Energy Storage

Overview of energy storage technologies

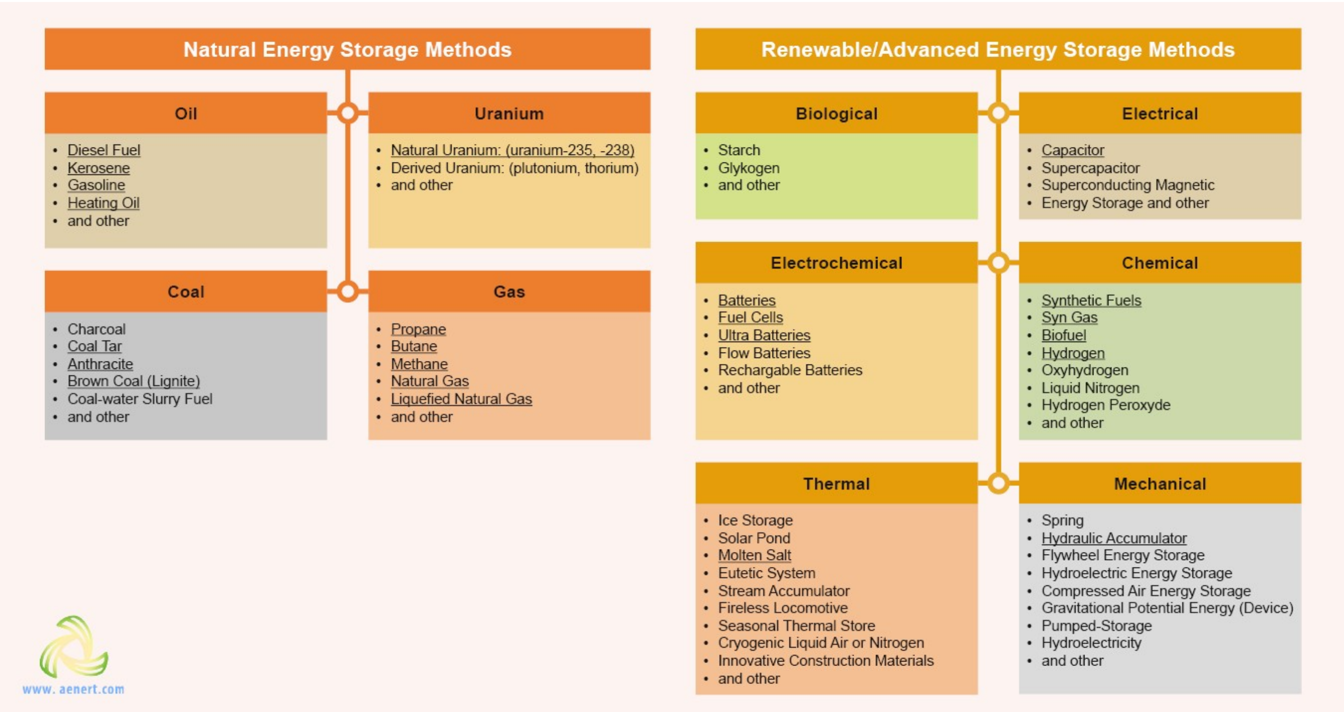
Basic definitions

The ability to store energy is one of the most important characteristics of any energy technology or energy resource. Fossil fuels, which, in addition to their physical and chemical properties that has led to their domination of the energy sector, have another tremendous advantage - the possibility of long-term storage. Thus, oil, gas or coal, either located in situ or extracted, can be delivered to the consumer exactly when as needed, including for the production of electricity. Moreover, despite the multiple cycles of energy conversion from one type to another, such a process is economically profitable and efficient. There are significant obstacles with other energy resources, especially renewable ones. Wind, solar, and marine resources, firstly, are intermittent, and direct storage of generated electricity on a large scale, as well as long-term storage at this stage of technological development is impossible. Technologies for the production of hydrogen via electrolysis and its storage are largely affected by economic constraints. Geothermal resources have a high degree of predictability for production and are capable of ensuring continuity of both electric and thermal energy, but are only available in certain regions. Bioenergy can deliver a variety of products to the energy market in the form of solid, liquid and gaseous fuels, as well as in the form of electric and thermal energy. Nevertheless, genuine competition between bioenergy and fossil fuels is still very far away. The only exception is hydropower, which, due to pumped storage, has huge potential with regard to energy storage, commensurate with the capabilities of fossil resources.

On the other hand, limited fossil fuel reserves and the environmental problems associated with its use have greatly stimulated the development of renewable energy and, accordingly, the intensive development of energy storage technologies. A list of the known methods of energy storage is presented in Fig. 1. Some of these technologies, unrelated to fossil fuels, are able to provide short-term storages, others long-term energy storage. Some renewable energy technologies are capable of delivering products similar in storage capacity to fossil fuels, for example, bioethanol, biodiesel, biogas, syngas, pellets, etc. Others allow for the storage of various external forms of energy through special devices, for example, capacitors, rotating flywheels or batteries. A further option involves converting the stored energy of intermediate substances used in renewable energy, such as water or molten salt, into energy that can be delivered to consumers.

Contemporary energy storage technologies utilize basic forms of energy: mechanical, thermal, chemical, nuclear, light, and electric. For example, the chemical energy of a battery is converted into electrical energy ; water

Figure 1. Basic energy storage methods.



Source: DOE Global Energy Storage Database[1], IRENA[2], Wikipedia[3], World Energy Council[4] in hydroelectric pumped storage can be converted into mechanical energy by rotating a turbine, and then into electrical energy; chemical energy stored in automotive fuel is released when it interacts with atmospheric oxygen at a given temperature, and is converted into thermal energy of expanding gases which in turn carry out mechanical work by driving the engine pistons; electrical energy in turn can be converted into mechanical, thermal or chemical energy.

The most important storage characteristic is energy density or volumetric energy density/gravimetric energy density. The basic units of energy in various systems are Joule, Erg, and Calorie, therefore energy density is most often measured in J/m^3 and other comparable units.

Other key characteristics of energy storage systems are discharge duration, response time, typical cycles, output capacity, efficiency, etc [5].

Currently, fossil fuel storage technologies have seen the greatest industrial development. Modern complexes for storing oil (oil products) or natural gas, in addition to tanks or natural storages (salt caverns, worked wells, etc.) include a fuel supply and extraction system, control and accounting systems, and security and firefighting systems. Where oil is utilised on an industrial scale, you can see the standard outlines of the cylindrical designs of tanks for storing oil or oil products (Fig. 2). Natural gas is mostly stored in underground storage facilities; liquefied gas can be stored in above-ground storage facilities or on specially designed offshore tankers (Fig. 3).

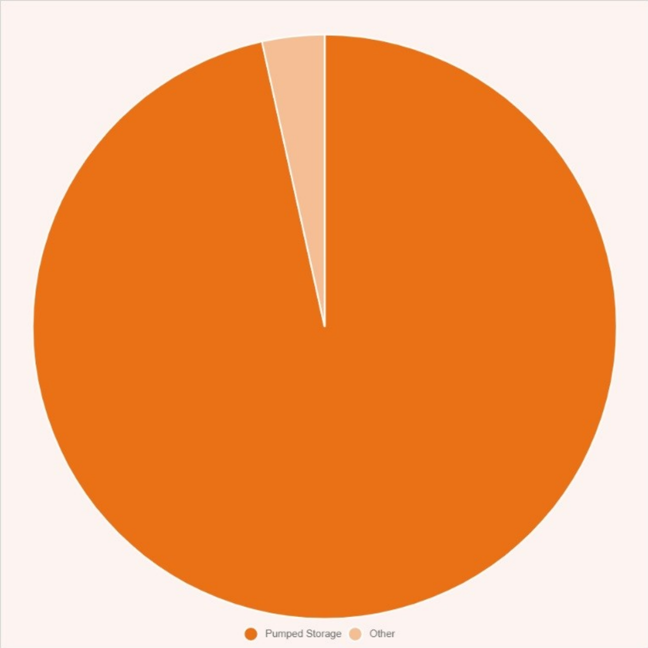
Figure 2-3. On the left is a petroleum products storage terminal, Ventspils, Latvia. On the right - the liquefied gas transhipment complex, Brazil

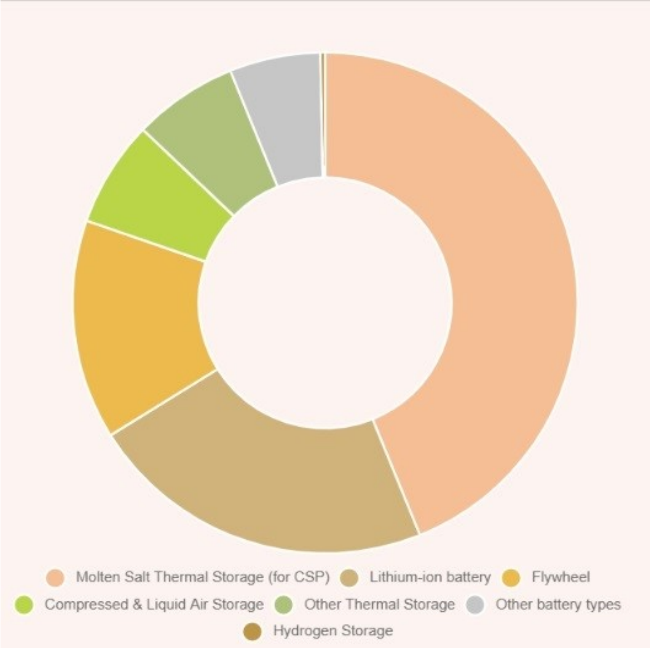
For storage of industrial gases, including hydrogen, spherical or cylindrical tanks are used (Fig. 4). Thermal tanks for storing processed salt, or hot or cold water are similar to oil tanks - Fig. 5.

Fig. 4-5. Left: Stockholm Loudden oil terminal, Sweden. Right - The Pearl of Reykjavik - a complex of reservoirs for storing hot water (water tank) from geothermal springs (4000 m^3) partially converted into a public building, Iceland

The main objective of the energy storage industry is the development of effective and competitive technologies for storing electric energy. Comparative diagrams of the share ratio of the main technologies for storing electric energy (Fig. 6-7) show that pumped storage stations are by far the most common. The share ratio of this type of energy storage when compared to all the other technologies combined is approximately 96.5% to 3.5%. Among those other technologies, Molten Salt Thermal Storage CSP and Lithium-Ion Battery have the highest capacity.

Fig. 6-7. Share ratio of total energy storage capacities for electricity generation. Left - Pumped Storage and all Other, Right - All Basic without Pumped Storage





Sources: DOE Global Energy Storage Database[1], NREL/SolarPACES; Sep. 2019[6]

Below is a brief overview of existing technologies for storing electric energy.

Mainstream technologies

The most frequently mentioned characteristics of the main energy storage systems are given in Table 1. More information about this can be obtained in [5,7]. Each system has both a number of important advantages and disadvantages. For example, Pumped Storage is one of the leaders in terms of storage capacity, energy storage time, and service life, however, it has a relatively low energy density. On the other hand, lithium-ion batteries have a high energy density, excellent efficiency, but are currently inferior to most other systems in terms of power and durability. Thus, it is possible to choose the system, depending on the specifications of the project.

Table. 1. Technical characteristics of the main energy storage systems

Name	Power rating (MW)	Storage duration	Cycling or lifetime	Energy density (W/l)	Efficiency
Pumped hydro storage	100 - 1000	4 - 12 hours	30 - 60 years	0.1 -0.2	70 - 80%
Compressed air energy storage	10 - 1000	2 - 30	20 - 40 years	0.2 - 0.6	40 - 75%
Flywheels	0,001 - 1	Sec - hours	20000 - 100000	5000	70 - 95%
NaS battery	10 - 100	1min - 8 hours	2500 - 4500	120 - 160	70 - 90%
Li-ion battery	0,1 - 20	1min - 8 hours	1000 - 10000	1300 - 10000	85 - 98%
Flow battery	0,1 - 100	1 - 0h	12000 - 14000	0.5 - 2	80 - 85%
Molten salt	1 - 150	hours	30 years	n/a	80 - 90%
Hydrogen	0,01 - 1000	min - weeks	5 - 30 years	0.2 - 20	25 - 45%

Source: Electricity Storage/ SBC Energy Institute/ September 2013 [7]

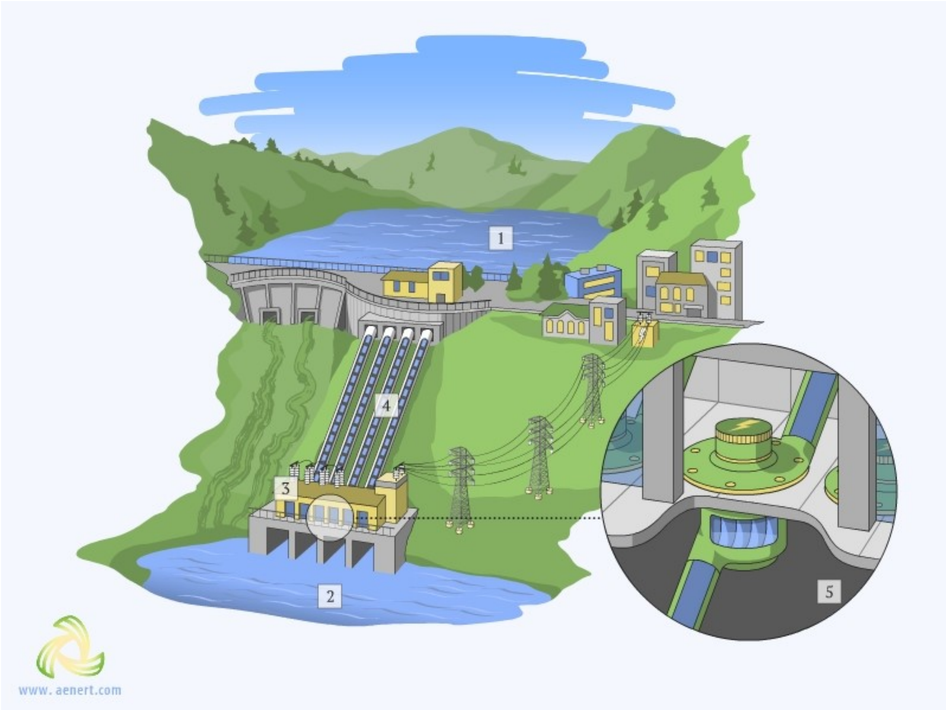
Pumped Storage

Pumped storage stores the energy of water in tanks located above the turbine unit. It is used to smooth out peak loads or derive additional economic benefits from the difference in electricity prices at different times of the day. When total energy consumption drops and electricity prices decrease (usually at night), the upper reservoir is filled with water from either the lower reservoir or directly from the river bed, Fig. 8. According to [8], the efficiency of this system is between 70% and 85%, therefore, such storages do not produce energy, but only store it in large volumes. According to [9], the main losses in efficiency of this system occur in the turbines (during Generating cycle) and pumps (during Pump cycle).

Open-loop pumped storage is a system based on an existing hydroelectric power station with an additional (usually upper or lower) reservoir. The closed-loop consists of two independent tanks, which are alternately filled with water depending on the generation cycle or the available capacity in the upper reservoir. The general scheme of a pump storage facility is shown in Fig. 8. During the cycle of filling the upper reservoir, the entire system consumes electricity from the network, during the reverse cycle it transfers it to the network. One of the main advantages of such a system is the ability to very quickly generate additional electricity and transfer it to the grid during peak loads, which neither thermal nor nuclear plants, can provide. The disadvantages of pump storage facilities are high one-time capital costs and the low density of stored water energy. The latter determines the need to increase the size of the upper reservoir and its placement at a higher level relative to the lower tank, while striving to provide high storage capacity.

Hydraulic storage stations today are the main and essentially only option for storing energy on a large-scale, excluding fossil fuels. The life cycle of such stations can be several decades.

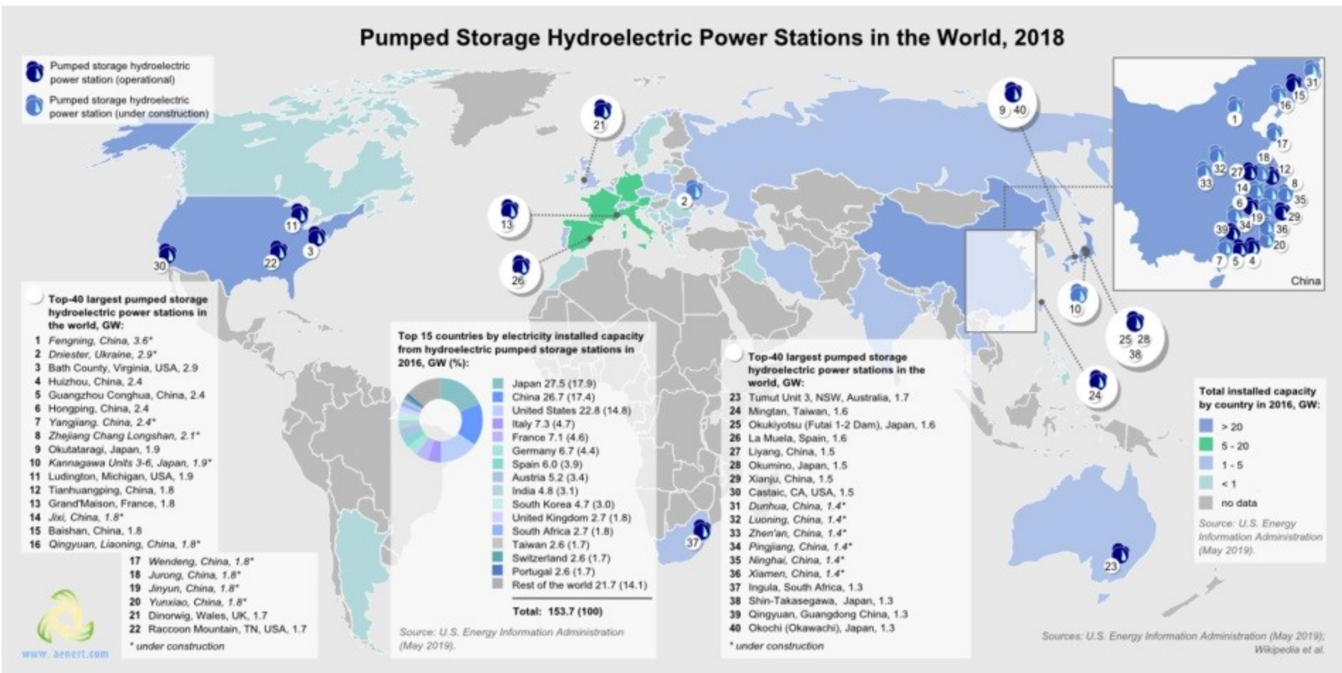
Fig. 8. The scheme of the pump storage or pumped storage station



1. *Upper reservoir*
2. *Lower reservoir*
3. *Penstock*
4. *Mashinen hall*
5. *Turbine / Generator*

The most powerful pumped storage stations in the world are shown in Fig. 9. Three countries are paving the way in terms of installed capacity of pumped storage plants - Japan with 27.5 GW (17.9% of the world total capacity in 2016), China, having 26.7 GW (17.4%) and the USA - 22.8 GW (14.8%). Together, their share is more than 50% of the total installed capacity.

Fig. 9. The world's largest pumped storage power plants



Pumped_storage_hydroelectric_power_stations_in_the_world_2018 [724 kB]

A large number of pumped storage stations are located in Europe - in Italy (7.3 GW), France (7.1 GW), Germany (6.7 GW), Spain (6.0 GW), Austria (5.2 GW), the United Kingdom (2.7 GW), and Switzerland (2.6 GW). The largest operating pumped storage system is Bath County in Virginia, USA with a capacity of 2.9 GW (Fig. 10-11). However, a more powerful pumped storage station is under construction in China - Fengning (3.6 GW). The largest stations in Japan, Okutataragi and Kannagawa, have a capacity of 1.9 GW each.

Fig. 10-11. One of the world's largest Pumped Storage Bath County, Virginia, USA, 2.9 GW. On the left - the upper and lower reservoirs. On the right - power station

Photos: www.google.com/maps

The main increase in the capacity of pumped storage stations in the world is happening in Southeast Asia. In general, this growth is not that substantial in comparison with the growth in wind power plants and solar stations. Between 2007 and 2016, the total volume increased by around 26% (Fig. 12).

The practical implementation of this technology requires an appropriate natural landscape, which severely limits its use on flat terrain. However, as shown in the study [10], this problem can be solved by implementing the concept of an energy island, first proposed by the Dutch company Kema. An energy island consists of a circular dam in the sea with an internal lake, 32-40 meters below sea level. The energy storage potential in such a structure can reach 1,500 MW. This development, that allows for the implementation of pumped storage systems without the need for traditional favourable terrain, can significantly expand the geographic distribution of storage technologies.

The results of a global audit of 530,000 potential sites for the construction of pumped storage stations made by the Australian National University (ANU), produced a startling outcome [11]. According to the authors of the project, it would require only a small fraction of these sites to be developed to provide 100% continuous energy supply to the whole world with renewable sources. If the results of the study turn out to be correct, this could lead to a fundamental rethink of the energy strategies of many countries and contribute to the accelerated development of wind and solar energy, the main drawback of which is intermittent operation

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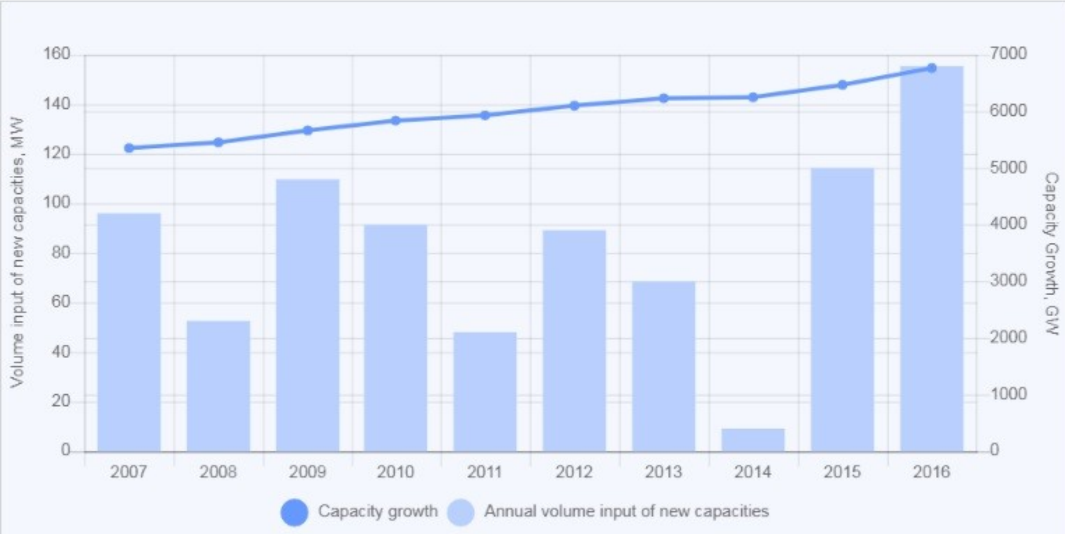
The use of pumped storage stations in combination with wind or photovoltaic stations allows for the storage of the electric energy they produce, in the event of a shut down during no-wind hours or at night. An analysis of the practical aspects of such an integration, with a list of existing projects, can be found in [9, 13-16].

Fig. 12. Rated power of pure pumped hydro storage capacities growth & Annual Volume Input of new Capacities in 2007-2016



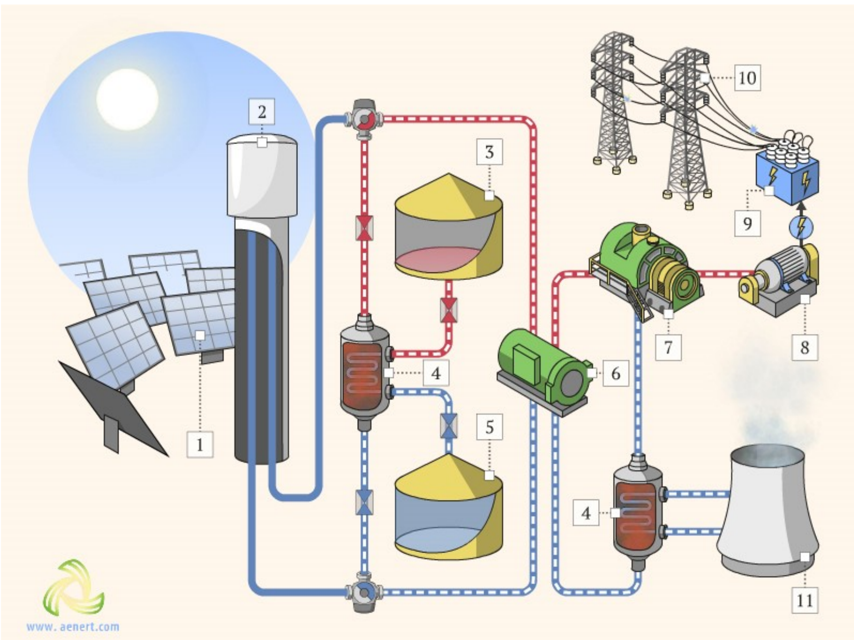
Source: Based on Data from U.S. Energy Information Administration (May 2019)[12]

More detailed information on pumped storage systems, as well as on existing facilities and companies operating in this market segment, can be seen in [7, 17-21].

Thermal Storage for CSP

Significant progress made in the use of CSP thermal energy storage in the last decade has made this option competitive and deserving of special attention. Despite the fact that the development of concentration technologies is significantly inferior in volume to simple photovoltaic systems for generating solar energy, they have a clear advantage- the ability to produce and store thermal energy. This partially compensates for their main drawback - the inability to work with scattered solar irradiation. The general principle of CSP station operation with a thermal energy storage unit is shown in Figure 13 [7, 22-24].

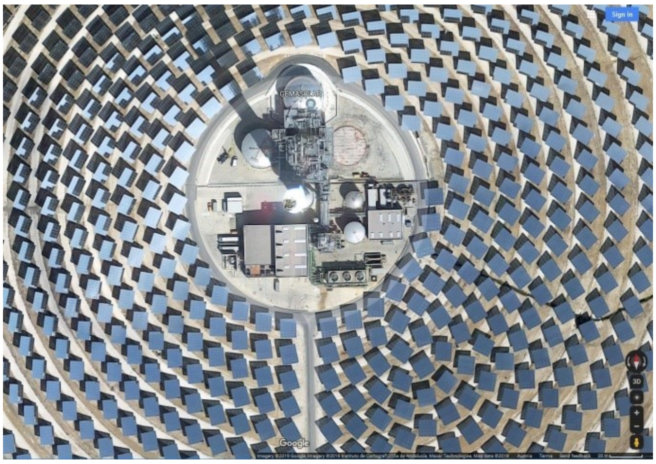
Fig. 13. Solar station with an energy storage system



1. *Heliostat field*
2. *Central receiver*
3. *Salt tank (hot 565C0)*
4. *Condenser*
5. *Salt tank (cold 290C0)*
6. *Steam generator*
7. *Turbine*
8. *Generator,*
9. *Transformer*
10. *Grid*
11. *Cooling tower*

The storage system consists of two tanks, one of which contains the working fluid heated to the maximum temperature, the other contains the lower temperature liquid after it has been used in the steam generator. During periods of solar activity, the first tank is replenished with heated working fluid, which is then used to produce steam that will be pumped into the second tank. The maximum storage temperature depends on kind of working fluid that is pumped through the system. Parabolic trough systems normally use oil as the heat carrier, and its temperature does not usually exceed 400°C. A solar power tower uses salt melts, while the upper limit of the storage temperature rises to 565°C. The working fluid from the "hot" tank, when needed (at night, during short repair works, or when the functioning of the solar energy concentrators stops) is sent to heat the transfer agent, which in turn is supplied to the steam generator, creating superheated steam that then enters a turbine unit for generating electricity. The waste liquid from the heat exchanger is sent to the "cold" tank. Thus, the working fluid is reused in order to maintain the operation of the station, regardless of solar activity. According to [22], modern tanks for storing molten salts have excellent heat-insulating properties and, during the day, the temperature of the working fluid decreases by only 1°C. The lifetime of these storage systems can last up to 30 years, and their efficiency reaches 80-90% [7]. Figure 14-15 shows pictures and characteristics of some solar stations with energy storage systems.

*Fig. 14-15. Thermal Energy Storage for Concentrated Solar Power. Left - Termosol Plant 1-2, Parabolic Trough, 2 * 2-tank indirect, Storage Capacity 9 hours, Spain. Right - Gemasolar Thermosolar Plant, Power Tower, 2-tank direct, Storage Capacity 15 hours, Spain*



Photos: www.google.com/maps Source:NREL/SolarPACES; Sep. 2019[6].

Molten salts such as potassium and sodium nitrates are currently been used as working fluids, other substances — $ZnCl_2$, $MgCl_2$, Na_2CO_3, etc. — are also being tested [25]. The substances used must have a high heat capacity, low corrosion activity, a low melting point and low cost. More detailed information about the various options for storing energy for solar stations and the materials used can be found in [25-31]. According to [27], a mixture of $NaNO_3$ and KNO_3 salts has a number of beneficial properties — it has a low melting point (220°C), low density, and a relatively low cost. A mixture of magnesium and potassium chlorides is one of the cheapest suitable compositions, but has a rather high melting point - 426°C; a mixture of zinc, potassium and sodium chlorides has the lowest melting point among the mixtures under consideration(204°C), but has a higher density and is more expensive compared to other options.

Some research organizations are conducting experiments with completely new materials for storing solar energy, such as ceramic particles, and have invented new designs of receivers [32-33]. Recently. scientists from the German Aerospace Center (DeutschesZentrumfürLuft-und Raumfahrt; DLR) have carried out experiments researching the technological possibilities of the high-temperature centrifugal solar receiver CentRec. The centrifugal receiver CentRec, designed by the research institute, consists of a rotating chamber which is fixed to a solar tower and faces towards a field of solar heliostats which are adjusted so that they reflect sunlight onto the receiver. Inside the top of the chamber is a device that introduces small aluminium-ceramic particles of around one millimetre. When the chamber is rotating centrifugal force causes the particles to be pressed against the interior wall of the chamber and the particles are heated to an extremely high temperature.

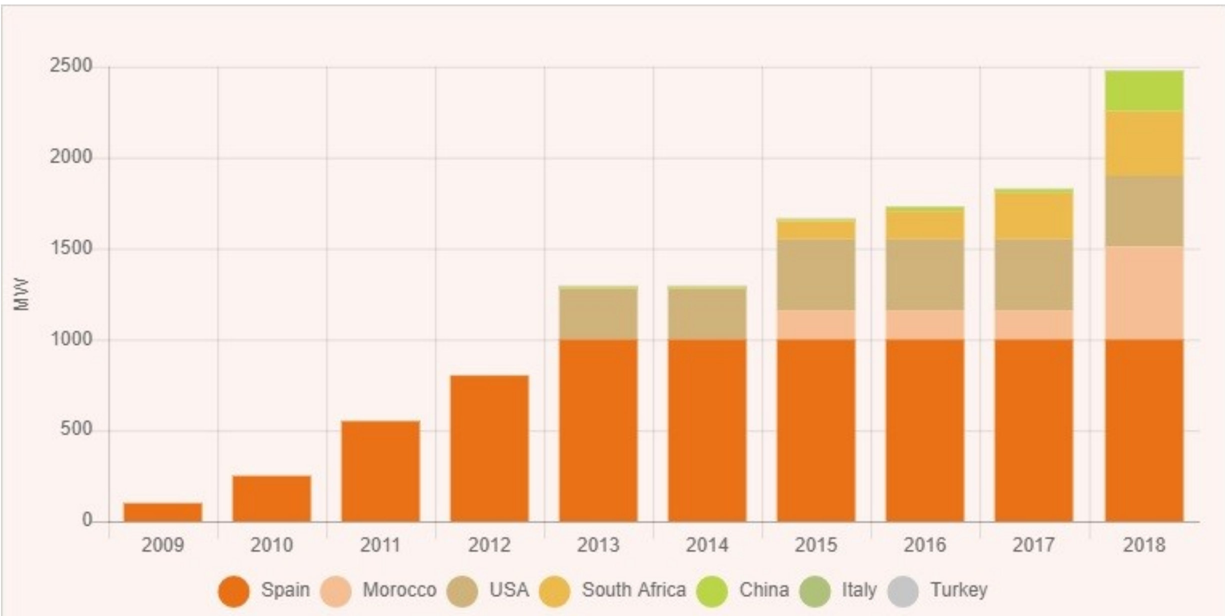
Aided by gravity, the hot particles fall out of the chamber; they are collected at the particle outlet in special thermally insulated containers and can be used in various technological processes, such as steam production at power stations or heat storage. Particle temperature can be controlled either by regulating the concentration of the solar radiation reflected by the heliostats or the rotation speed of the chamber .

In May 2018 a unique experiment was carried out at the Jülich Solar Tower where the particles in the receiver were heated up to more than 965°C, thus demonstrating the high potential of concentrated solar energy and the effectiveness of the new receiver. The advantages of the CentRec receiver construction are clear: firstly, increasing the temperature of the receiver can also boost the efficiency of solar power stations; secondly, the device can improve energy storage systems, which ensure that solar power stations work properly even when solar irradiation levels are low; thirdly, its design can effectively reduce the costs of the receiver. Contemporary energy storage systems installed at solar power stations use liquid salts that only work at temperatures up to approximately 550°C - 565°C, and the temperature of the steam which enters the turbine is even lower. The system discussed in this report, however, can produce steam up to 620°C. During downtime, power stations that use molten salts need to have an emergency heating system in place to avoid the liquid salts from freezing. Also, as the molten salts are not heated directly by solar radiation but by means of additional metal tubes, efficiency losses in the thermal process, as well as further costs, are incurred. The bauxite particles used in this design possess favourable characteristics, such as thermal conductivity, thermal activity, ready availability, and low cost. They are also environmentally safe.

Thus, thermal energy storage systems can be based not only on the principle of storage of heated molten salts or other similar materials in metal tanks, but also on the storage of solid substances in special insulated containers. This can significantly expand the possibilities of using such systems not only for the solar energy, but for other industries.

The geographic spread and capacity of solar stations with thermal energy storage systems is steadily expanding (Fig. 16). Initially only Spain and the United States had significant capacities in this area, but in recent years Morocco, South Africa and China have been catching up, and if trends continue, will surpass the pioneers in terms of the total volume of installed storage capacities.

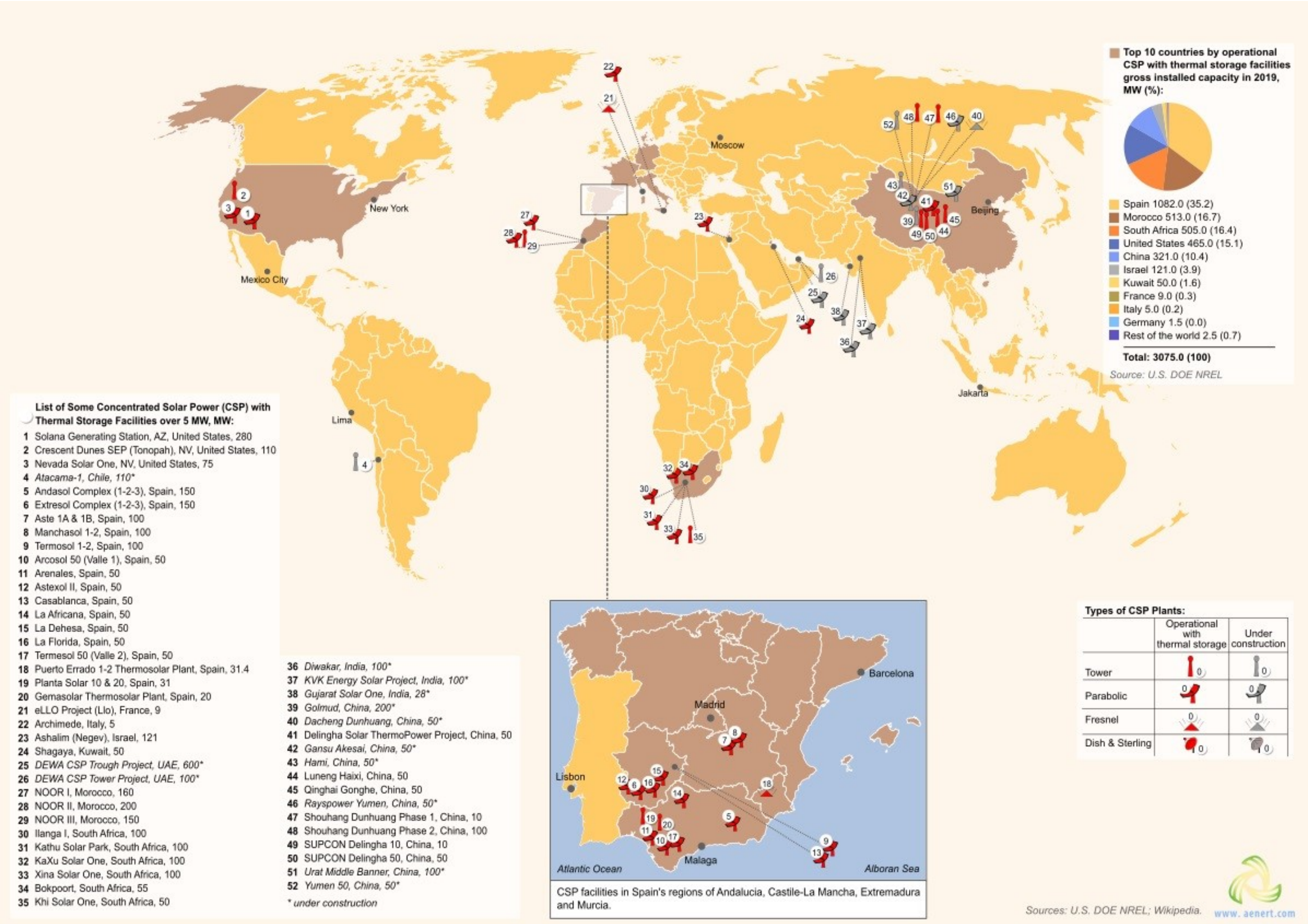
Fig. 16. The total output power of solar stations with energy storage systems



Source: Concentrating Solar Power Projects / NREL / September 2019.

A detailed list of existing solar stations with thermal energy storage systems and stations under construction can be found in Fig. 17, as well as on the website [34]. There is also information about companies involved in the development and operation of these facilities, as well as the main technical characteristics of the projects.

Fig.17. Concentrated Solar Power Plants with Thermal Energy Storage Systems



[Solar_thermal_csp_plants_world_map-2018](), [1 Mbt]
Source: Concentrating Solar Power Projects / NREL / September 2019

Other types of thermal energy storage, for example, Hot or Chilled Water Thermal Storage or Ice Thermal Storage have also gained popularity. However, they usually have a small capacity. A review of technological and economic indicators of such systems is available in [35], a detailed list of facilities is presented in the database [1]. Hot water storage is widely used in regions rich in geothermal springs, such as Iceland. One of the largest chilled water storage facilities in the world can be found at a gas turbine station in Texas [1, 36]. Here, chilled water is supplied to cool the air at the inlet of the gas turbine, to prevent energy losses. Systems like Ice Thermal Storage are primarily used to cool buildings. For example, The Sarasota School District project, located in South Florida, has a capacity of 20MW and provides air conditioning for schools using thermal energy storage [1,37].

Lithium-Ion Battery

Electrochemical cells

Electrochemical energy storage devices (electrochemical cells, galvanic cells, voltaic cells) convert electric energy into chemical energy via reversible chemical reactions, store it for a sufficiently long time and then convert it back into electricity. These devices are the most popular and promising energy storage technologies that have found wide application in various fields of human activity. Most commonly, individual electrochemical cells are combined into a battery to increase the capacity of the device. The voltage of one electrochemical cell is usually between 1 and 6 volts [38]. Examples of batteries include primary batteries or disposable primary batteries and secondary battery or rechargeable batteries, with liquid electrolyte or dry cell, high-power or high-energy batteries. Despite the advantages of rechargeable batteries, disposable devices dominate the market. However, to solve the problems of energy storage in renewable energy (wind power, PV power), and electric vehicle, etc., rechargeable batteries need to be modified first.

The technical specification of each battery includes several basic characteristics that make it possible to compare them, for example [38]:

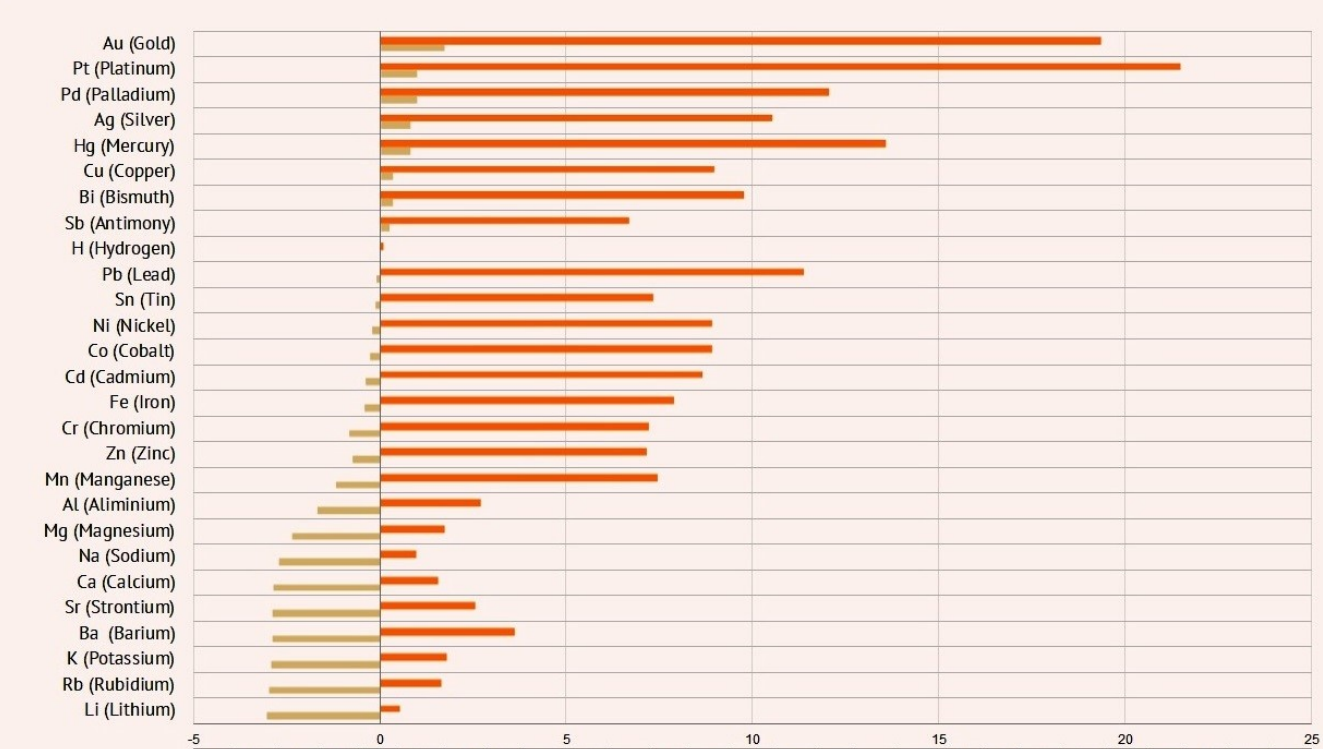
- Nominal Voltage
- Cut-off Voltage
- Nominal Capacity
- Nominal Energy
- Cycle Life (The number of discharge-charge cycles)
- Specific Power (W/kg)
- Power Density (W/L)
- Charge Voltage
- Maximum Continuous Discharge Current

There are many types of rechargeable batteries, a detailed list of which can be found in [39]. The most widespread are Lead – acid batteries, Nickel – cadmium batteries, Sodium – sulphur batteries, Flow batteries, Metal – air electrochemical cells, and Lithium-ion batteries.

The basic design of any electrochemical cell (galvanic cell) features two electrodes of specially selected materials, called the anode and cathode, placed in an electrically conductive substance or electrolyte. The electrolyte can be liquid, solid and even gaseous, but regardless must have a certain level of ionic conductivity. When interacting with the electrodes, electrolyte ions form stable chemical compounds with a decrease in the total free energy of the system in the discharge mode. However, with sufficient external energy exposure, these chemical compounds decompose to their initial state in the charging mode. For example, in a charged lead-acid battery one electrode consists of lead (Pb) and the other of lead dioxide (PbO_2), which is placed in an aqueous solution of sulfuric acid. At the first electrode, lead interacts with sulfuric acid forming $PbSO_4$, hydrogen ions and conducting electrons, giving the electrode a negative charge. As electrons accumulate, the resulting electric field attracts hydrogen ions, which isolate the charged electrode from the electrolyte. However, this does not prevent the movement of electrons through the external circuit if it turns out to be closed. At the same time, lead dioxide interacting with sulfuric acid and hydrogen ions and excess electrons transferred from the first electrode to the second through an external circuit at the second electrode is also converted into lead sulphide with the release of water. This significantly dilutes the initial electrolyte and reduces its initial properties. If the external circuit remains open, all reactions are inhibited, and the battery remains charged for a long time. To prevent short circuits, porous insulating separators are installed between the individual battery plates. With a charge cycle, i.e. when external voltage is applied to a discharged battery, the reverse reaction occurs, restoring the battery to its prior state.

Significant progress in the development of electrochemical energy storage was made with the development of lithium-ion batteries. They have a number of beneficial properties, above all a very high energy storage density in relation to other technologies (Table 1). The reasons for such disparity become clear if you look at a comparative table of the density and standard electrode potential of selected chemical elements (Fig. 18). Each of the elements or their chemical compounds in solutions are able to react with the loss (oxidation) or acquisition (reduction) of an electron with a certain degree of intensity, i.e. they have a specific electrode potential. By ranking elements according to the value of electrode potential under standard conditions (and with respect to hydrogen having zero potential) allows one to determine the potential of the electrochemical cell and the direction of the main chemical reactions when choosing each pair of electrodes [40, 41]. From here several fundamental rules follow - the elements to the left of hydrogen will displace the elements to the right of hydrogen from solutions of salts, as well as hydrogen. The electricity generated in the electrostatic cell will be determined by the difference in electrode potential of electrodes and electrolyte. Based on this, and according to the data in Fig. 18, it follows that lithium is the strongest reductant, whose standard electrode potential with respect to hydrogen is 3.04 Eo (V). For comparison, the potential of the standard reaction of the electrochemical element of the lead-acid battery $PbSO_4$ (s) + $2e^-$ $\rightleftharpoons$ Pb (s) + SO_4^{2-}(aq) is only 0.356 Eo (V). For the water dissociation reaction, the value of the standard electrode potential is 1.763 Eo (V).

Fig.18. Standard electrode potential and density of some elements



	Li (Lithium)	Rb (Rubidium)	K (Potassium)	Ba (Barium)	Sr (Strontium)	Ca (Calcium)	Na (Sodium)	Mg (Magnesium)	Al (Aliminium)	Mn (Manganese)	Zn (Zinc)	Cr (Chromium)	Fe (Iron)	Cd (Cadmium)
Density	0,53	1,63	1,78	3,59	2,54	1,55	0,97	1,74	2,7	7,43	7,13	7,19	7,87	8,65
Standard Electrode Potential, V	-3,0401	-2,98	-2,931	-2,905	-2,899	-2,868	-2,71	-2,372	-1,7	-1,185	-0,763	-0,852	-0,441	-0,404

	Co (Cobalt)	Ni (Nickel)	Sn (Tin)	Pb (Lead)	H (Hydrogen)	Sb (Antimony)	Bi (Bismuth)	Cu (Copper)	Hg (Mercury)	Ag (Silver)	Pd (Palladium)	Pt (Platinum)	Au (Gold)
Density	8,9	8,9	7,31	11,35	0,09	6,68	9,75	8,96	13,55	10,5	12,02	21,45	19,32
Standard Electrode Potential, V	-0,28	-0,234	-0,141	-0,126	0	0,24	0,317	0,338	0,7973	0,799	0,98	0,963	1,691

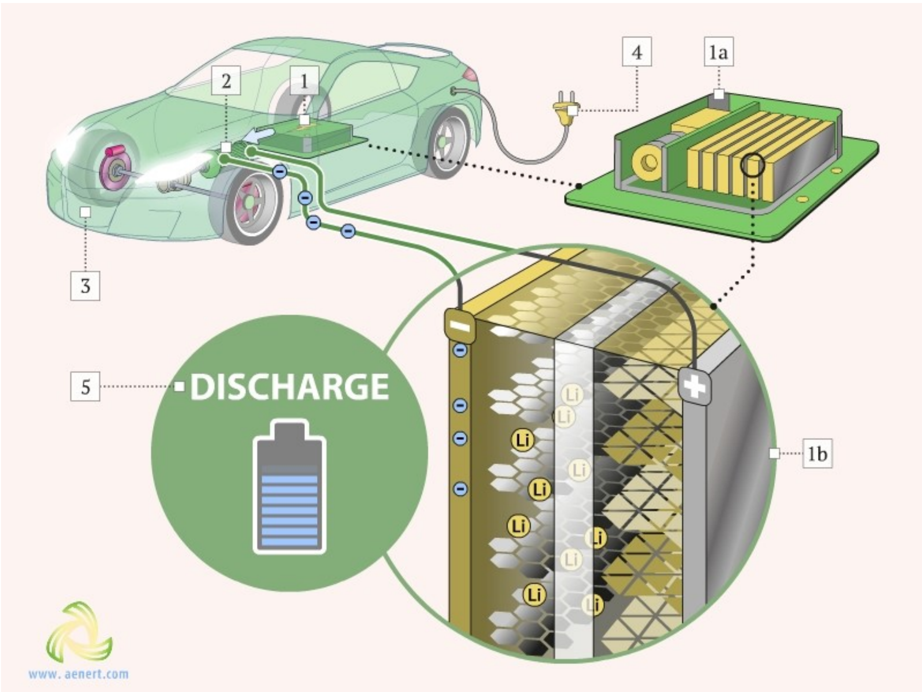
Source: Chemistry Library [40], Wikipedia [42]

In addition, lithium is one of the lightest metals with a density of only 534 kg/m^3, while for comparison, aluminium (also a relatively light metal) has a density of 2700 kg/m^3, cobalt, nickel and lead, which are also used in the production of batteries have a density of 8840 kg/m^3, 8900 kg/m^3 and 11340 kg/m^3 respectively. Thus, lithium has the best combination of density and electrode potential, which is especially important for creating batteries for portable devices and vehicles.

Operating principle

The operating principle behind a lithium-ion battery is shown in Fig. 19. The electrochemical cell of such a battery includes a set of standard components - two electrodes and an electrolyte. The chemical composition of these components may vary depending on the required properties. Most commonly, the negative electrode is made of carbon, and the positive of lithium cobalt oxide (LiCoO) or lithium iron phosphate ($LiFePO_4$). Non-aqueous solutions of lithium salts in organic carbonate blends, for example, lithium hexafluorophosphate ($LiPF_6$), lithium tetrafluoroborate (LiBF) and others, are used as the electrolyte. Since lithium has a high reactivity when in contact with water, the use of water is excluded. Special protection against air moisture is also therefore necessary and emergency pressure relief valves are installed.

Fig. 19. The principle of the functioning of the lithium-ion battery



1. Lithium-Ion battery system

1a. Battery case

1b. Lithium-Ion battery cell

2. Electric motor

3. Electric vehicle

4. Power cord

5. Charge-discharge indicator

In the discharge mode, the electrolytic cell of a lithium-ion battery will produce electricity due to the oxidation of pre-intercalated lithium atoms into graphite and the formation of free electrons, which are delivered through an external circuit to the positive electrode, where they are connected to lithium ions transferred to the positive electrode through the electrolyte. When the battery is charged by an external voltage, lithium ions leave the crystal lattice of the positive electrode material and move to graphite, increasing the total internal energy of the system. The most important role in this process is played by the processes of intercalation - deintercalation. Intercalation is the introduction of atoms or ions of one substance into the crystal structure of another substance, while maintaining the crystal structure of the receiving side. Intercalation - deintercalation reactions are determined by the diffusion rate of lithium in the crystal lattice of the electrode material. Graphite is an excellent material for intercalation, since it is able to maintain its crystal structure without being destroyed by the introduction of a large number of external atoms with significant changes in the size of the crystal lattice.

The Nobel Prize in Chemistry in 2019 was awarded to three specialists for their research on the creation of lithium-ion batteries - the Americans John Bannister Goodenough and Stanley Whittingham and the Japanese Akira Yoshino [43]. Stanley Whittingham studied the intercalation of various compounds and created the first electrochemical cell based on electrodes of lithium and titanium disulphide. John Goodenough replaced metal sulphides with their oxides and, for the first time, used cobalt oxide for a positive electrode. Akira Yoshino substituted the material for the positive electrode using lithium cobalt oxide (LiCoO2), which is still in use, and also replaced unsafe lithium as the material for the negative electrode with safe carbon in the form of petroleum coke. Since the beginning of the 1990s, lithium-ion batteries began to be produced on a commercial scale.

Thus, the main advantages of lithium - low density and high electrode potential were successfully utilized. In addition to the above advantages, lithium-ion batteries allow multiple recharges, they conserve energy well with a small self-discharge and do not have a significant memory effect, i.e. irreversible loss of battery capacity. However, this type of battery is not without shortcomings. Safety issues surrounding their use exist including the possibility of a short circuit inside the battery, moisture ingress, overheating, overcharging, the encapsulation effect i.e., the formation of an insulating film on lithium particles and the subsequent loss of part of the active substance, and others. Of particular concern is the use of expensive cobalt, a limited resource, the production of which poses serious environmental problems. The development of more reliable and efficient separators is also important [44].

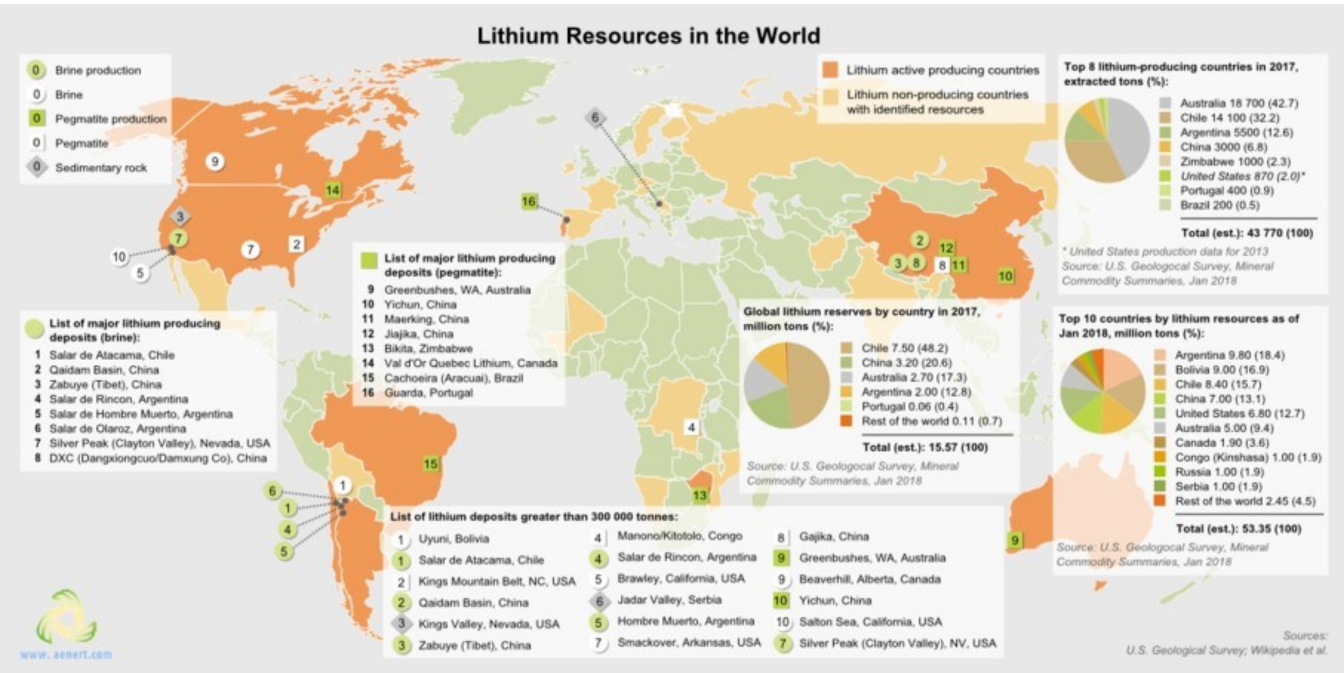
Intensive research is currently underway on the development and commercial use of other types of lithium batteries, characterized by a set of special properties. Notable among them are the lithium-ion polymer battery or LIP (which instead of a liquid electrolyte uses a gel polymer electrolyte) and lithium-sulphur battery or Li-S battery, which are characterized by low weight and low cost. More detailed information about the technology, research and application of various types of lithium batteries can be found in the proposed list of papers [45 - 54].

Reserves of key materials

To ensure sustainable growth in the production of lithium-ion batteries, regular assessments of the resource base of basic materials are necessary, especially on lithium, cobalt and graphite. The annual information regarding the reserves of these minerals is published by BP [55]. The resource base of cobalt is of particular concern to manufacturers. According to [55], the Democratic Republic of Congo holds more than 50% of the explored cobalt reserves, and Australia holds about 20%. Thus, global reserves are highly concentrated in only two countries, with total reserves calculated to be not more than 6569 thousand tons at the end of 2018 [55]. This figure is approximately half the global lithium reserves. The availability of graphite is higher, with total reserves exceeding 300 million tons. Brazil, Canada, Mozambique, Russia, and India possess large reserves of natural graphite [55].

Extensive information on lithium reserves and global production is presented in [56]. Based on this data, a map of lithium resources and related statistical diagrams can be seen in Fig. 20 and 21.

Fig. 20. Resources and lithium production in the world



Lithium_resources_in_the_world_2018_feb2019 [1.1 MB]
Source: Based on USGS [56]

As follows from the above data, the main lithium resources are concentrated in six countries (more than 85% of the total world's resources) - Argentina, Bolivia, Chile, China, the USA and Australia, amounting to a total of 55.53 million tons. Proved reserves are significantly lower - 15.57 million tons. Four countries, Chile (almost 50% of the reserves), China, Australia and Argentina possess the largest reserves. Lithium production occurs in eight countries, while between 2016-2018 a significant increase in production has been observed in Australia (Fig. 21), producing more than 60% of marketable lithium.

Fig. 21. Changes in stocks and global lithium production over the past 10 years

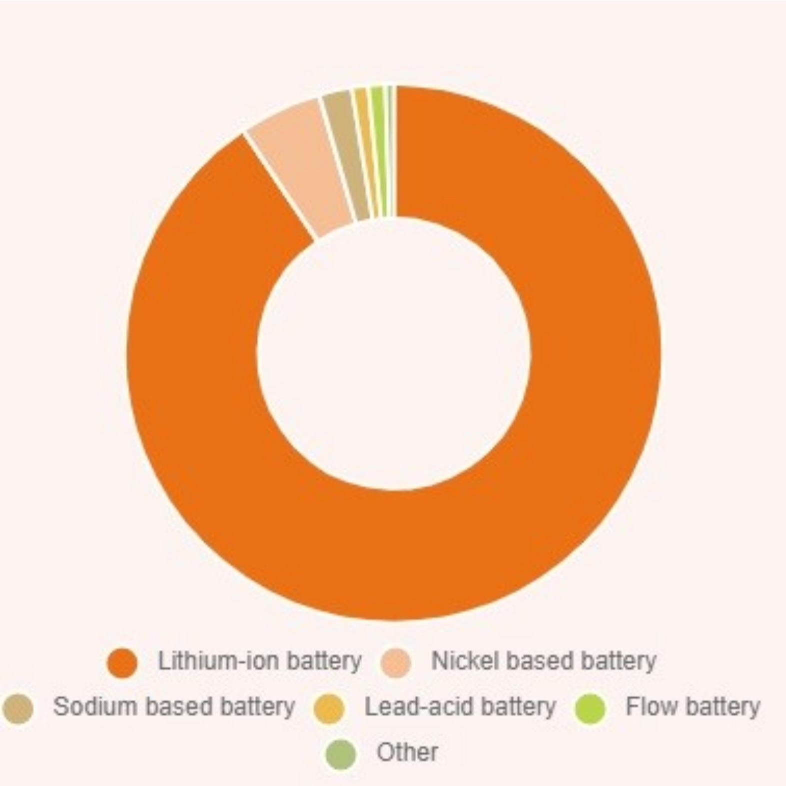
Source: Based on USGS [56]

Between 2009 and 2018, global lithium reserves increased by more than 25%, while production increased by more than 4.5 times. Thus, there is a significant imbalance between lithium production and its replenishment.

Lithium-ion battery manufacturing

The production of lithium-ion rechargeable batteries is mainly aimed at meeting the growing demand from electric vehicle manufacturers and, to a lesser extent, to save energy in other areas including commercial buildings and households. The authors in [57] analysed the growth trends of the large-scale battery market in the USA. At the end of 2017, the total electric power was 708 MW of power capacity or 867 MWh of energy capacity. More than 80% of the cumulative capacity is provided by lithium-ion batteries (Fig. 22). Batteries can be used for backup power, following a catastrophic failure of the grid, or for storing excess wind and solar energy, as well as to ensure reliable operation of the electrical network, including frequency regulation, voltage or reactive power support and others. In this case, the maintenance of frequency plays a dominant role, and about 10% of the total capacity falls on meeting the needs of renewable energy. Arbitrage occurs when batteries charge with inexpensive electrical energy and discharge when prices for electricity are high [57].

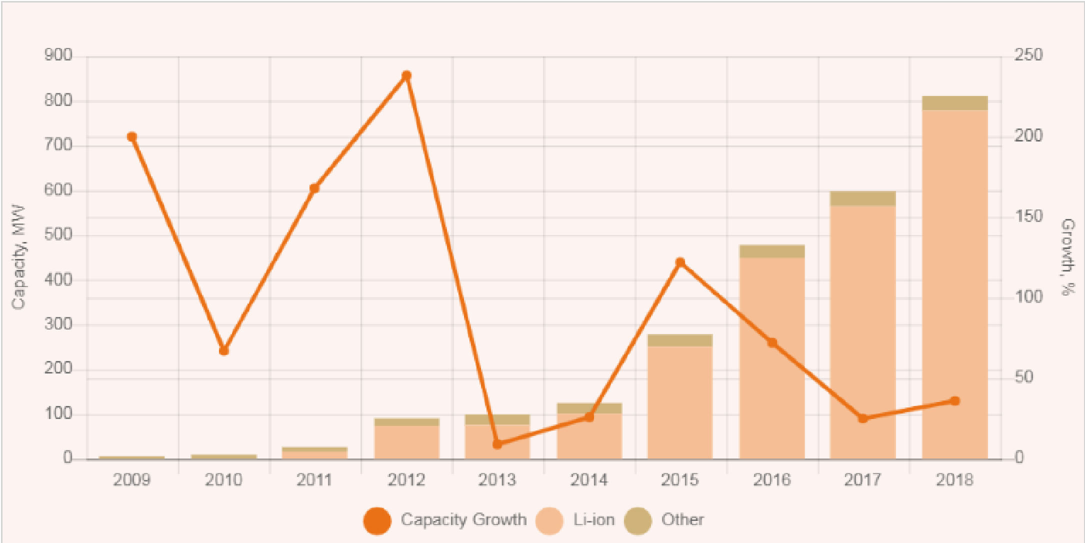
Fig. 22. U.S. Large-Scale Battery Storage Capacity by type



Source: Based on Data from U.S. Energy Information Administration (Sep 2019), [58]

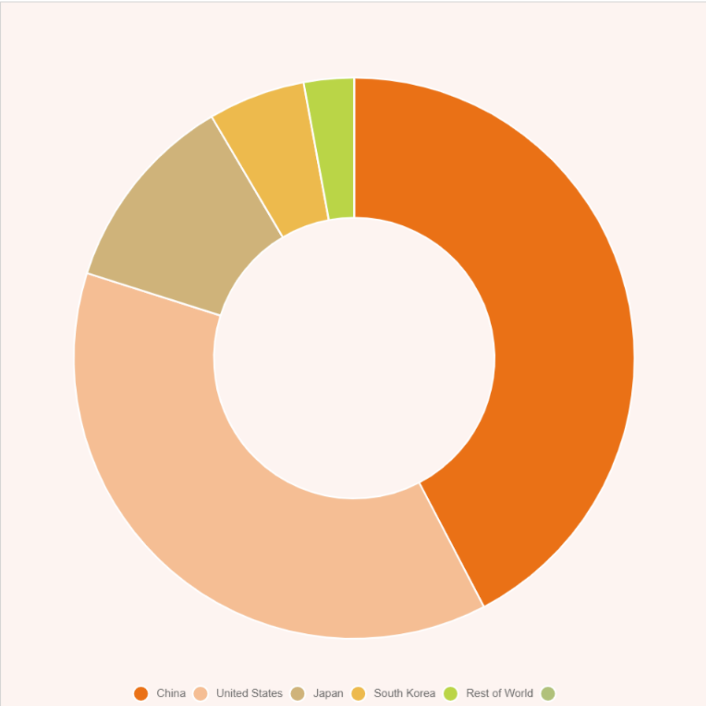
Explosive growth in the production of large-scale batteries in the United States began in 2015 and has continued in subsequent years, including 2018 (Fig. 23). This growth was mainly associated with the manufacture of lithium-ion batteries. In 2014 the share of this type of battery in the total volume was 81%, but had increased to 95% by 2018. This rise can further be seen in that in 2009 lithium-ion batteries had a negligible presence in the battery and storage market, but by 2018 their total capacity had expanded to 777 MW [58].

Fig. 23. U.S. Large-Scale Battery Storage Capacity growing



Source: Based on Data from U.S. Energy Information Administration (Sep 2019), [58] In [59], the global battery market was evaluated. It shows that 80% of production capacity is concentrated in North America, East Asia and the Pacific region, including the USA, Japan and South Korea. In [60] the authors examined in detail the supply chains of batteries for the automotive industry. They indicate that in 2015, global production capacities for end-use applications were concentrated in China, Japan and South Korea, with the largest number of components being manufactured in this region, particularly anodes (93%), cathodes (85%) and separators (84%). The authors also emphasize that this situation has arisen as a result of strong government support for scientific research and technological development, that started in Japan. However, according to [60], based on data from BNEF in 2016, the list of countries that had production capacities, where those capacities were partially commissioned, under construction, or announced, only China and the United States were included. Moreover, in the United States, for the most part, these facilities are under construction, while in China they have only been announced. Taking into account all these stages of projects for the introduction of new capacities, the share ratio of producers is changing significantly in favour of China and the USA (Fig. 24).

Fig. 24. Share of courtiers in Global automotive lithium-ion batteries manufacturing capacity



Source: BNEF, NREL, [60]

Thus, the United States has been the main source of significant market changes in recent years. It should be borne in mind that in 2009, the US share in the global production of lithium-ion batteries was about 1%, and not a single American company was among the world's top ten manufacturers [45].

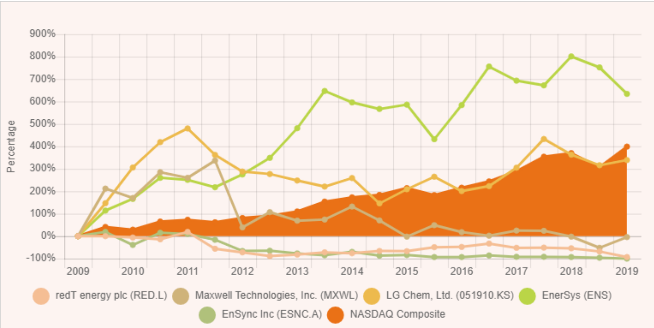
An analysis of the global market of lithium-ion batteries and their components, including raw materials, for the development of production in Europe is given in [61]. Europe is a promising region for both the production and use of lithium-ion batteries. In particular, according to [62], the volume of large-scale batteries in Germany grew similarly to the US market, and total power capacity in 2018 reached more than 370 MW, with more than 200 MW installed in 2017-2018.

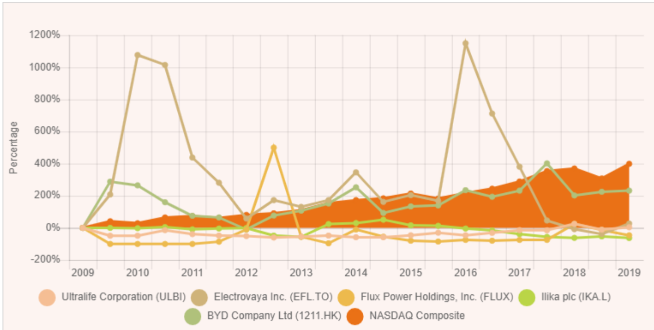
A global overview of lithium-ion batteries for vehicles, major manufacturers and components is presented in [45]. The manufacturing of anode materials, is dominated by Japanese companies - Hitachi Chemical, Kansai Gas Kagaku, Kureha, Nippon Carbon, Osaka Gas Chemical. Active cathode material is produced, among others by the following companies - 3M, A123 Systems, BASF Catalysts, Tronox (USA); Dow Kokam, L&F (S. Korea); Seimi Chemical, Tanaka Chemical, Toda, Nichia Chemical, Nihon Chemical (Japan); Phostech (Canada); Umicore (Belgium). The main manufacturers of separators are Applied materials, Celgard, DuPont, ENTEK Membranes (USA); Asahi Kasei, Toray Tonen (Japan); Evonik Industries (Germany); SK Energy (Korea), and the major electrolyte manufacturers include Cheil industries Panex (S.Korea); LithChem (USA); Mitsubishi Chemical, Ube Industries, Mitsui Chemical, Tomiyama Yakuhin (Japan); Novolyte Technologies, Shan ShanShinestar (China) [45].

The list of the largest manufacturers of lithium-ion cells and batteries includes Samsung SDI, LG Chem (S.Korea), Lishen (China), Tesla Motors, A123 Systems (USA), Sanyo, SONY, Panasonic (Japan) [45, 62].

Some large energy companies are publicly listed companies and also produce units for energy storage. Below you can find charts of changes in the value of shares of some of these companies (Fig. 25-26).

Fig. 25-26. Change in the value of shares of public companies operating in the field of energy storage over the past 10 years





Source: Yahoo Finance

In the figures presented, the stock price at the beginning of 2009 was equalized for all companies and estimated in comparison with the change in the Nasdaq Composite index, focused on innovative and, above all, information companies. The stocks have shown a very strong positive trend. At the end of 2019, three of the represented companies - the American Ener Sys, the South Korean Lg Chem and the Chinese BYD – have had indicators higher or comparable with the Nasdaq Composite Index, which is a very high result. EnerSys is one of the world leaders in the field of energy storage, including the production of backup power supplies, control systems and special batteries, system solutions and after-sales services (manufacturing and distributes reserve power and motive power batteries, battery management systems, battery chargers) [63]. LG Chem is a large-scale industrial company and the production of rechargeable batteries (battery cells) is a large part of their business [64].

With headquarters in Shenzhen, BYD is a high-tech company dedicated to technological innovations. The business model of the company lies in the production and storage of renewable energy - PV + Storage (BYD has developed PV + Storage, a new business model focused on renewable energy production, storage and applications) [65].

Advantages and disadvantages

The advantages and disadvantages of various energy storage technologies are determined both by comparative technical characteristics (Table 1) and the level of capital and operating costs. A comparative analysis of LCOS (levelized cost of storage) of various technologies for storing electric energy in combination with solar and wind stations as of 2015 is presented in [4]. In terms of commercialisation, as well as representation and deployment, pumped storage is ahead of the others, with LCOS significantly below 200 EUR/MWh. It is also noted here that Compressed air energy storage and ThermoChem have similar but slightly higher LCOS values. For storage technologies using lithium-ion batteries there are significantly higher LCOS values. They also demonstrate a large spread of data between the maximum and minimum values, which demonstrates their relatively weak competitiveness compared to the leading technologies.

A detailed analysis of the advantages and disadvantages of energy storage technologies was carried out in [2,66]. The shares of Global energy storage power capacity by main-use case and technology group assessment provides important information on the degree of penetration of each technology into the main technical sectors of electric energy production. Thus in [2] it was noted that for pumped storage stations the main area of application in almost 90% of cases is Electric Energy Time Shift. Electro-chemical storage systems are mainly used for frequency regulation; electro-mechanical - local On-Site Power; while thermal storages provide Renewables Capacity Firming. In other words, each group of energy storage technology is principally involved in various technical applications of the electric power industry. In this sense, a direct comparison in terms of both technical and economic characteristics is not entirely correct. Nevertheless, the identification of the main advantages and disadvantages of each technology, is necessary for their respective competitive targeted development.

In [2], the main advantages of pumped storage stations are attributed to a high level of technical maturity and extensive operational experience: long life and low costs of storage and reasonable round-trip efficiency etc. The main shortcomings are: geographic restrictions; low energy density; high initial investment costs and a long time to recover investment; and intensive environmental impact. The main capital expenditures, based on the data from [67], are the following: powerhouse - 37%, upper reservoir - 19%, operator's costs - 17%, engineering, procurement, construction and management - 17%.

Thermal energy storage technologies are significantly inferior to pumped storage stations in terms of accumulated storage capacities, but are ahead of all other technologies. In [35] it is noted that the sector driving development is the new concentrating solar power (CSP) with thermal energy storage technology, which is also seen in Fig. 7. Despite the fact that, according to technical indicators, thermal energy storage systems are relatively simple, their share in the capital costs of solar stations is 6–9% [67]. According to [68], the Solar thermal Total overnight cost in the US market was estimated at $4,291/kW in 2018, which is more than twice as expensive as photovoltaic stations with tracker mechanisms - $1969/kW (solar PV-tracking). In [69] at the global level, the average capital expenditures of CSP stations in 2018 were estimated to be even higher - at $5,204/kW (a 28% drop from the previous year). However, following a significant increase in the capacity factor a decrease was observed in 2018, the LCOE increased to between $0.10/kWh and $0.19/kWh. It is also noted that in recent years almost all new stations were equipped with energy storage systems, with storage duration gradually increasing up to 4-8 hours or more. For example, in 2018, the average storage time was calculated at 8.3 hours, while in 2010 it was only 3.6 hours. Thus, thermal storage systems are becoming an integral part of solar stations with concentrators, having won a stable commercial niche offering, unlike PV technologies, an uninterrupted supply of electric energy to consumers.

The advantages, disadvantages and cost of various types of rechargeable batteries, such as lithium-ion, are discussed in detail in [2, 5, 7, 60, 66, 67, 70-72]. According to [70], the main advantages of lithium-ion batteries are: long cycle and extended shelf-life; very low maintenance; high capacity; low internal resistance; simple charge algorithm; and reasonably short charge time. The disadvantages are: the need for protective circuits against possible thermal overloads; degradation at high temperature and when stored at high voltage; the inability to quickly charge at relatively low temperatures (below 0^{o}C); and special transportation requirements for large quantities.

Fig. 27-28. Li-ion Battery Racks - The Most Popular Energy Storage Design. Left - Commeo stand, right - Tesvolt

Similar characteristics of lithium-ion batteries were also analysed in [2], where, in addition, capital and operating costs were examined. A cost analysis of the main components and materials of lithium-ion batteries conducted in [2] indicated that, according to the majority of sources, the cathode material (usually lithium cobalt oxide) is the most expensive component of this design. This also applies, to a lesser extent, to anode materials (most often graphite) of separators and electrolytes. In total, these materials account for more than 75% of the cost of all used materials (cathode - 32%, anode - 11%, separator - 18%, electrolyte - 16%) [60], while all materials combined account for 74% of the total cost of lithium ion battery.

The cathode is not only the most expensive element of a lithium-ion battery, but also the heaviest [71] - about twice as heavy as the anode and one and a half times heavier than the electrolyte material. Continuing the list of these indicators we note that, according to [67], the cost of batteries is about 50% of the total capital cost per unit of capacity of an energy storage plant. Intensive research into new materials and design improvements of lithium batteries is largely determined by not only the technical, but the economic shortcomings of the components of lithium-ion batteries. Nevertheless, the alternative options, both with and without lithium, have not yet demonstrated the same overall advantages provided by lithium-ion batteries with a pair of cathodes - anode based on Lithium cobalt oxide - graphite. For example, according to [72], energy storage systems based on lithium-ion batteries with these materials have the lowest installation cost, especially in the case of utility scale projects and the highest energy density [73].

Research and innovations

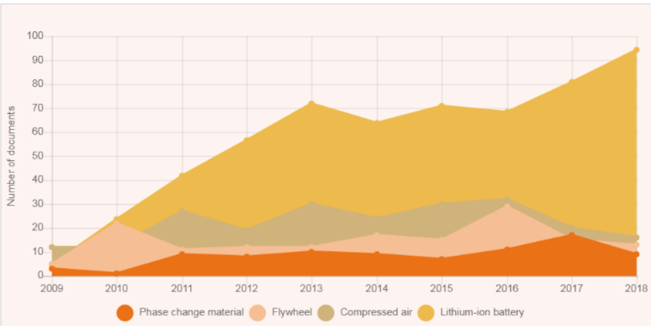
A significant amount of information on the latest innovations in energy storage can be obtained by analysing patent applications filed with the World Intellectual Property Organization (WIPO). Below is a brief overview of WIPO patent applications over the past 10 years for most popular technologies - compressed air, flywheel, phase change materials and heat storage, all types of lithium and lithium-ion batteries (Li-accumulators).

To search for patent documents, the following search codes were used:

DP:[2009 TO 2018] AND CTR:WO AND (IC:(H01M10/052*) OR (TI:("Compressed air" AND storage) OR FP:((CAES OR RCAES OR ACAES) AND storage) OR CL:((CAES OR RCAES OR ACAES) AND storage) OR IC:(F02C6/16) OR (IC:(H02J15/00 OR F04B41/02 OR F02C1/02) AND (FP:"compressed air" OR CL:("compressed air")))) OR ((IC:(F28D20/02 OR F28D20/00) AND (FP:(("Phase change" OR PCM) AND ("heat storage")) OR CL:(("Phase change" OR PCM) AND ("heat storage")))) OR (TI:("Phase change" OR PCM) AND TI:("heat storage"))) OR ((IC:(H02K7/02 OR F03G3/08 OR F16F15/30 OR F16F15/315 OR F16H33/02 OR H02J3/30) OR (TI:flywheel)) AND (FP:((energy NEAR storage) OR (power NEAR storage) OR (storing NEAR energy) OR (storing NEAR power)) OR CL:((energy NEAR storage) OR (power NEAR storage) OR (storing NEAR energy) OR (storing NEAR power)))))

A total of 6,225 patent applications, filed by 4,794 applicants were identified. The distribution of the total number of patent applications by major technologies and by years is shown in charts 29-30. Firstly, the steady increase in the annual number of patent applications is striking, and secondly, the overwhelming number of patent applications are related to lithium batteries. Moreover, even with a tenfold decrease in digital values for applications related to lithium batteries (see diagram 29 for a visualization), they maintain dominance over other technologies.

Figure 29-30. Distribution of WIPO patent applications for the last ten years in the field of energy storage. On the left is the distribution of the total number of patent applications by major technologies, on the right is the distribution by year. The numerical values for lithium batteries in the diagram are reduced by 10 times

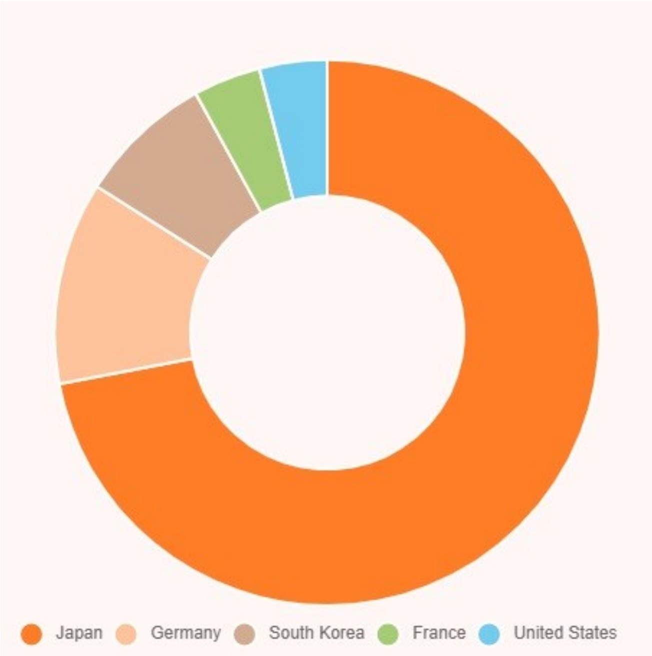


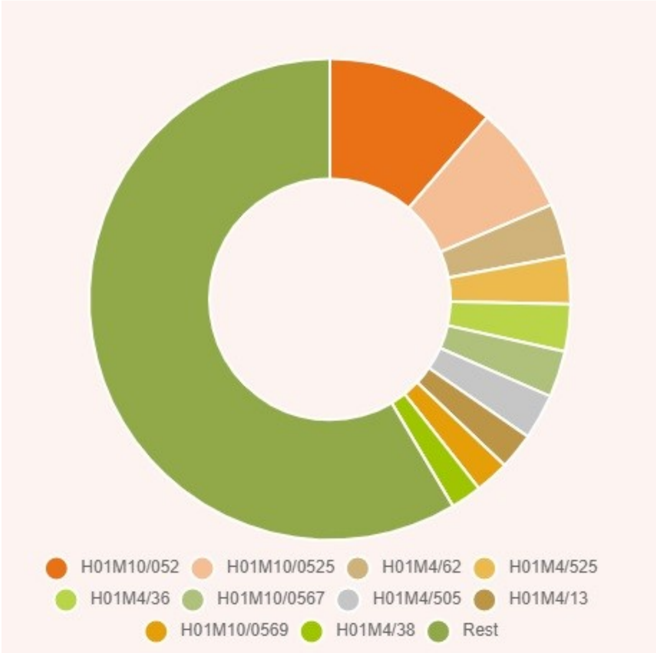
Source: Based on WIPO data

The annual number of patent applications filed with WIPO related to lithium technologies amounts to hundreds, and exceeds the total annual number of applications for other competing technologies by 10-20 times. The following key words were most often found in the titles of patent applications: BATTERY - in more than 77% of cases; SECONDARY - in almost 55% of cases; LITHIUM - 53%; METHOD - 30%; ELECTROLYTE - 28%; ION - 27%; ELECTRODE -26%; MATERIAL - 18%; CELL -14%; STORAGE -12%.

Of the total number of applicants, the top 25 accounted for 45% of all patent documents. 18 applicants were from Japan, 3 from Germany, 2 from South Korea, one from France and one from the United States (Fig. 31).

Figure. 31 - 32. On the left is the representation of countries among the top 25 applicants, on the right is the distribution of IPC subgroups among the total patent applications





Source: Based on WIPO data

In total, more than 31,000 subgroups of the International Patent Classification - IPC were mentioned in patent documents. The top ten accounted for almost 40% of all patent documents (Fig. 32). The list of the first ten most popular classes is as follows: H01M10/052 - Li-accumulators; H01M10/0525 - Rocking-chair batteries, i.e. batteries with lithium insertion or intercalation in both electrodes; Lithium-ion batteries; H01M4/62 - Selection of inactive substances as ingredients for active masses, e.g. binders, fillers; H01M4/525 - Electrodes - Electrodes composed of, or comprising, active material - Selection of substances as active materials, active masses, active liquids - of inorganic oxides or hydroxides - of nickel, cobalt or iron - of mixed oxides or hydroxides containing iron, cobalt or nickel for inserting or intercalating light metals, e.g. $LiNiO_2$, $LiCoO_2$ or $LiCoO_xF_y$; H01M4/36 - Selection of substances as active materials, active masses, active liquids; H01M10/0567 - the electrolyte being constituted of organic materials only - Liquid materials - characterised by the additives; H01M4/505 - Electrodes composed of, or comprising, active material - Selection of substances as active materials, active masses, active liquids - of inorganic oxides or hydroxides - of manganese - of mixed oxides or hydroxides containing manganese for inserting or intercalating light metals, e.g. $LiMn_2O_4$ or $LiMn_2O_xF_y$; H01M4/13- Electrodes for accumulators with non-aqueous electrolyte, e.g. for lithium-accumulators; Processes of manufacture thereof; H01M10/0569 - the electrolyte being constituted of organic materials only - Liquid materials - characterised by the solvents; H01M4/38 - Electrodes composed of, or comprising, active material - Selection of substances as active materials, active masses, active liquids - of elements or alloys.

Among the applicants, Lg Chem, Ltd (South Korea) filed the largest number of applications (619 applications with WIPO for inventions or 9.94% of the total number of registered applications). 8 companies filed more than 100 patent applications, 18 companies filed 50 or more applications. 43 applicants filed 25 or more patent applications with a total of 3355 or almost 54% of the total. A list of the top 10 applicants is presented in table 2. This list includes 2 companies from South Korea: Lg Chem, Ltd. and Samsung Sdi Co., Ltd.; 2 companies from Germany - Robert Bosch Gmbh and Basf Se; and 6 companies from Japan - Toyota Jidosha Kabushiki Kaisha; Nec Corporation; Sanyo Electric Co. Ltd.; Murata Manufacturing Co. Ltd.; Panasonic Corporation and Hitachi Ltd. Together they accounted for more than 17% of all patent applications.

Table 2. Top 10 applicants in the collection of WIPO patent applications in the field of energy storage technologies, 2009-2018

Applicant	Country	No. of applications	Share of applications, %
Lg Chem, Ltd.	South Korea	619	9.94
Robert Bosch Gmbh	Germany	260	4.18
Toyota Jidosha Kabushiki Kaisha	Japan	235	3.78
Nec Corporation	Japan	192	3.08
Samsung Sdi Co., Ltd.	South Korea	142	2.28
Sanyo Electric Co., Ltd.	Japan	124	1.99
Murata Manufacturing Co., Ltd.	Japan	103	1.65
Panasonic Corporation	Japan	103	1.65
BASF SE	Germany	85	1.37
Hitachi, Ltd.	Japan	85	1.37

Source: Based on WIPO data

Trends of development

Various forecasts of the development of energy technologies, including energy storage technologies, focus on two fundamental indicators - the volumes of installed capacities and their price characteristics. In addition, climate change and the subsequent introduction of low-carbon technologies, limiting the rise in global temperature to below 2°C above pre-industrial levels, has become an important parameter for assessing the development of modern energy. In particular, such a scenario - REmap Case - is proposed in [74]. This perhaps represents an overly optimistic development option, the implementation of which would require an unprecedented level of coordination and effective action by governments, developers and investors. The data obtained on the basis of these scenarios represents more of a desired guideline than a practical guide for businesses and administrations. So in [74] in the REmap Case it is assumed that by 2050 the total capacities of pumped storage stations in the world will increase to 325 GW, or approximately twice as much as current levels. An even more optimistic forecast for the development of pumped storage energy is given in [75]. Here, according to the “low” estimate, the total volume of pumped storage will reach 412 GW by 2050, of which 119 GW will be installed in China, with 58 GW in the USA and 91 GW in Europe. According to the Hi-REN study, which factors in a more intensive development of renewable energy sources that require support from energy storage systems, the total capacity of the pumped storage stations will reach 700 GW.

Similar prospects have been forecasted for CSP technology. According to [74], the total capacity can increase from the current 5 GW to 633 GW by 2050. It was noted above that most of these stations are now equipped with thermal energy storage systems, which allows us to conclude that the pumped storage stations will finally have a strong competitor in terms of scale.

The most complete analysis of the future development of electric energy storage systems up to 2030 is given in [2]. Here it is assumed that between 2017 and 2030 the total accumulated electric power capacity will increase from 4.67 TWh to 6.62 - 7.82 TWh per the REmap Reference case or to 11.89 - 15.27 TWh per the REmap Doubling case. In the latter case, this means an increase of 155-227% compared with 2017 figures. These developments, according to [2] will be provided by three main technologies - PHS (pumped hydro storage), CSP (concentrating solar power) and BES (battery electricity storage). The total PHS capacities are expected to increase from 1560 GW in 2017 to 2340 GW by 2030, while the share of storage tanks will drop from about 96% in 2017 to 83-88% in 2030 per the Reference case and to 45% - 51% by 2030 per the doubling REmap case [2]. Replacing the decreasing share of PHS could be provided by CSP with thermal storage - 225-405 GWh with 45 GW of installed capacity in 2030 (Reference case) or, in a completely fantastical option, 385 GW of installed CSP capacity (REmap Doubling case) which “could become a major source of electricity storage, with 1,925 to 3,465 GWh in place by 2030” [2].

According to [2], BES can contribute to this process by increasing the total number of electric vehicles (from 59 to 159 million, depending on the scenario). This corresponds to an increase in stored energy from 22 GWh in 2017 to 918 - 1,377 GWh in 2030 in the Reference case and to 3,290 - 4,021 GWh in the REmap Doubling case.

With dynamic development. by 2030, PHS may account for 45% of all stored energy, CSP - 23% and passenger electric vehicles - 21% [2].

In this document, it is also assumed that BES and PV systems have serious prospects both at the utility-scale level and for rooftops. By 2030 «... in the Reference case, approximately 9 GW of global small-scale PV capacity will be retrofitted with BES, resulting in a storage capacity of 11-18 GWh...» and «...in the REmap Doubling scenario, this level could be approximately doubled and result in 22-36 GWh of retrofitted storage in 2030» [2].

In [4], a Levelized Cost of Storage (LCOS) analysis was conducted for the period 2015 to 2030 for major energy storage technologies. First of all, a sharp decrease in price discrepancy is predicted for almost all technologies, and this is especially notable for lithium batteries. For most technologies, LCOS will be in the price range of 50-150 EUR / MWh, including Sodium-sulphur batteries, Compressed-air energy storage, Pumped Storage, Lead acid batteries, and Flywheel technology. Slightly higher LCOS values are predicted for Redox flow batteries and Lithium-ion batteries (between 100 and 200 EUR / MWh). In more near-term forecast until 2024 [72] it is assumed that the cost of Utility-Scale Energy Storage Systems based on Pumped Storage, Lithium-ion batteries, and Flow batteries will be approximately $350/KWh, and for Compressed-air - $200/KWh. It also provides detailed forecasts of the annual growth of Stationary Energy Storage Power Capacity for most regions of the world.

In [57] the U.S. International Energy Administration evaluated the growth of U.S. Large-Scale Battery Storage Capacity up to 2050. The most explosive growth is predicted to occur between 2020 and 2030 with an increase to 37-38 GW by 2040, eventually reaching an estimated total capacity of 40 GW by 2050. It was previously noted (Fig. 22) that in 2018 this figure amounted to just over 800 MW, the vast majority of which was provided by lithium-ion batteries.

In [76], with reference to Bloomberg New Energy Finance, the authors presented the data on the cumulative growth of battery storage for the main consumer countries until 2030. By this time, the global market is estimated to be approximately 120-130 GW, with around 25% of this capacity forecasted in the United States, and 10-12% for Japan, China and India.

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