrochemical cell whereas the energy depends on the size of the tanks. With this characteristic flow batteries can be fitted to a wide range of stationary applications. Originally developed by NASA in the early 70s as EES for long-term space flights, flow batteries are now receiving attention for storing energy for durations of hours or days with a power of up to several MW.

Flow batteries are classified into redox flow batteries and hybrid flow batteries.

Redox flow battery (RFB)

In redox flow batteries (RFB) two liquid electrolyte dissolutions containing dissolved metal ions as active masses are pumped to the opposite sides of the electrochemical cell. The electrolytes at the negative and positive electrodes are called anolyte and catholyte respectively. During charging and discharging the metal ions stay dissolved in the fluid electrolyte as liquid; no phase change of these active masses takes place. Anolyte and catholyte flow through porous electrodes, separated by a membrane which allows protons to pass through it for the electron transfer process. During the exchange of charge a current flows over the electrodes, which can be used by a battery-powered device. During discharge the electrodes are continually supplied with the dissolved active masses from the tanks; once they are converted the resulting product is removed to the tank. Theoretically a RFB can be "recharged" within a few minutes by pumping out the discharged electrolyte and replacing it with recharged electrolyte. That is why redox flow batteries are under discussion for mobile applications.

However, up to now the energy density of the electrolytes has been too low for electric vehicles. Today various redox couples have been investigated and tested in RFBs, such as a Fe-Ti system, a Fe-Cr system and a polyS-Br system (Rareness installation in UK with 15 MW and 120 MWh, but never commissioned). The vanadium redox flow battery (VRFB, Figure 2-7) has been developed the furthest; it has been piloted since around 2000 by companies such as Prudent Energy (CN) and Cell strom (AU). The VRFB uses a V^{2+}/V^{3+} redox couple as oxidizing agent and a V^{5+}/V^{4+} redox couple in mild sulphuric acid solution as reducing agent. The main advantage of this battery is the use of ions of the same metal on both sides. Although crossing of metal ions over the membrane cannot be prevented completely (as is the case for every redox flow battery), in VRFBs the only result is a loss in energy. In other RFBs, which use ions of different metals, the crossover causes an irreversible degradation of the electrolytes and a loss in capacity. The VRFB was pioneered at the University of New South Wales, Australia, in the early 1980s. A VRFB storage system of up to 500 kW and 10 hrs has been installed in Japan by SEI. SEI has also used a VRFB in power quality applications (e.g. 3 MW, 1.5 sec.).



Schematic of a Vanadium Redox Flow Battery

Hybrid flow battery (HFB)

In a hybrid flow battery (HFB) one of the active masses is internally stored within the electrochemical cell, whereas the other remains in the liquid electrolyte and is stored externally in a tank. Therefore hybrid flow cells combine features of conventional secondary batteries and redox flow batteries: the capacity of the battery depends on the size of the electrochemical cell. Typical examples of a HFB are the Zn-Ce and the Zn-Br systems. In both cases the anolyte consists of an acid solution of Zn2+ ions. During charging Zn is deposited at the electrode and at discharging Zn2+ goes back into solution. As membrane a micro porous polyolefin material is used; most of the electrodes are carbon-plastic composites. Various companies are working on the commercialization of the Zn-Br hybrid flow battery, which was developed by Exxon in the early 1970s. In the United States, ZBB Energy and Premium Power sell trailer-transportable Zn-Br systems with unit capacities of up to 1 MW / 3 MWh for utility-scale applications [iee10]. 5 kW / 20 kWh systems for community energy storage are in development as well.

4.8 Chemical energy storage

In this the chemical energy storage focuses on hydrogen and synthetic natural gas (SNG) as secondary energy carriers, since these could have a significant impact on the storage of electrical energy in large quantities (see section 4.2.2). The main purpose of such a chemical energy storage system is to use “excess” electricity to produce hydrogen via water electrolysis. Once hydrogen is produced different ways are available for using it as an energy carrier, either as pure hydrogen or as SNG. Although the overall efficiency of hydrogen and SNG is low compared to storage technologies such as PHS and Li-ion, chemical energy storage is the only concept which allows storage of large amounts of energy, up to the TWh range, and for greater periods of time – even as seasonal storage. Another advantage of hydrogen and SNG is that these universal energy carriers can be used in different sectors, such as transport, mobility, heating and the chemical industry.

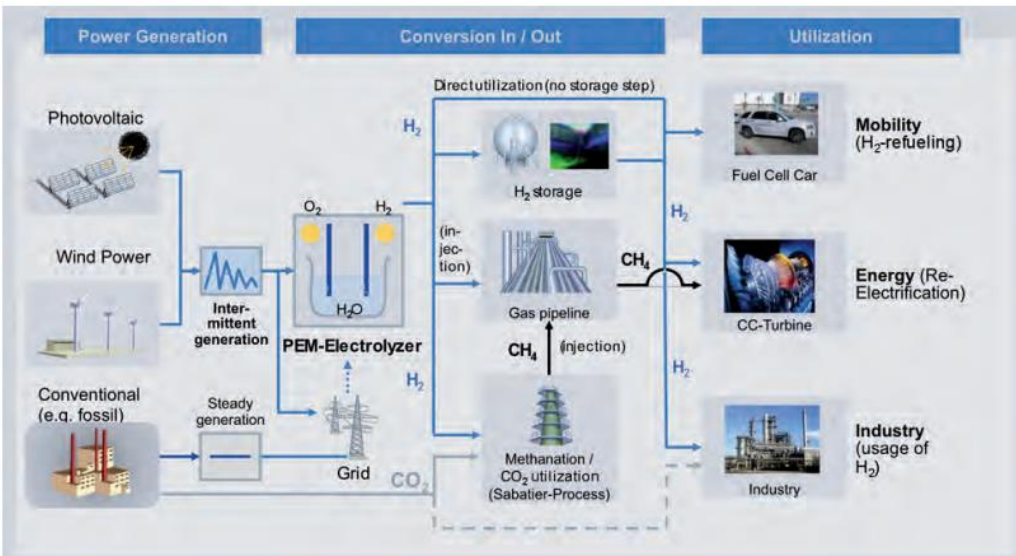
Hydrogen (H2)

A typical hydrogen storage system consists of an electrolyzer, a hydrogen storage tank and a fuel cell. An electrolyzer is an electrochemical converter which splits water with the help of electricity into hydrogen and oxygen. It is an end thermal process, i.e. heat is required during the reaction. Hydrogen is stored under pressure in gas bottles or tanks, and this can be done practically for an unlimited time. To generate electricity, both gases flow into the fuel cell where an electrochemical reaction which is the reverse of water splitting takes place: hydrogen and oxygen react and produce water, heat is released and electricity is generated. For economic and practical reasons oxygen is not stored but vented to the atmosphere on electrolysis, and oxygen from the air is taken for the power generation. In addition to fuel cells, gas motors, gas turbines and combined cycles of gas and steam turbines are in discussion for power generation. Hydrogen systems with fuel cells (less than 1 MW) and gas motors (under 10 MW) can be adopted for combined heat and power generation in decentralized installations. Gas and steam turbines with up to several hundred MW could be used as peaking power plants. The overall AC-AC efficiency is around 40 %.

Different approaches exist to storing the hydrogen, either as a gas under high pressure, a liquid at very low temperature, adsorbed on metal hydrides or chemically bonded in complex hydrides. However, for stationary applications gaseous storage under high pressure is the most popular choice. Smaller amounts of hydrogen can be stored in above-ground tanks or bottles under pressures up to 900 bar. For larger amounts of hydrogen, underground piping systems or even salt caverns with several 100 000 m^3 volumes under pressures up to 200 bar can be used. Up to now there has not been any commercial hydrogen storage systems used for renewable energies. Various R&D projects carried out over the last 25 years have successfully demonstrated the feasibility of hydrogen technology, such as a project on the self-sufficient island of Utsira in Norway. Another example is a hybrid power plant from Enertrag in Germany which is currently under construction [ene11]. Wind energy is used to produce hydrogen via electrolysis if the power cannot be directly fed into the grid. On demand, the stored hydrogen is added to the biogas used to run a gas motor. Moreover the hydrogen produced will be used for a hydrogen refilling station at the international airport in Berlin. Water electrolysis plants on a large scale (up to 160 MW) are state-of-the-art for industrial applications; several were built in different locations (Norway, Egypt, Peru etc.) in the late 1990s.

Synthetic natural gas (SNG)

Synthesis of methane (also called synthetic natural gas, SNG) is the second option to store electricity as chemical energy. Here a second step is required beyond the water splitting process in an electrolyzer, a step in which hydrogen and carbon dioxide react to methane in a methanation reactor. As is the case for hydrogen, the SNG produced can be stored in pressure tanks, underground, or fed directly into the gas grid. Several CO2 sources are conceivable for the methanation process, such as fossil-fuelled power stations, industrial installations or biogas plants. To minimize losses in energy, transport of the gases CO2 (from the CO2 source) and H2 (from the electrolysis plant) to the methanation plant should be avoided. The production of SNG is preferable at locations where CO2 and excess electricity are both available. In particular, the use of CO2 from biogas production processes is promising as it is a widely-used technology. Nevertheless, intermediate on-site storage of the gases is required, as the methanation is a constantly running process. Recently this concept "power to methane" has been the subject of different R&D projects (e.g. in Germany, where a pilot-scale production plant is under construction [kuh11]). The main advantage of this approach is the use of an already existing gas grid infrastructure (e.g. in Europe). Pure hydrogen can be fed into the gas grid only up to a certain concentration, in order to keep the gas mixture within specifications (e.g. heating value). Moreover, methane has a higher energy density, and transport in pipelines requires less energy (higher density of the gas). The main disadvantage of SNG is the relatively low efficiency due to the conversion losses in electrolysis, methanation, storage, transport and the subsequent power generation. The overall AC-AC efficiency, < 35 %, is even lower than with hydrogen [ste09]. A comprehensive overview of the combined use of hydrogen and SNG as chemical energy storage is shown in Figure 2-8.



Overall concept for the use of hydrogen and SNG as energy carriers

4.9 Electrical storage systems

4.9.1 Double-layer capacitors (DLC)

Electrochemical double-layer capacitors (DLC), also known as super capacitors, are a technology which has been known for 60 years. They fill the gap between classical capacitors used in electronics and general batteries, because of their nearly unlimited cycle stability as well as extremely high power capability and their many orders of magnitude higher energy storage capability when compared to traditional capacitors.

This technology still exhibits a large development potential that could lead to much greater capacitance and energy density than conventional capacitors, thus enabling compact designs. The two main features are the extremely high capacitance values, of the order of many thousand farads, and the possibility of very fast charges and discharges due to extraordinarily low inner resistance which are features not available with conventional batteries. Still other advantages are durability, high reliability, no maintenance, long lifetime and operation over a wide temperature range and in diverse environments (hot, cold and moist).

The lifetime reaches one million cycles (or ten years of operation) without any degradation, except for the solvent used in the capacitors whose disadvantage is that it deteriorates in 5 or 6 years irrespective of the number of cycles. They are environmentally friendly and easily recycled or neutralized. The efficiency is typically around 90 % and discharge times are in the range of seconds to hours.

They can reach a specific power density which is about ten times higher than that of conventional batteries (only very-high-power lithium batteries can reach nearly the same specific power density), but their specific energy density is about ten times lower. Because of their properties, DLCs are suited especially to applications with a large number of short charge/discharge cycles, where their high performance characteristics can be used.

DLCs are not suitable for the storage of energy over longer periods of time, because of their high self-discharge rate, their low energy density and high investment costs. Since about 1980 they have been widely applied in consumer electronics and power electronics. A DLC is also ideally suited as a UPS to bridge short voltage failures. A new application could be the electric vehicle, where they could be used as a buffer system for the acceleration process and regenerative braking.

4.9.2 Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) systems work according to an electrodynamic principle. The energy is stored in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature. 100 years ago at the discovery of superconductivity a temperature of about 4 °K was needed. Much research and some luck has now produced superconducting materials with higher critical temperatures. Today materials are available which can function at around 100 °K.

The main component of this storage system is a coil made of superconducting material. Additional components include power conditioning equipment and a cryogenically cooled refrigeration system. The main advantage of SMES is the very quick response time: the requested power is available almost instantaneously. Moreover the system is characterized by its high overall round-trip efficiency (85 % - 90 %) and the very high power output which can be provided for a short period of time.

There are no moving parts in the main portion of SMES, but the overall reliability depends crucially on the refrigeration system. In principle the energy can be stored indefinitely as long as the cooling system is operational, but longer storage times are limited by the energy demand of the refrigeration system. Large SMES systems with more than 10 MW power are mainly used in particle detectors for high-energy physics experiments and nuclear fusion. To date a few, rather small SMES products are commercially available; these are mainly used for power quality control in manufacturing plants such as microchip fabrication facilities.

Thermal storage systems

Thermal (energy) storage systems store available heat by different means in an insulated repository for later use in different industrial and residential applications, such as space heating or cooling, hot water production or electricity generation. Thermal storage systems are deployed to overcome the mismatch between demand and supply of thermal energy and thus they are important for the integration of renewable energy sources.

Thermal storage can be subdivided into different technologies: storage of sensible heat, storage of latent heat, and thermo-chemical adand absorption storage. The storage of sensible heat is one of the best-known and most widespread technologies, with the domestic hot water tank as an example. The storage medium may be a liquid such as water or thermo-oil, or a solid such as concrete or the ground. Thermal energy is stored solely through a change of temperature of the storage medium.

The capacity of a storage system is defined by the specific heat capacity and the mass of the medium used. Latent heat storage is accomplished by using phase change materials (PCMs) as storage media. There are organic (paraffins) and inorganic PCMs (salt hydrates) available for such storage systems. Latent heat is the energy exchanged during a phase change such as the melting of ice. It is also called "hidden" heat, because there is no change of temperature during energy transfer.

The best-known latent heat – or cold – storage method is the ice cooler, which uses ice in an insulated box or room to keep food cool during hot days. Currently most PCMs use the solid-liquid phase change, such as molten salts as a thermal storage medium for concentrated solar power (CSP) plants [iee08]. The advantage of latent heat storage is its capacity to store large amounts of energy in a small volume and with a minimal temperature change, which allows efficient heat transfer. Sorption (adsorption, absorption) storage systems work as thermo-chemical heat pumps under vacuum conditions and have a more complex design.

Heat from a high-temperature source heats up an adsorbent (e.g. silica gel or zeolite), and vapour (working fluid, e.g. water) is desorbed from this adsorbent and condensed in a condenser at low temperatures. The heat of condensation is withdrawn from the system. The dried adsorbent and the separated working fluid can be stored as long as desired. During the discharging process the working fluid takes up low-temperature heat in an evaporator. Subsequently, the vapour of the working fluid adsorbs on the adsorbent and heat of adsorption is released at high temperature.

Depending on the adsorbent/working fluid pair the temperature level of the released heat can be up to 200 °C [sch08] and the energy density is up to three times higher than that of sensible heat storage with water. However, sorption storage systems are more expensive due to their complexity. In the context of EES, it is mainly sensible/latent heat storage systems which are important. CSP plants primarily produce heat, and this can be stored easily before conversion to electricity and thus provide dispatchable electrical energy. State-of-the-art technology is a two-tank system for solar tower plants, with one single molten salt as heat transfer fluid and storage medium.

The molten salt is heated by solar radiation and then transported to the hot salt storage tank. To produce electricity the hot salt passes through a steam generator which powers a steam turbine. Subsequently, the cold salt (still molten) is stored in a second tank before it is pumped to the solar tower again. The main disadvantages are the risk of liquid salt freezing at low temperatures and the risk of salt decomposition at higher temperatures. In solar trough plants a dual-medium storage system.

with an intermediate oil/salt heat exchanger is preferred [tam06]. Typical salt mixtures such as Na-K-NO3 have freezing temperatures > 200 °C, and storage materials and containment require a higher volume than storage systems for solar tower plants. The two-tank indirect system is being deployed in "Andasol 1-3", three 50 MW parabolic trough plants in southern Spain, and is planned for Abengoa Solar's 280 MW Solana plant in Arizona. Apart from sensible heat storage systems for CSP, latent heat storage is under development by a German-Spanish consortium – including DLR and Endesa – at Endesa's Litoral Power Plant in Carboneras, Spain.

The storage system at the pilot facility is based on sodium nitrate, has a capacity of 700 kWh and works at a temperature of 305 °C [csp11]. In adiabatic CAES the heat released during compression of the air may be stored in large solid or liquid sensible heat storage systems. Various R&D projects are exploring this technology [rwe11] [bul04], but so far there are no adiabatic CAES plants in operation. As solid materials concrete, cast iron or even a rock bed can be employed. For liquid systems different concepts with a combination of nitrate salts and oil are in discussion.

The round-trip efficiency is expected to be over 70 % [rad08]. Of particular relevance is whether a pressurized tank is needed for the thermal storage, or if a non-pressurized compartment can be used. In liquid systems, a heat exchanger can be used to avoid the need for a large pressurized tank for the liquid, but the heat exchanger means additional costs and increases the complexity. A dual-media approach (salt and oil) must be used to cover the temperature range from 50 °C to 650 °C. Direct contact between the pressurized air and the storage medium in a solid thermal storage system has the advantage of a high surface area for heat transfer. The storage material is generally cheap, but the pressurized container costs are greater.

2.7 Standards for EES

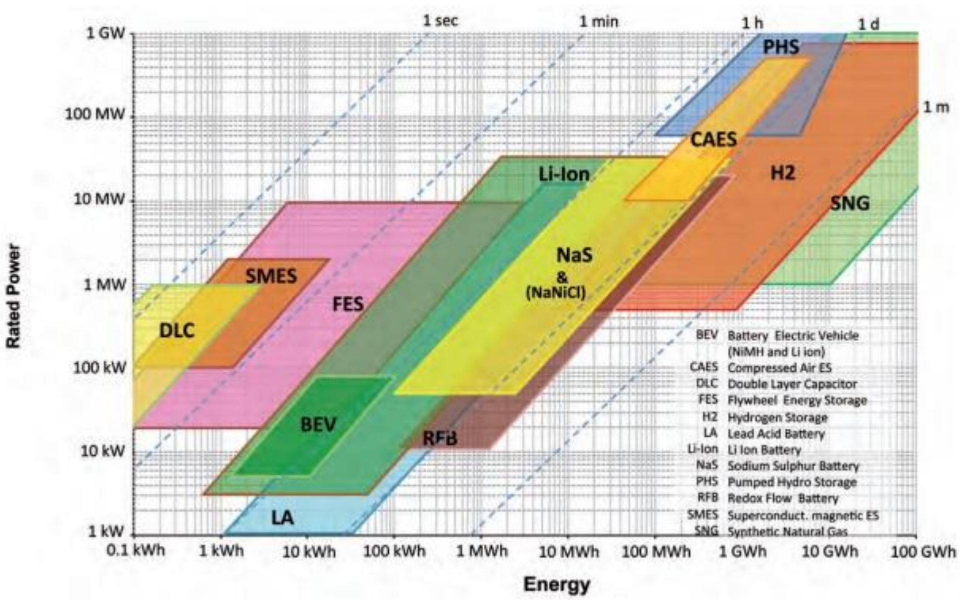
For mature EES systems such as PHS, LA, NiCd, NiMH and Li-ion various IEC standards exist. The standards cover technical features, testing and system integration. For the other technologies there are only a few standards, covering special topics. Up to now no general, technology-independent standard for EES integration into a utility or a stand-alone grid has been developed.

A standard is planned for rechargeable batteries of any chemistry. Standardization topics for EES include:

- terminology
- basic characteristics of EES components and systems, especially definitions and measuring methods for comparison and technical evaluation - capacity, power, discharge time, lifetime, standard EES unit sizes
- communication between components - protocols, security
- interconnection requirements - power quality, voltage tolerances, frequency, synchronization, metering
- safety: electrical, mechanical, etc.
- testing
- guides for implementation.

2.8 Technical comparison of EES technologies

The previous sections have shown that a wide range of different technologies exists to store electrical energy. Different applications with different requirements demand different features from EES. Hence a comprehensive comparison and assessment of all storage technologies is rather ambitious, but in Figure 2-9 a general overview of EES is given. In this doublelogarithmic chart the rated power (W) is plotted against the energy content (Wh) of EES systems. The nominal discharge time at rated power can also be seen, covering a range from seconds to months. Figure 2-9 comprises not only the application areas of today's EES systems but also the predicted range in future applications. Not all EES systems are commercially available in the ranges shown at present, but all are expected to become important. Most of the technologies could be implemented with even larger power output and energy capacity, as all systems have a modular design, or could at least be doubled (apart from PHS and some restrictions for underground storage of H2 , SNG and CAES). If a larger power range or higher energy capacity is not realized, it will be mainly for economic reasons (cost per kW and cost per kWh, respectively).



Comparison of rated power, energy content and discharge time of different EES technologies

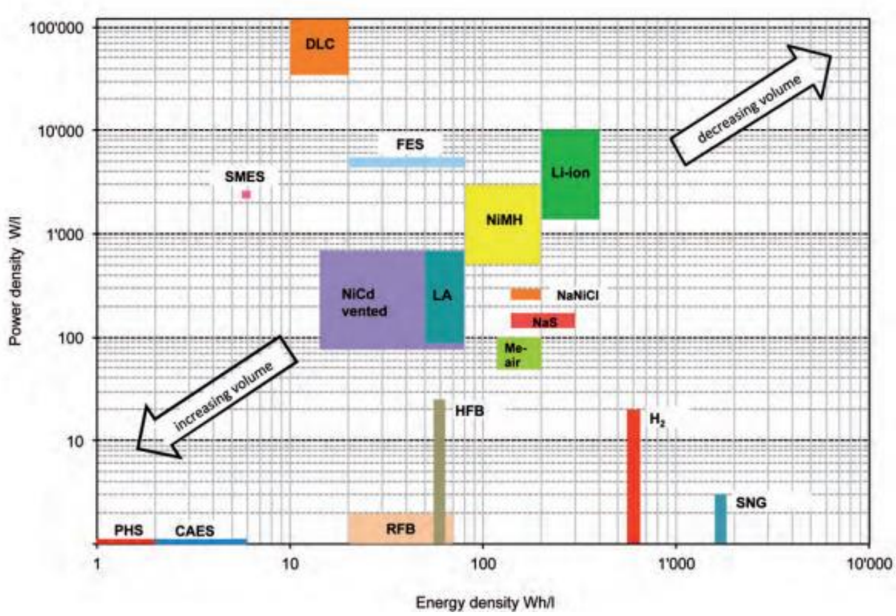
On the basis of Figure 2-9 EES technologies can be categorized as being suitable for applications with:

• Short discharge time (seconds to minutes): double-layer capacitors (DLC), superconducting magnetic energy storage (SMES) and flywheels (FES). The energy-topower ratio is less than 1 (e.g. a capacity of less than 1 kWh for a system with a power of 1 kW).

• Medium discharge time (minutes to hours): flywheel energy storage (FES) and – for larger capacities – electrochemical EES, which is the dominant technology: lead-acid (LA), Lithium ion (Li-ion) and sodium sulphur (NaS) batteries. The technical features of the different electrochemical techniques are relatively similar. They have advantages in the kW - MW and kWh - MWh range when compared to other technologies. Typical discharge times are up to several hours, with an energy-to-power ratio of between 1 and 10 (e.g. between 1 kWh and 10 kWh for a 1 kW system). Batteries can be tailored to the needs of an application: tradeoffs may be made for high energy or high power density, fast charging behaviour or long life, etc.

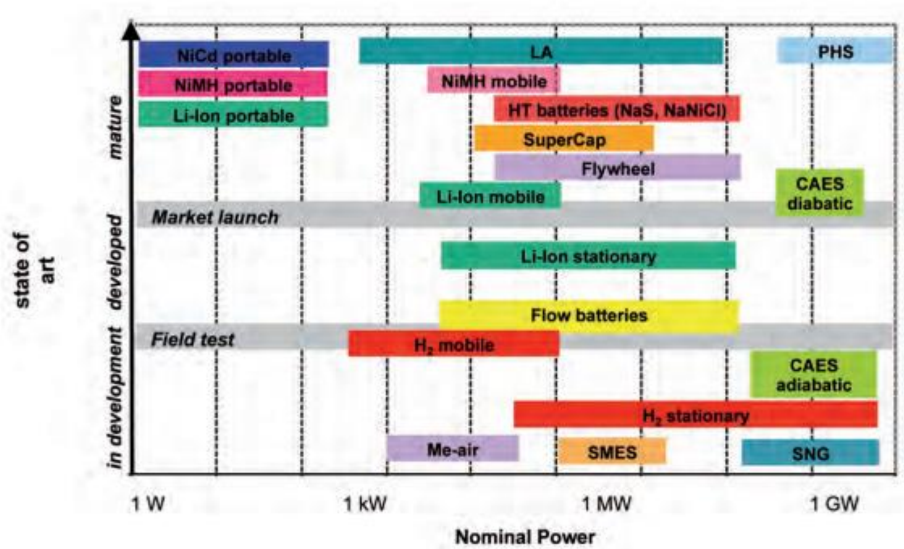
• Long discharge time (days to months): hydrogen (H2) and synthetic natural gas (SNG). For these EES systems the energyto-power ratio is considerably greater than 10. Pumped hydro storage (PHS), compressed air energy storage (CAES) and redox flow batteries are situated between storage systems for medium and long discharge times. Like H2 and SNG systems, these EES technologies have external storage tanks. But the energy densities are rather low, which limits the energy-to-power ratio to values between approximately 5 and 30.

In Figure 2-10 the power density (per unit volume, not weight) of different EES technologies is plotted versus the energy density. The higher the power and energy density, the lower the required volume for the storage system. Highly compact EES technologies suitable for mobile applications can be found at the top right. Large area and volume-consuming storage systems are located at the bottom left. Here it is again clear that PHS, CAES and flow batteries have a low energy density compared to other storage technologies. SMES, DLC and FES have high power densities but low energy densities. Li-ion has both a high energy density and high power density, which explains the broad range of applications where Li-ion is currently deployed. NaS and NaNiCl have higher energy densities in comparison to the mature battery types such as LA and NiCd, but their power density is lower in comparison to NiMH and Li-ion. Metal air cells have the highest potential in terms of energy density. Flow batteries have a high potential for larger battery systems (MW/MWh) but have only moderate energy densities. The main advantage of H2 and SNG is the high energy density, superior to all other storage systems.



Comparison of power density and energy density (in relation to volume) of EES technologies

Figure 2-11 summarizes the maturity of the storage technologies discussed. The state of the art for each EES technology is plotted versus the power range. Thus the suitability for different applications of the available technologies covered can be compared. Clearly PHS, CAES, H2 and SNG are the only storage technologies available for high power ranges and energy capacities, although energy density is rather low for PHS and CAES. Large power ranges are feasible as these EES systems use the turbines and compressors familiar from other power generation plants. However, only PHS is mature and available. Restrictions in locations (topography) and land consumption are a more severe limit for this technology than the characteristic of low energy density (although the two may be linked in some cases). Figure 2-11 shows a lack of immediately deployable storage systems in the range from 10 MW to some hundreds of MW. Diabatic CAES is well-developed but adiabatic CAES is yet to be demonstrated. Single components of H2 and SNG storage systems are available and in some cases have been used in industrial applications for decades. However, such storage systems become viable and economically reasonable only if the grids have to carry and distribute large amounts of volatile electricity from REs. The first demonstration and pilot plants are currently under construction (e.g. in Europe).



Maturity and state of the art of storage systems for electrical energy

From the technical comparison it can be concluded that a single universal storage technology superior to all other storage systems does not exist. Today and in the future different types of EES will be necessary to suit all the applications described in section 1. Bearing in mind the findings from Figures 2-9 and 2-10, Figure 2-11 suggests the following conclusions. 1) EES systems for short and medium discharge times cover wide ranges of rated power and energy density. Several mature EES technologies, in particular FES, DLC and battery systems, can be used in these ranges. 2) PHS is the only currently feasible largecapacity EES for medium discharge times; further development in CAES is expected. Suitable locations for large PHS and CAES systems are topographically limited. An increase in the capacity of other EES systems, and control and integration of dispersed EES systems (see section 3.3), will be required for medium-duration use. 3) For long discharge times, days to months, and huge capacities (GWh - TWh), no EES technologies have so far been put into practical operation. New EES technologies such as H2 and SNG have to be developed.

UNIT – V

DESIGN AND APPLICATIONS OF ELECTRICAL ENERGY STORAGE

Renewable energy storage-Battery sizing and stand-alone applications, stationary (Power Grid application), Small scale application-Portable storage systems and medical devices, Mobile storage Applications- Electric vehicles (EVs), types of EVs, batteries and fuel cells, future technologies, hybrid systems for energy storage.

System Description
2.1. Components

Solar PV system includes different components that should be selected according to your system type, site location and applications. A Balance-of- System that wired together to form the entire fully functional system capable of supplying electric power and these components are:

1- PV module: It is made from semiconductor and convert sunlight to electricity. The PV converts sunlight into DC electricity. The most common PV modules include single and polycrystalline silicon and amorphous silicon with other technologies entering the market.

2- Battery – stores energy for supplying to electrical appliances when there is a demand. Battery bank, which is involved in the system to make the energy available at night or at days of autonomy (sometimes called no-sun-days or dark days), when the sun is not providing enough radiation. These batteries, usually lead-acid, are designed to gradually discharge and recharge 80% of their capacity hundreds of times. Automotive batteries are shallow cycle batteries and should not be used in PV systems because they are designed to discharge only about 20% of their capacity.

3- Solar charge controller – regulates the voltage and current coming from the PV panels going to battery and prevents battery overcharging and prolongs the battery life.

4- Inverter – converts DC output of PV panels or wind turbine into a clean AC current for AC appliances or fed back into grid line. It is one of the solar energy system's main elements, as the solar panels generate dc dc voltage. Inverters are different by the output wave format, output power and installation type. It is also called power conditioner because it changes the form of the electric power. The efficiency of all inverters reaches their nominal efficiency (around 90 percent) when the load demand is greater than about 50 percent of rated load. 5- Load – is electrical appliances that connected to solar PV system such as lights, radio, TV, computer, refrigerator, etc.

5.2. Design Analysis

The photovoltaic systems are classified according to how the system components are connected to other power sources such as standalone (SA) and utility-interactive (UI) systems. In a stand-alone system depicted in Figure 1, the system is designed to operate independent of the electric utility grid, and is generally designed and sized to supply certain DC- and/or AC electrical loads.

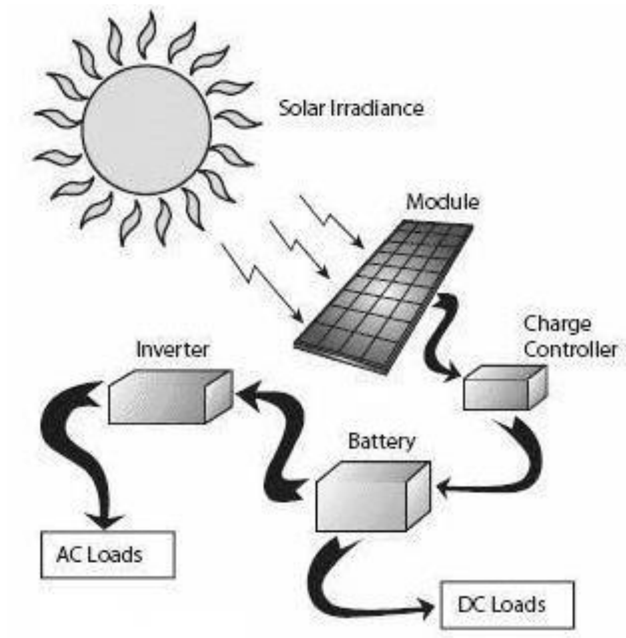


Fig. Stand-alone photovoltaic System

System sizing

System sizing is the process of evaluating the adequate voltage and current ratings for each component of the photovoltaic system to meet the electric demand at the facility and at the same time calculating the total price of the entire system from the design phase to the fully functional system including, shipment, and labor.

As a first step, the electrical devices available at the residence are itemized with their power ratings and time of operation during the day to obtain the average energy demand in Watt-hour per day as shown below in Table 1. The total average energy consumption is used to determine the equipment sizes and ratings starting with the solar array and ending with system wiring and cost estimate as explained below.

Sizing of the Solar Array

Before sizing the array, the total daily energy in Watt-hours (E), the average sun hour per day Tmin, and the DC-voltage of the system (VDC) must be determined. Once these factors are made available we move to the sizing process. To avoid under sizing, losses must be considered by dividing the total power demand in Wh.day-1 by the product of efficiencies of all components in the system to get the required energy Er. To avoid under sizing we begin by dividing the total average energy demand per day by the efficiencies of the system components to obtain the daily energy requirement from the solar array:

$$\mathrm{E_r} = \frac{\text{daily average energy consuption}}{\text{product of component's efficiencies}} = \frac{\mathrm{E}}{\eta_{\text{overall}}} \qquad \text{..... (1)}$$

To obtain the peak power, the previous result is divided by the average sun hours per day for the geographical location Tmin.

$$\mathrm{P_p} = \frac{\text{daily energy requirement}}{\text{minimum peak sun} - \text{hours per day}} = \frac{\mathrm{E_r}}{\mathrm{T_{min}}} \qquad \text{...... (2)}$$

The total current needed can be calculated by dividing the peak power by the DC- voltage of the system.

$$I_{DC} = \frac{Peak\ power}{System\ DC\ Voltage} = \frac{P_p}{V_{DC}} \qquad \text{.......(3)}$$

Modules must be connected in series and parallel according to the need to meet the desired voltage and current in accordance with:

First, the number of parallel modules which equals the whole modules current divided by the rated current of one module Ir.

$$N_p = \frac{\text{whole module current}}{\text{rated current of one module}} = \frac{I_{DC}}{I_r} \qquad \text{.....(4)}$$

Second, the number of series modules which equals the DC voltage of the system divided by the rated voltage of each module Vr.

$$N_s = \frac{system\ DC\ voltage}{module\ rated\ voltage} = \frac{V_{DC}}{V_r} \qquad \text{......(5)}$$

Finally, the total number of modules Nm equals the series modules multiplied by the parallel ones:

$$N_m = N_s * N_p \qquad \text{......(6)}$$

Battery Sizing Analysis

The amount of initial energy storage required equals the multiplication of the total power demand and the number of autonomy days for the PV solar battery storage autonomy.

$Einitial = Total\ Power\ Demand\ (WH)\ x\ Days\ of\ Autonomy$ ………(7)

Considering the safety of the system,

$Esafe = Initial\ Energy\ Storage\ Required\ Maximum\ Depth\ of\ Discharge = Einitial\ MDOD\%$ …..(8)

The battery bank's capacity (Cb) for battery sizing autonomy is estimated by dividing the safe energy storage required by the rated voltage (Vb) of one of the batteries selected.

$Cb = Esafe\ /Vb$ ……(9)

Based on the number obtained for the battery bank's capacity (Cb), the capacity of each battery of the battery bank is denoted by (Ce). The battery bank is composed of several batteries, and the total number of batteries is obtained by dividing the battery bank capacity (Cb) in ampere-hours by the capacity of one of the selected batteries (Ce) in ampere-hours.

$Nbattries = Cb\ /Ce$ …..(10)

The number of batteries in series is estimated by dividing the DC voltage of the system (VDC) by one of the selected batteries rated voltage (Vb).

$Ns = VDC\ /Vb$ ……..(11)

Then the number of parallel paths (Np) is approximated by dividing the total number of batteries by the number of batteries that are connected in series (Ns).

$Np = Nbattries/\ Ns$ ……(12)

Equation (12) above completes the PV solar battery sizing autonomy for residential home.

Once the sizing of the battery bank is made available, we proceed to the next system component.

Electric Vehicle (EVs)

Electric Vehicle (EV) Configurations Compared to HEV, the configuration of EV is flexible. The reasons for this flexibility are:

- The energy flow in EV is mainly via flexible electrical wires rather than bolted flanges or rigid shafts. Hence, distributed subsystems in the EV are really achievable.
- The EVs allow different propulsion arrangements such as independent four wheels and in wheel drives. In Figure 1 the general configuration of the EV is shown.

The EV has three major subsystems:

- Electric propulsion
- Energy source
- Auxiliary system

The electric propulsion subsystem comprises of:

- The electronic controller Power converter
- Electric Motor(EM)
- Mechanical transmission
- Driving wheels

The energy source subsystem consists of The energy source (battery, fuel cell, ultracapacitor)

- Energy management unit
- Energy refueling unit

The auxiliary subsystem consists of Power steering unit

- Temperature control unit
- Auxiliary power supply

Electric Vehicle Types (EVs)

Electric Vehicles In this section, we present a classification of the different types of electric vehicles, commenting on their main characteristics. We also discuss the current market situation, analyzing the sales data of this kind of vehicles and sales forecast in different countries in the world.

3.1. Electric VEHICLES Taxonomy Nowadays, we can encounter different types of EVs, according to their engines technology. In general, they are sorted in five types (See Figure 3): Smart Cities

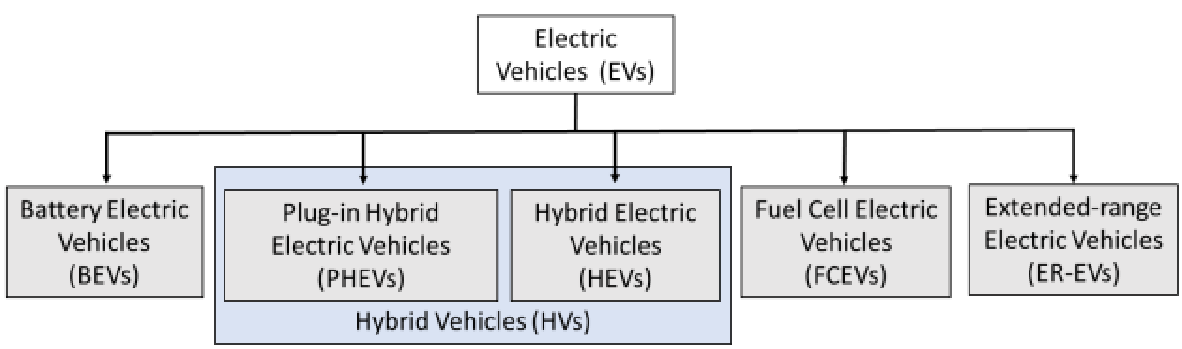
• Battery Electric Vehicles (BEVs): vehicles 100% are propelled by electric power. BEVs do not have an internal combustion engine and they do not use any kind of liquid fuel. BEVs normally use large packs of batteries in order to give the vehicle an acceptable autonomy. A typical BEV will reach from 160 to 250 km, although some of them can travel as far as 500 km with just one charge. An example of this type of vehicle is the Nissan Leaf [24], which is 100% electric and it currently provides a 62 kWh battery that allows users to have an autonomy of 360 km.

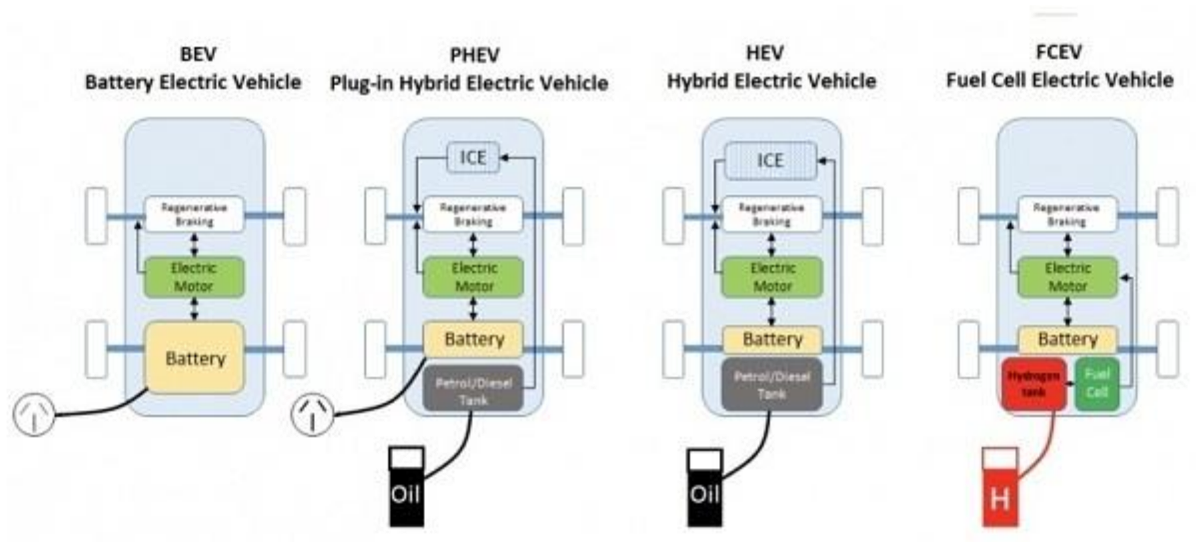
• Plug-In Hybrid Electric Vehicles (PHEVs): hybrid vehicles are propelled by a conventional combustible engine and an electric engine charged by a pluggable external electric source. PHEVs can store enough electricity from the grid to significantly reduce their fuel consumption in regular driving conditions. The Mitsubishi Outlander PHEV provides a 12 kWh battery, which allows it to drive around 50 km just with the electric engine. However, it is also noteworthy that PHEVs fuel consumption is higher than indicated by car manufacturers.

• Hybrid Electric Vehicles (HEVs): hybrid vehicles are propelled by a combination of a conventional internal combustion engine and an electric engine. The difference with regard to PHEVs is that HEVs cannot be plugged to the grid. In fact, the battery that provides energy to the electric engine is charged thanks to the power generated by the vehicle's combustion engine. In modern models, the batteries can also be charged thanks to the energy generated during braking, turning the kinetic energy into electric energy. The Toyota Prius, in its hybrid model (4th generation), provided a 1.3 kWh battery that theoretically allowed it an autonomy as far as 25 km in its all-electric mode.

• Fuel Cell Electric Vehicles (FCEVs): these vehicles are provided with an electric engine that uses a mix of compressed hydrogen and oxygen obtained from the air, having water as the only waste resulting from this process. Although these kinds of vehicles are considered to present "zero emissions", it is worth highlighting that, although there is green hydrogen, most of the used hydrogen is extracted from natural gas. The Hyundai Nexo FCEV [28] is an example of this type of vehicles, being able to travel 650 km without refueling.

• Extended-range EVs (ER-EVs): these vehicles are very similar to those ones in the BEV category. However, the ER-EVs are also provided with a supplementary combustion engine, which charges the batteries of the vehicle if needed. This type of engine, unlike those provided by PHEVs and HEVs, is only used for charging, so that it is not connected to the wheels of the vehicle. An example of this type of vehicles is the BMW i3 [29], which has a 42.2 kWh battery that results in a 260 km autonomy in electric mode, and users can benefit an additional 130 km from the extended-range mode.





An electric vehicle (EV) is a vehicle that uses one or more electric motors for propulsion. It can be powered by a collector system, with electricity from extravehicular sources, or it can be powered autonomously by a battery (sometimes charged by solar panels, or by converting fuel to electricity using fuel cells or a generator).EVs include, but are not limited to, road and rail vehicles, surface and underwater vessels, electric aircraft, and electric spacecraft. For road vehicles, together with other emerging automotive technologies such as autonomous driving, connected vehicles, and shared mobility, EVs form a future mobility vision called Connected, Autonomous, Shared, and Electric (CASE) Mobility.

EVs first came into existence in the late 19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. Internal combustion engines were the dominant propulsion method for cars and trucks for about 100 years, but electric power remained commonplace in other vehicle types, such as trains and smaller vehicles of all types.

Government incentives to increase adoption were first introduced in the late 2000s, including in the United States and the European Union, leading to a growing market for vehicles in the 2010s. Increasing public interest and awareness and structural incentives, such as those being built into the green recovery from the COVID-19 pandemic, are expected to greatly increase the electric vehicle market. During the COVID-19 pandemic, lockdowns reduced the number of greenhouse gases in gasoline or diesel vehicles. The International Energy Agency has stated that governments should do more to meet climate goals, including policies for heavy electric vehicles. A total of 14% of all new cars sold were electric in 2022, up from 9% in 2021 and less than 5% in 2020.[8] Electric vehicle sales may increase from 1% of the global share in 2016 to more than 35% by 2030. As of July 2022 the global EV market size was $280 billion and was expected to grow to $1 trillion by 2026. Much of this growth is expected in markets like North America, Europe, and China; a 2020 literature review suggested that growth in the use of electric 4-wheeled vehicles appears economically unlikely in developing economies, but that electric 2-wheeler growth is likely. There are more 2 and 3 wheel EVs than any other type.

Electricity sources

There are many ways to generate electricity, of varying costs, efficiency and ecological desirability.

A passenger train, taking power through a third rail with return through the traction rails

An electric locomotive at Brig, Switzerland

The MAZ-7907 uses an on-board generator to power in-wheel electric motors.

Connection to generator plants

Direct connection to generation plants as is common among electric trains, trams, trolleybuses, and trolleytrucks (See also: overhead lines, third rail and conduit current collection)

Online electric vehicle collects power from electric power strips buried under the road surface through electromagnetic induction

Onboard generators and hybrid EVs

Diesel–electric transmission, Petrol–electric transmission, and Hybrid vehicle

Generated on-board using a diesel engine: diesel–electric locomotive and diesel–electric multiple unit (DEMU)

Generated on-board using a fuel cell: fuel cell vehicle

Generated on-board using nuclear energy: nuclear submarines and aircraft carriers

Renewable sources such as solar power: solar vehicle

It is also possible to have hybrid EVs that derive electricity from multiple sources, such as:

On-board rechargeable electricity storage system (RESS) and a direct continuous connection to land-based generation plants for purposes of on-highway recharging with unrestricted highway range[37]

On-board rechargeable electricity storage system and a fueled propulsion power source (internal combustion engine): plug-in hybrid

For especially large EVs, such as submarines, the chemical energy of the diesel–electric can be replaced by a nuclear reactor. The nuclear reactor usually provides heat, which drives a steam turbine, which drives a generator, which is then fed to the propulsion. See Nuclear marine propulsion.

A few experimental vehicles, such as some cars and a handful of aircraft use solar panels for electricity.

Onboard storage

Fuel use in vehicle designs

Vehicle type	Fuel used
All-petroleum vehicle (aka all-combustion vehicle)	Most use of petroleum or other fuel.
Regular hybrid electric vehicle	Less use of petroleum or other fuel, but unable to be plugged in.
Plug-in hybrid vehicle	Less use of petroleum or other fuel, residual use of electricity.
All-electric vehicle (BEV, AEV)	Exclusively uses electricity.

These systems are powered from an external generator plant (nearly always when stationary), and then disconnected before motion occurs, and the electricity is stored in the vehicle until needed.

Full Electric Vehicles (FEV).Power storage methods include:

Chemical energy stored on the vehicle in on-board batteries: Battery electric vehicle (BEV) typically with a lithium-ion battery

Kinetic energy storage: flywheels

Static energy stored on the vehicle in on-board electric double-layer capacitors

Batteries, electric double-layer capacitors and flywheel energy storage are forms of rechargeable on-board electricity storage systems. By avoiding an intermediate mechanical step, the energy conversion efficiency can be improved compared to hybrids by avoiding unnecessary energy conversions. Furthermore, electro-chemical batteries conversions are reversible, allowing electrical energy to be stored in chemical form.[39]

Lithium-ion battery[edit]

Namsan E-Bus, the first commercially used battery electric bus system which is powered with lithium-ion batteries[40]

Electric vehicle battery

Most electric vehicles use lithium-ion batteries (Li-Ions or LIBs). Lithium-ion batteries have a higher energy density, longer life span , and higher power density than most other practical batteries. Complicating factors include safety, durability, thermal breakdown, environmental impact , and cost. Li-ion batteries should be used within safe temperature and voltage ranges to operate safely and efficiently.

Increasing the battery's lifespan decreases effective costs. One technique is to operate a subset of the battery cells at a time and switching these subsets.

In the past, nickel–metal hydride batteries were used in some electric cars, such as those made by General Motors. These battery types are considered outdated due to their tendencies to self-discharge in the heat. Furthermore, a patent for this type of battery was held by Chevron, which created a problem for their widespread development.[45] These factors, coupled with their high cost, has led to lithium-ion batteries leading as the predominant battery for EVs.

The prices of lithium-ion batteries have declined dramatically over the past decade, contributing to a reduction in price for electric vehicles, but an increase in the price of critical minerals such as lithium from 2021 to the end of 2022 has put pressure on historical battery price decreases.[8][47]

Electric motor[edit]

Electric truck e-Force One

Vehicle types

Neighborhood Electric Vehicle, Squad Solar NEV, with solar panel roof

It is generally possible to equip any kind of vehicle with an electric power-train.

Ground vehicles

Pure-electric vehicles

Electric car and Battery electric vehicle

A pure-electric vehicle or all-electric vehicle is powered exclusively through electric motors. The electricity may come from a battery (battery electric vehicle), solar panel (solar vehicle) or fuel cell (fuel cell vehicle).

Hybrid EVs

This section is an excerpt from Hybrid electric vehicle. A hybrid electric vehicle (HEV) is a type of hybrid vehicle that combines a conventional internal combustion engine (ICE) system with an electric propulsion system (hybrid vehicle drive train). The presence of the electric power train is intended to achieve either better fuel economy than a conventional vehicle or better performance. There is a variety of HEV types and the degree to which each function as an electric vehicle (EV) also varies. The most common form of HEV is the hybrid electric car, although hybrid electric trucks (pickups and tractors), buses, boats and aircraft also exist.

Modern HEVs make use of efficiency-improving technologies such as regenerative brakes which convert the vehicle's kinetic energy to electric energy, which is stored in a battery or super capacitor. Some varieties of HEV use an internal combustion engine to turn an electrical generator, which either recharges the vehicle's batteries or directly powers its electric drive motors; this combination is known as a motor–generator.[50] Many HEVs reduce idle emissions by shutting down the engine at idle and restarting it when needed; this is known as a start-stop system. A hybrid-electric produces lower tailpipe emissions than a comparably sized gasoline car since the hybrid's gasoline engine is usually smaller than that of a gasoline-powered vehicle. If the engine is not used to drive the car directly, it can be geared to run at maximum efficiency, further improving fuel economy.

There are different ways that a hybrid electric vehicle can combine the power from an electric motor and the internal combustion engine. The most common type is a parallel hybrid that connects the engine and the electric motor to the wheels through mechanical coupling. In this scenario, the electric motor and the engine can drive the wheels directly. Series hybrids only use the electric motor to drive the wheels and can often be referred to as extended-range electric vehicles (EREVs) or range-extended electric vehicles (REEVs). There are also series-parallel hybrids where the vehicle can be powered by the engine working alone, the electric motor on its own, or by both working together; this is designed so that the engine can run at its optimum range as often as possible.[51]

Togg C-SUV[52] produced by Togg,[53] a Turkish automotive company established in 2018 for producing EVs.[54][55][52]

A plug-in electric vehicle (PEV) is any motor vehicle that can be recharged from any external source of electricity, such as wall sockets, and the electricity stored in the Rechargeable battery packs drives or contributes to drive the wheels. PEV is a subcategory of electric vehicles that includes battery electric vehicles (BEVs), plug-in hybrid vehicles, (PHEVs), and electric vehicle conversions of hybrid electric vehicles and conventional internal combustion engine vehicles.[56][57][58]

Range-extended electric vehicle

Range extender

A range-extended electric vehicle (REEV) is a vehicle powered by an electric motor and a plug-in battery. An auxiliary combustion engine is used only to supplement battery charging and not as the primary source of power.[59]

On- and off-road EVs

On-road electric vehicles include electric cars, electric trolleybuses, electric buses, battery electric buses, electric trucks, electric bicycles, electric motorcycles and scooters, personal transporters, neighborhood electric vehicles, golf carts, milk floats, and forklifts. Off-road vehicles include electrified all-terrain vehicles and tractors.

Rail borne EVs

Railway electrification system

A streetcar (or tram) in Hanover drawing current from a single overhead wire through a pantograph

The fixed nature of a rail line makes it relatively easy to power EVs through permanent overhead lines or electrified third rails, eliminating the need for heavy onboard batteries. Electric locomotives, electric multiple units, electric trams (also called streetcars or trolleys), electric light rail systems, and electric rapid transit are all in common use today, especially in Europe and Asia.

Since electric trains do not need to carry a heavy internal combustion engine or large batteries, they can have very good power-to-weight ratios. This allows high speed trains such as France's double-deck TGVs to operate at speeds of 320 km/h (200 mph) or higher, and electric locomotives to have a much higher power output than diesel locomotives. In addition, they have higher short-term surge power for fast acceleration, and using regenerative brakes can put braking power back into the electrical grid rather than wasting it.

Maglev trains are also nearly always EVs.

There are also battery electric passenger trains operating on non-electrified rail lines.

Seaborne EVs

Submarine § Propulsion, Ship § Propulsion systems, and electric boat

Oceanvolt SD8.6 electric saildrive motor

Electric boats were popular around the turn of the 20th century. Interest in quiet and potentially renewable marine transportation has steadily increased since the late 20th century, as solar cells have given motorboats the infinite range of sailboats. Electric motors can and have also been used in sailboats instead of traditional diesel engines.[61] Electric ferries operate routinely.[62] Submarines use batteries (charged by diesel or gasoline engines at the surface), nuclear power, fuel cells[63] or Stirling engines to run electric motor-driven propellers.

Airborne EVs[edit]

Mars helicopter Ingenuity

Electric aircraft

Since the beginnings of aviation, electric power for aircraft has received a great deal of experimentation. Currently, flying electric aircraft include manned and unmanned aerial vehicles.

Electrically powered spacecraft

Electrically powered spacecraft propulsion

Electric power has a long history of use in spacecraft.[64][65] The power sources used for spacecraft are batteries, solar panels and nuclear power. Current methods of propelling a spacecraft with electricity include the arcjet rocket, the electrostatic ion thruster, the Hall-effect thruster, and Field Emission Electric Propulsion.

Space rover vehicles[edit]

Main article: Rover (space exploration)

Crewed and uncrewed vehicles have been used to explore the Moon and other planets in the Solar System. On the last three missions of the Apollo program in 1971 and 1972, astronauts drove silver-oxide battery-powered Lunar Roving Vehicles distances up to 35.7 kilometers (22.2 mi) on the lunar surface.[66] Uncrewed, solar-powered rovers have explored the Moon and Mars.[67][68]

Energy and motors[edit]

An electric powertrain used by Power Vehicle Innovation for trucks or buses[69]

Most large electric transport systems are powered by stationary sources of electricity that are directly connected to the vehicles through wires. Electric traction allows the use of regenerative braking, in which the motors are used as brakes and become generators that transform the motion of, usually, a train into electrical power that is then fed back into the lines. This system is particularly advantageous in mountainous operations, as descending vehicles can produce a large portion of the power required for those ascending. This regenerative system is only viable if the system is large enough to utilise the power generated by descending vehicles.

In the systems above, motion is provided by a rotary electric motor. However, it is possible to "unroll" the motor to drive directly against a special matched track. These linear motors are used in maglev trains which float above the rails supported by magnetic levitation. This allows for almost no rolling resistance of the vehicle and no mechanical wear and tear of the train or track. In addition to the high-performance control systems needed, switching and curving of the tracks becomes difficult with linear motors, which to date has restricted their operations to high-speed point to point services.

Records[edit]

World record on a electric motorcycle by Michel von Tell on a LiveWire in 2020

Rimac Nevera, an electric hypercar, sets 23 world speed records in one day.[70][71]

Fastest acceleration of an electric car, 0 to 100 km/h in 1.461 seconds by university students at the University of Stuttgart.[72]

Electric Land Speed Record 353 mph (568 km/h).[73]

Electric Car Distance Record 1,725 miles (2,776 km) in 24 hours by Bjørn Nyland.[74]

Greatest distance by electric vehicle, single charge 999.5 miles (1,608.5 km).[75]

Solar-powered EV is fastest EV to go over 1,000 km without stopping to recharge, the Sunswift 7.[76]

Electric Motorcycle: 1,070 miles (1,720 km) under 24 hours. Michel von Tell on a Harley LiveWire.[77]

Electric flight: 439.5 miles (707.3 km) without charge.[78]

Properties

Components

The type of battery, the type of traction motor and the motor controller design vary according to the size, power and proposed application, which can be as small as a motorized shopping cart or wheelchair, through pedelecs, electric motorcycles and scooters, neighborhood electric vehicles, industrial fork-lift trucks and including many hybrid vehicles.

Energy sources

EVs are much more efficient than fossil fuel vehicles and have few direct emissions. At the same time, they do rely on electrical energy that is generally provided by a combination of non-fossil fuel plants and fossil fuel plants. Consequently, EVs can be made less polluting overall by modifying the source of electricity. In some areas, persons can ask utilities to provide their electricity from renewable energy.

Fossil fuel vehicle efficiency and pollution standards take years to filter through a nation's fleet of vehicles. New efficiency and pollution standards rely on the purchase of new vehicles, often as the current vehicles already on the road reach their end-of-life. Only a few nations set a retirement age for old vehicles, such as Japan or Singapore, forcing periodic upgrading of all vehicles already on the road.

Batteries

Electric vehicle battery

Lithium ion battery for motorbikes or powersport vehicles

An electric-vehicle battery (EVB) in addition to the traction battery speciality systems used for industrial (or recreational) vehicles, are batteries used to power the propulsion system of a battery electric vehicle (BEVs). These batteries are usually a secondary (rechargeable) battery, and are typically lithium-ion batteries.

Traction batteries, specifically designed with a high ampere-hour capacity, are used in forklifts, electric golf carts, riding floor scrubbers, electric motorcycles, electric cars, trucks, vans, and other electric vehicles.[79][80]

Efficiency[

EVs convert over 59–62% of grid energy to the wheels. Conventional gasoline vehicles convert around 17–21%.[81]

Charging

Grid capacity

If almost all road vehicles were electric it would increase global demand for electricity by up to 25% by 2050 compared to 2020.[82] However, overall energy consumption and emissions would diminish because of the higher efficiency of EVs over the entire cycle, and the reduction in energy needed to refine fossil fuels.

Charging stations

This section is an excerpt from Charging station.[edit]

Charging stations for electric vehicles:

Top-left: a Tesla Roadster (2008) being charged at an electric charging station in Iwata city, Japan.

Top-right: Brammo Empulse electric motorcycle at an AeroVironment charging station and Pay as you go electric vehicle charging point.

Bottom-left: Nissan Leaf recharging from a NRG Energy eVgo station in Houston, Texas.

Bottom-right: converted Toyota Priuses recharging at public charging stations in San Francisco (2009).

A charging station, also known as a charge point or electric vehicle supply equipment (EVSE), is a power supply device that supplies electrical power for recharging plug-in electric vehicles (including battery electric vehicles, electric trucks, electric buses, neighborhood electric vehicles and plug-in hybrid vehicles).

There are two main types: AC charging stations and DC charging stations. Electric vehicle batteries can only be charged by direct current (DC) electricity, while most mains electricity is delivered from the power grid as alternating current (AC). For this reason, most electric vehicles have a built-in AC-to-DC converter commonly known as the "onboard charger". At an AC charging station, AC power from the grid is supplied to this onboard charger, which converts it into DC power to then recharge the battery. DC chargers facilitate higher power charging (which requires much larger AC-to-DC converters) by building the converter into the charging station instead of the vehicle to avoid size and weight restrictions. The station then supplies DC power to the vehicle directly, bypassing the onboard converter. Most modern electric car models can accept both AC and DC power.

Charging stations provide connectors that conform to a variety of international standards. DC charging stations are commonly equipped with multiple connectors to be able to charge a wide variety of vehicles that utilize competing standards.

Public charging stations are typically found street-side or at retail shopping centers, government facilities, and other parking areas. Private charging stations are typically found at residences, workplaces, and hotels.

Battery swapping

Instead of recharging EVs from electric sockets, batteries could be mechanically replaced at special stations in a few minutes (battery swapping).

Batteries with greater energy density such as metal-air fuel cells cannot always be recharged in a purely electric way, so some form of mechanical recharge may be used instead. A zinc–air battery, technically a fuel cell, is difficult to recharge electrically so may be "refueled" by periodically replacing the anode or electrolyte instead.[83]

Mechanical

Tesla Model S chassis with drive motor

Cutaway view of a Tesla Model S drive motor

Electric motors are mechanically very simple and often achieve 90% energy conversion efficiency[111] over the full range of speeds and power output and can be precisely controlled. They can also be combined with regenerative braking systems that have the ability to convert movement energy back into stored electricity. This can be used to reduce the wear on brake systems (and consequent brake pad dust) and reduce the total energy requirement of a trip. Regenerative braking is especially effective for start-and-stop city use.

They can be finely controlled and provide high torque from stationary-to-moving, unlike internal combustion engines, and do not need multiple gears to match power curves. This removes the need for gearboxes and torque converters.

EVs provide quiet and smooth operation and consequently have less noise and vibration than internal combustion engines.[112] While this is a desirable attribute, it has also evoked concern that the absence of the usual sounds of an approaching vehicle poses a danger to blind, elderly and very young pedestrians. To mitigate this situation, many countries mandate warning sounds when EVs are moving slowly, up to a speed when normal motion and rotation (road, suspension, electric motor, etc.) noises become audible.[113]

Electric motors do not require oxygen, unlike internal combustion engines; this is useful for submarines and for space rovers.

Energy resilience

Electricity can be produced from a variety of sources; therefore, it gives the greatest degree of energy resilience.[114]

Energy efficiency

EV 'tank-to-wheels' efficiency is about a factor of three higher than internal combustion engine vehicles.[112] Energy is not consumed while the vehicle is stationary, unlike internal combustion engines which consume fuel while idling. However, looking at the well-to-wheel efficiency of EVs, their total emissions, while still lower,[clarification needed] are closer[clarification needed] to an efficient gasoline or diesel in most countries where electricity generation relies on fossil fuels.[115][116]

In 2022, EVs enabled a net reduction of about 80 Mt of GHG emissions, on a well to-wheels basis, and the net GHG benefit of EVs will increase over time as the electricity sector is decarbonised.[93]

Well-to-wheel efficiency of an EV has less to do with the vehicle itself and more to do with the method of electricity production. A particular EV would instantly become twice as efficient if electricity production were switched from fossil fuels to renewable energy, such as wind power, tidal power, solar power, and nuclear power. Thus, when "well-to-wheels" is cited, the discussion is no longer about the vehicle, but rather about the entire energy supply infrastructure – in the case of fossil fuels this should also include energy spent on exploration, mining, refining, and distribution.

The lifecycle analysis of EVs shows that even when powered by the most carbon-intensive electricity in Europe, they emit less greenhouse gases than a conventional diesel vehicle.[117]

Total cost

As of 2021 the purchase price of an EV is often more, but the total cost of ownership of an EV varies wildly depending on location[118] and distance travelled per year:[119] in parts of the world where fossil fuels are subsidized, lifecycle costs of diesel or gas-powered vehicle are sometimes less than a comparable EV.[120]

European carmakers face significant pressure from more affordable Chinese models and price cuts by US-based Tesla Motor. From 2021 to 2022, the European market share of Chinese EV manufacturers doubled to almost 9%, prompting the CEO of Stellantis to describe it as an "invasion".[121]

Range

Electric vehicles may have shorter range compared to vehicles with internal combustion engines,[122][123] which is why the electrification of long-distance transport, such as long-distance shipping, remains challenging.

In 2022, the sales-weighted average range of small BEVs sold in the United States was nearly 350 km, while in France, Germany and the United Kingdom it was just under 300 km, compared to under 220km in China.[93]

Heating of EVs

In cold climates, considerable energy is needed to heat the interior of a vehicle and to defrost the windows. With internal combustion engines, this heat already exists as waste combustion heat diverted from the engine cooling circuit. This process offsets the greenhouse gases' external costs. If this is done with battery EVs, the interior heating requires extra energy from the vehicles' batteries. Although some heat could be harvested from the motor or motors and battery, their greater efficiency means there is not as much waste heat available as from a combustion engine. However, for vehicles which are connected to the grid, battery EVs can be preheated, or cooled, with little or no need for battery energy, especially for short trips.

Newer designs are focused on using super-insulated cabins which can heat the vehicle using the body heat of the passengers. This is not enough, however, in colder climates as a driver delivers only about 100 W of heating power. A heat pump system, capable of cooling the cabin during summer and heating it during winter, is a more efficient way of heating and cooling EVs.[124]

Electric public transit efficiency[edit]

One of the few trolleybuses in Europe, this trolleybus uses two overhead wires to provide electric current supply and return to the power source, 2005

Shifts from private to public transport (train, trolleybus, personal rapid transit or tram) have the potential for large gains in efficiency in terms of an individual's distance traveled per kWh.

Future

Rimac Concept One, electric supercar, since 2013. 0 to 100 km/h in 2.8 seconds, with a total output of 800 kW (1,073 hp).

Public perception

A European survey based on climate found that as of 2022, 39% of European citizens tend to prefer hybrid vehicles, 33% prefer petrol or diesel vehicles, followed by electric cars which were preferred by 28% of Europeans.[132] 44% Chinese car buyers are the most likely to buy an electric car, while 38% of Americans would opt for a hybrid car, 33% would prefer petrol or diesel, while only 29% would go for an electric car.[132]

Environmental considerations

By reducing air pollution, such as nitrogen dioxide, EVs could prevent hundreds of thousands of early deaths every year,[133][134] especially from trucks and old cars in cities.[135]

Many vehicle battery chemistries rely heavily on the mining of rare earth metals such as cobalt, nickel, and copper.[136][137][dubious – discuss] In 2023 the US State Department said that the supply of lithium would need to increase 42-fold by 2050 globally to support a transition to clean energy.[138] Rare-earth metals (neodymium, dysprosium) and other mined metals (copper, nickel, iron) are used by EV motors, while lithium, cobalt, manganese are used by the batteries.[139][137] The full environmental impact of electric vehicles includes the life cycle impacts of carbon and sulfur emissions, as well as toxic metals entering the environment. Most of the lithium ion battery production occurs in China, where the bulk of energy used is supplied by coal burning power plants. A study of hundreds of cars on sale in 2021 concluded that the life cycle GHG emissions of full electric cars are slightly less than hybrids and that both are less than gasoline and diesel fuelled cars.[140]

An alternative method of sourcing essential battery materials being deliberated by the International Seabed Authority is deep sea mining, however carmakers are not using this as of 2023.[141]

Improved batteries

Advances in lithium-ion batteries, driven at first by the personal-use electronics industry, allow full-sized, highway-capable EVs to travel nearly as far on a single charge as conventional cars go on a single tank of gasoline. Lithium batteries have been made safe, can be recharged in minutes instead of hours (see recharging time), and now last longer than the typical vehicle (see lifespan). The production cost of these lighter, higher-capacity lithium-ion batteries is gradually decreasing as the technology matures and production volumes increase.[142][143]

Many companies and researchers are also working on newer battery technologies, including solid state batteries[144] and alternate technologies.[145]