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Review

Comparative Analysis of Energy Storage Methods for Energy Systems and Complexes

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Abstract: The daily non-uniform power demand is a serious problem in power industry. In addition, recent decades show a trend for the transition to renewable power sources, but their power output depends upon weather and daily conditions. These factors determine the urgency of energy accumulation technology research and development. The presence of a wide variety of energy storage mechanisms leads to the need for their classification and comparison as well as a consideration of possible options for their application in modern power units. This paper presents a comparative analysis of energy storage methods for energy systems and complexes. Recommendations are made on the choice of storage technologies for the modern energy industry. The change in the cost of supplied energy at power plants by integrating various energy storage systems is estimated and the technologies for their implementation are considered. It is revealed that in the large-scale power production industry, the most productive accumulation methods for energy systems and complexes are the following: pumped hydroelectric energy storage systems, thermal and thermochemical accumulations, and hydrogen systems. These methods have the best technical and economic characteristics. The resulting recommendations allow for the assessment of the economic and energy effect achieved by integration of storage systems at the stage of designing new power units.

Keywords: energy storage; hydrogen energy; energy systems; CAES; thermochemical accumulation

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1. Introduction

1.1. Relevance of the Development and Introduction of Energy Storage Systems

The rapid increases in world population and industrialization have caused an increase in power consumption. The International Energy Agency data show a power consumption growth of more than 36% in the last 20 years [1]. This has led to the active development of thermal and electric power production technology, transport, storage, and consumption. New renewable sources of technology, experimental power production facilities which run on traditional hydro-carbon fuels with zero harmful emissions [2], and R&D works on hydrogen power production [3] are all being developed.

The increase in renewable power sources is part of a global trend in the industry. New solar, wind, and other facilities are being constructed and entering operation. The portion of these sources in the world power production balance is 28%, and this will grow in the near future. The main factors that determine this trend are the number of practically inexhaustible primary energy sources and the prospect of almost zero harmful atmospheric emissions. On the other hand, the inconstancy in terms of supplied energy and its direct relationship with weather conditions, i.e., wind or clouds, remarkably limit the direct use of renewable sources in power supply systems.

A key feature of power supply system operation is power demand time non-uniformity. Uneven electric power consumption during daytime, week, and year periods requires the operation of production facilities with similar non-uniform loads. Modern thermal and nuclear power plants operating on steam–water energy cycles are by far the most common sources of power supply and are characterized by relatively low maneuverability in terms of the main equipment. Their operation in dynamic and low loads modes causes faster equipment wear and lower reliability and efficiency, which results in increased energy supply costs. In nuclear facilities, dynamic operation of reactor circuits is impossible because of design-specific features.

These factors bring about the necessity of creating the conditions for system load smoothening. Here, one of the prospective directions is the introduction of energy accumulation systems to stabilize the power consumption and production and to expand the controllability ranges of low maneuverability facilities [4]. These systems may cover system peak loads by using the energy accumulated during low power consumption periods (Figure 1a) or by using the constant power of the facility (Figure 1b) [5–7]. In the electricity market, accumulation systems may accumulate energy during the low price periods and supply it during the higher demand periods at higher electricity prices [8,9].

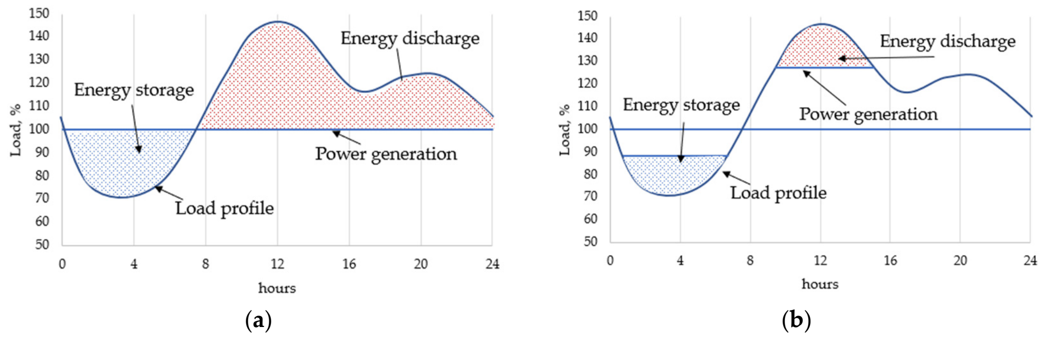


Figure 1. Accumulation system operation in a power grid: (**a**) load leveling; (**b**) peak shaving.

1.2. Energy Storage Methods Classification

The energy accumulation principle is based on the transformation of primary energy into a form that is easier to accumulate and store as well as its further transformation into a customer-acceptable form (Figure 2). The accumulation process may consist of sequential transformation elements or of direct accumulation without transformation, for example, the accumulation of water in a municipal heat supply system. Nowadays, the methods of energy accumulation differ with the type of primary energy and storage form.

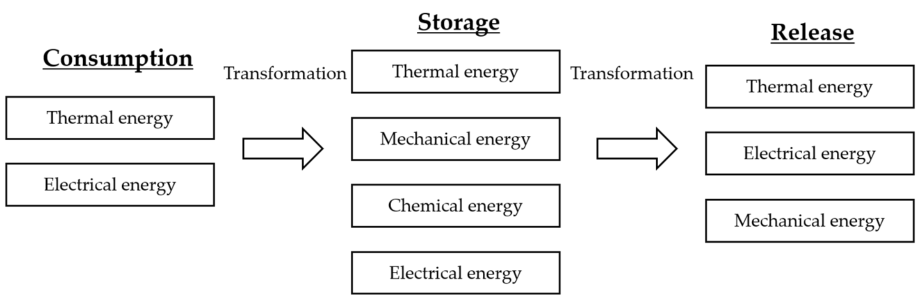


Figure 2. Energy transformation sequence of an accumulation system.

The classification of accumulation methods is necessary because of the variety of methods. The classification approaches are based on the stored energy type, the forms of consumed and supplied energy, the storage capacity, or the form of primary energy. Figure 3 presents the classification by primary energy type of the accumulation methods that may be applied to power supply systems. The accumulation systems may be split into electrical or thermal primary energy forms. The thermal energy supplied to the system may be accumulated in the form of heat capacity internal energy or the heat carrier storage in heat insulation systems, for example, accumulating tanks in a city water network. These are known as heat capacity accumulation systems. Another method involves the application of thermal energy to a special material, such as salt alloys or low melt metals, so as to change the material. This so-called phase transition accumulator method uses phase transition internal heat. Another prospective technology is known as thermochemical energy accumulation, whereby thermal energy is used in a reversible chemical reaction and the energy is accumulated via the storage of reaction products.

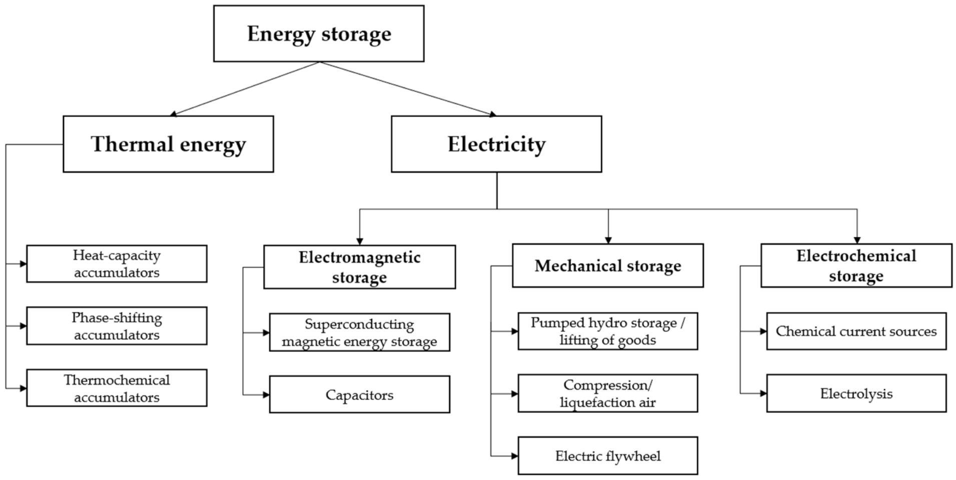


Figure 3. Classification of energy storage systems.

Another class of accumulation system may be defined as the transformation of primary electrical energy by electro-magnet accumulators, which store energy in the form of electrical or magnet fields. Mechanical accumulators transform electrical energy into the potential or kinetic energy of a working substance. Electro-chemical accumulators store the energy via chemical processes.

The performance of the mentioned accumulation methods may be described by their specific energy transformation sequences, maximal capacities, power, costs, etc. The application of methods to a power production systems ought to be preceded by an analysis of the performance and specific features of existing and prospective accumulation methods, the possible versions available, and the methods of introducing them into power production systems.

This paper presents a review and comparison of energy accumulation methods. The most prospective schemes are chosen and recommended for their application to power production systems.

2. Methods for Electric Energy Accumulation

If the primary energy is electricity, it may be accumulated in the form of an electromagnetic field. The energy may be accumulated in magnetic field form promoted by a superconductive coil (superconducting magnetic energy storage—SMES). This system can promptly release its energy into a grid. The use this type of accumulator for grid operation support is promising [10]. However, these systems are not widely used because of the necessity to keep the temperature low in the superconductive coils, which results in high costs [11].

Capacitors and supercapacitors accumulate energy in the form of an electrical field formed between electrodes by a potentials difference. Such devices may produce up to high power levels but their capacity is smaller than that of other systems [12] and the cost for 1 kWh storage may be too high, making this accumulation method uncompetitive [13].

Additionally, electric energy may be transformed into the potential or kinetic mechanical energy of various solid bodies. The Figure 4 shows an accumulating facility that uses electricity to lift a massive object. This facility accumulates potential energy by lifting the load against gravity forces, with the load descending to discharge electricity production [14]. This technology can be used separately from energy systems, where the special materials are used as cargo, or it can be integrated into technological processes at facilities and enterprises where it is necessary to frequently lift and release various objects [15]. There are works that consider the use of gravitational energy storage systems with the integration of renewable energy sources [16,17]. The authors of [18] analyzed the prospect of using of a gravitational energy storage system in existing shafts of hard coal mines in Poland. The authors found that the obtained economic effects of the solution were low, and therefore there was no economic justification for activities related to its implementation.

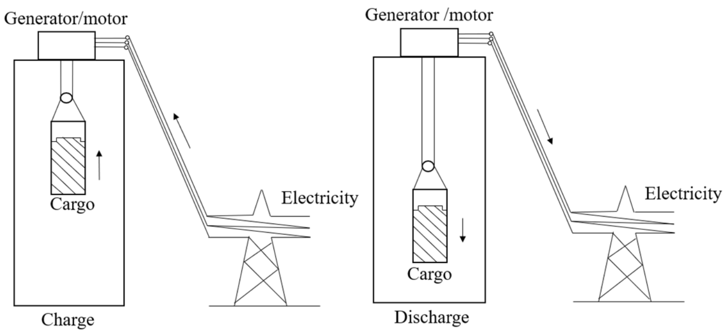


Figure 4. Gravitational energy storage system.

The pumped hydroelectric energy storage (PHES) principle is similar. A PHES uses either a set of generators and pumps or a convertible hydroelectric facility that can operate in generator or pump modes (Figure 5). During the power consumption drop which occurs at night, the PHES system takes power from an electric grid and uses it to pump water into the pool located high up. During peak power consumption in the morning and afternoon, the PHES system releases water from the high pool to a lower one, producing electricity and supplying it into a grid. Modern PHES systems exhibit 60–80% efficiency [19].

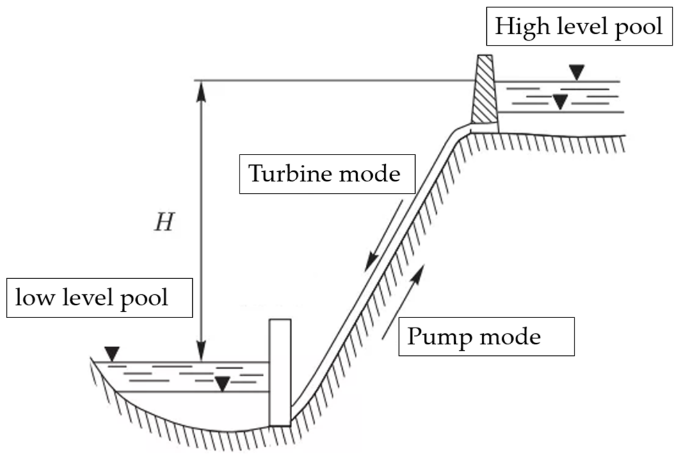


Figure 5. Pumped hydroelectric energy storage.

The remarkably large amount of accumulated energy is limited by the pool volume. Nowadays. PHES systems are widely used and make up over 96% of world energy accumulation storage [20]. In addition to its high capacity, a PHES system can produce high power at high discharge velocities. Furthermore, this method has almost zero storage losses or a nearly zero self-discharge level. The shortcoming of this method is the necessity of the facility to be located nearby to a water source and the necessity of a water pond buildup, which may be environmentally harmful and capital intensive because of the water pond levels.

Certain projects store electricity in the form of compressed air potential energy (compressed air energy storage—CAES). Electricity drives an air compressor that supplies compressed atmospheric air to accumulator vessels. In high-capacity systems, the compressed air is usually stored in natural caverns or salt caves (Figure 6). For system discharge, the high-pressure air is supplied to a combustor or to an air heater, and then the energy is utilized in a gas turbine [21].

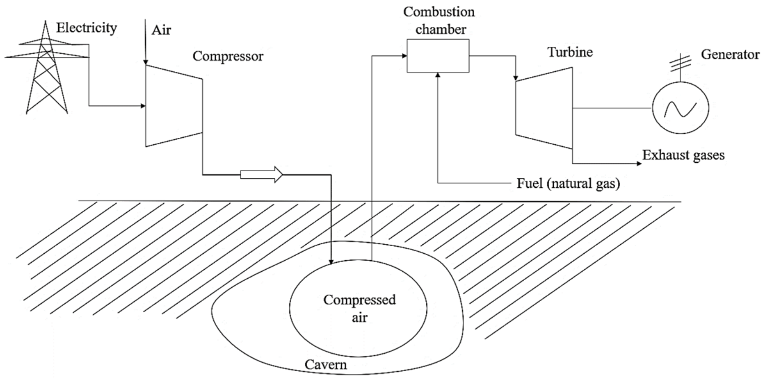


Figure 6. Compressed air energy storage system.

Nowadays, at least six CAES projects have been introduced and at least seven projects are being developed (Table 1). The existing CAES projects have a maximal power of 290 MW (Huntorf plant) and a 2860 MWh capacity (McIntosh) [22]. Nearly all operating CAES systems store air in salt caves [23].

Table 1. Operating and planned CAES projects.

Location	Year	Power, MW	Capacity, MWh	Efficiency, %
Operating CAES projects				
Huntorf plant, Germany	1978	290	580	42
McIntosh, Alabama	1991	110	2860	54
Gaines, Texas	2012	2	-	-
Goderich, Ontario	2019	2.2	10	-
Jiangsu, China	2022	60	300	60
Zhangjiakou, China	2022	100	400	70.4
Sardinia, Italy	2022	2.5	4	-
Planned (and unrealized) CAES projects				
Bakersfield, California	2009	300	-	-
Watkins Glen, New York	2010	150	-	-
Essen, Germany	2013	200	1040	70
Cheshire, Britain	2017	40	800	-
Northern Ireland	2019	330	-	-
New South Wales, Australia	2022	200	1600	-
San Luis Obispo, California	2022	400	3200	-
Rosamond, California	2022	500	4000	-

In addition to the transformation of electricity into potential energy, certain systems transform it into kinetic energy, specifically into flywheel rotation energy. An electric motor rotates a massive body located in a vacuum pit. The friction losses are small, so the flywheel shaft saves its rotation energy for a time. In the discharge, this energy is spent for the electricity generator drive [24]. The capacity of such accumulators is mostly determined by the flywheel mass and size, so these systems are not widely used. The flywheel can store energy for a short amount of time, and these systems have a high degree of self-discharge. The maximum storage period usually does not exceed 1 h, so this technology has not been widely used in power systems and complexes.

Electric energy may be accumulated in a secondary power source or an electric accumulator. This method is widely used in modern devices, from domestic gadgets to transport. In the power industry, accumulators are not so widely used, especially in high-capacity systems. Most of the projects of this type are based on the application of lithium-ion accumulators. Lithium-ion batteries have a high energy density, high efficiency, and low self-discharge. Existing storage projects based on the operation of Li-ion batteries can develop a discharge power of up to 100 MW, with their round-trip efficiency reaching 95% [25]. Another important advantage of these batteries is their high specific mass and volume capacity.

This is due to the advantages and efficiency of this type of system. To compare the capacities and power parameters of different chemical batteries, lithium-ion accumulators have the best capacity and specific power and smallest self-discharge degree. Because of these advantages, most existing high-power projects use systems of this type.

Electrolysis facilities with hydrogen fuel accumulation are also a prospective energy accumulation direction. These systems use electricity for water electrolysis and hydrogen production. The hydrogen is stored in storage systems, vessels, or natural subterranean cavities. Then, electricity is produced by hydrogen combustion in a gas turbine or in a fuel cell (Figure 7) [26]. The accumulation capacity is directly determined by the amount of stored hydrogen. The power of the facility is determined by the electrolyzer and gas turbine or the fuel cell performance.

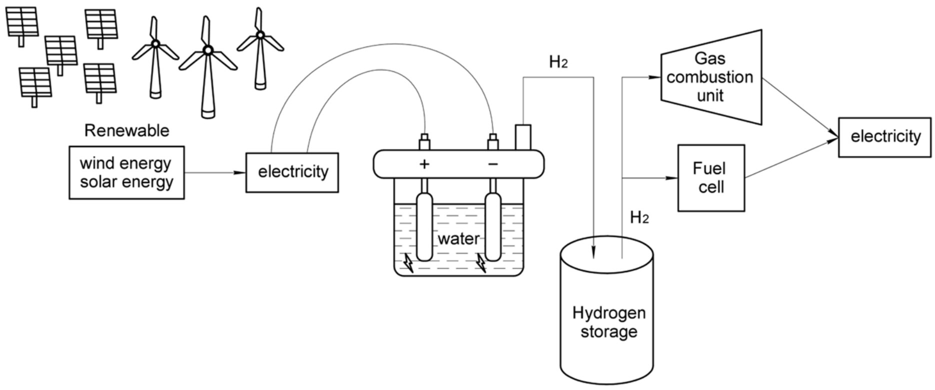


Figure 7. Hydrogen energy accumulation scheme.

This technology is promising due to the possibility of a large amount of energy being stored and a high-power capacity. In [27], the authors showed that the hydrogen storage capacity may be equal to or even higher than a PHES system. However, this technology has many problems which are yet to be solved concerning the production, transportation, and storage of hydrogen fuel. Furthermore, the high capital costs of the main components of hydrogen storage systems (fuel cells and electrolyzers) is one of the key problems concerning their implementation in the energy sector [28]. Although the system's efficiency is still comparatively low, hydrogen accumulation system technology is a prospective R&D direction [29].

3. Thermal Energy Accumulation Methods

In heat insulating systems, a heat accumulator stores energy as the internal energy of a heat-accumulating material (thermal capacity filling) or as the physical storage of a high potential heat carrier. Currently, the most widely used accumulators of this type are heated water accumulators. These are favored because of the low price of water, their high heat capacity, and their availability [30].

These systems require the efficient heat insulation of the accumulator tank walls since the thermal resistance directly determines the self-discharge rate. The water tanks are often subterranean or semi-subterranean, with the walls partly or completely located below ground level, which reduces the heat flux through walls [31]. These systems have a high accumulation capacity and a low self-discharge rate. Systems featuring heat storage in the ground or the storage of underground material are more simple from a structural point of view, but they have a lower energy storage capacity [32].

A system may store high temperature or cool water. When used with the cool water, the system works as a frost accumulator. Ice accumulation forms another class of system.

Heat accumulation systems with high potential heat carriers have an efficiency of 59 to 90 % due to pumping and heat conductivity losses. Their storage capacity is determined by the accumulator tank volume and the allowable temperature of the heat carrier. In Russia, subterranean or semi-subterranean tanks of 20 thousand cubic meters are currently available. An increase in tank volume reduces the specific capital investment in terms of energy storage [33,34].

In addition to accumulation in the heat capacity of a carrier, heat may be stored by means of phase transition accumulators. During low power demand periods, a portion of the produced energy may be used for the phase transition of a low melting agent, for example salt alloy [35]. At the moment of the peak load, the heat is usually released by the crystallization of the agent. This accumulator type has a high energy capacity that is due to the accumulation process performance. The phase transition heat of salt alloys and low melt metals is much higher than that needed to hear water up to 95 °C. Table 2 summarizes the main parameters of the metals used for phase transition accumulators (PTA). Works are also underway to develop new materials for phase transition energy storage systems [36–38].

Table 2. Materials for phase transition accumulators.

PTA Type	Melt Temperature Range, °C	Accumulated Energy Density, MJ/m^3
Organic staff	20–70	150–250
Salt hydrate and mixtures	25–80	200–400
Salts and mixtures	140–1000	300–1900
Metals and alloys	270–1000	540–3000

Thermochemical energy storage (TCES) systems represent a promising developmental direction. In such systems, heat is used in convertible reactions followed by heat consumption and release. In these systems, energy is accumulated via the storage of chemical transformation components. The thermochemical accumulation reactions may be between a solid and a gas where carbonates, hydroxides, metal hydrides, or metal oxides are used [39]. Additionally, the reaction may be between gases: ammonia synthesis/dissociation, methane reforming, or sulfur base reactions (Figure 8).

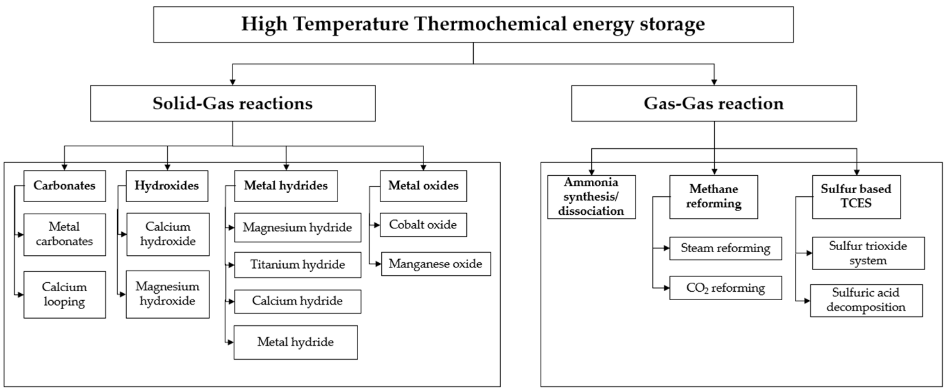


Figure 8. Thermochemical accumulation reactions.

From the point of view of TCES research and development, the main convertible reaction parameters are the mass and volume-specific reaction heat, the operating temperature and pressure, and the availability of components. More than 20 different types of reversible thermochemical reactions are known in the context of energy storage and transportation systems, including the dissociation of ammonia (1), calcium carbonate and calcium hydroxide (2), (3) steam and carbon dioxide reforming (4), and others (5) [40]:

$$2NH_3(g) + 67\ kJ/mol <—> N_2(g) + 3H_2(g) \tag{1}$$

$$CaCO_3(s) + 178\ kJ/mol <—> CaO(s) + CO_2(g) \tag{2}$$

$$CaO + H_2O <—> Ca(OH)_2 + 104\ kJ/mol \tag{3}$$

$$CH_4(g) + H_2O(g) + 250\ kJ/mol <—> 3H_2(g) + CO(g) \tag{4}$$

$$CH_4(g) + CO_2(g) + 247\ kJ/mol <—> 2H_2(g) + 2CO(g) \tag{5}$$

The reversible reaction components may be used for accumulation or for long distance transportation. Heat is consumed in an endothermal reaction, and the reaction products may be stored or transported. An exothermal reaction takes place at the energy consumer site. The produced heat is consumed during the discharge periods. The reaction products are accumulated and transported to the heat source where they are used for charging [41].

4. Areas for the Application of Accumulation Methods

4.1. Main Performance Charactristics of the Accumulation Systems

The large variety of accumulation methods requires a comparative analysis of their performances based on the main parameters defined for the comparison. The main parameters to be marked are the following:

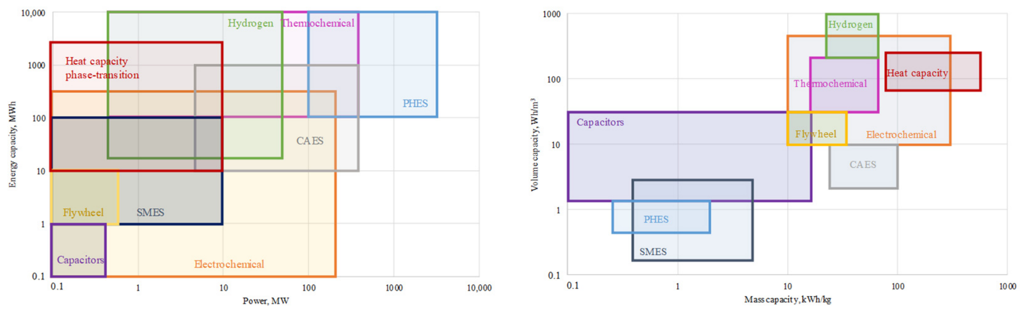
1. Energy capacity, which describes the maximal amount of stored energy, MWh;
2. The system charge/discharge power or round-trip power, MW;
3. The round-trip cycle efficiency, which describes the energy losses in the accumulation system transformation sequence, %;
4. Self-discharge, which describes the energy losses associated with long-term energy storage, %/day;
5. Specific mass/volume capacity and power, which determine the mass and dimensional system performance, MWh/kg (MWh/m^3);
6. Cost parameters, which show capital investments per unit of energy capacity ($/MWh) and power ($/MW).

In power production systems, these performance characteristics determine the applicability of the technology.

The performance of existing and prospective accumulation systems may be remarkably different. The review of published materials creates a foundation for a comparative analysis in term of operating and developing accumulation methods.

Figure 9a shows the storage capacity and power of each accumulation system. The capacity of the largest pumped hydroelectric energy storage system in the world (Fengning Pumped Storage Power Station, China) is currently up to 3.6 GW [42], with the storage capacity primarily being determined by the water reservoir volume. A thermochemical accumulation and hydrogen system capacity is primarily determined by the storage, gasholder, tank, subterranean cavity size, and its power is limited by the performance of the equipment.

Figure 9b compares the mass and dimensional performances of accumulation systems. The mass and dimensional capacity of hydro-accumulating plants is directly determined by the pool's height difference. These PHES parameters are comparatively low. Hydrogen, thermochemical, and thermo-capacity systems have perform better, first of all because of the high combustion heat of hydrogen or the power output in fuel cells and the heat of reversible reactions and phase transformation. Flywheel technology cannot be used for the storage of large amounts of energy.



(**a**) Power and storage capacity (**b**) Volume and mass capacity

Figure 9. Main performance of energy accumulation systems.

Heat capacity accumulation systems are among the cheapest type of system (Figure 10). Hydrogen and chemical accumulations are the most capital-intensive energy storage methods.

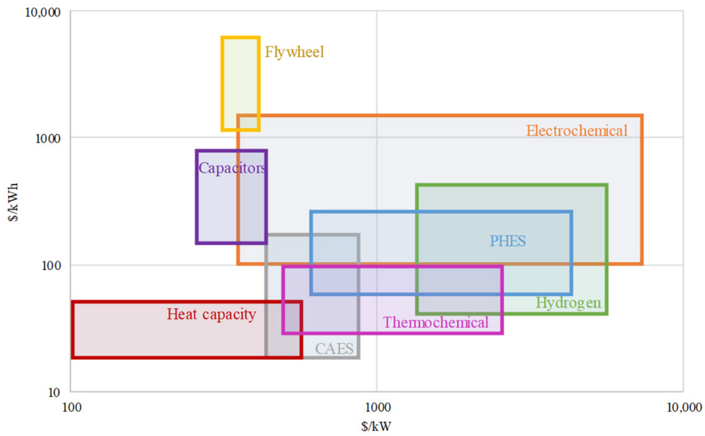


Figure 10. Cost of energy accumulation systems.

In addition to these parameters, an important applicability factor is the possibility of the accumulation facility location being at a short distance from power production or consumption objects. For example, hydro-accumulating power plants require water ponds or storage and the air accumulators require large subterranean cavities such as salt caves, which significantly limits the locations of such systems.

4.2. Accumulation Systems in Energy Production Systems and Complexes

The choice of the accumulation system type and scheme is a topical problem. Most of the reviewed methods may be combined with other power generation facilities such as solar or nuclear facilities. This may improve the flexibility and stability of a power plant. Also, this may help in support of the electricity grid regime.

Feed water accumulation (Figure 11) is a promising option for thermal and nuclear power plants that work in water–steam cycles. During the charge period, a pump supplies an additional condensate flow from the cold condensate tank. The feed water is heated up to the given temperature by an additional heater operating on primary steam, and the steam flow into the high-pressure heater (HPH) is increased. Additionally, a drop in the boiler steam production reduces the block power. During the discharge period, the feed water is supplied from the accumulator tank into the feed water pipeline after regeneration. The excessive condensate after low-pressure regeneration enters the "cold" condensate tank. The power increase is provided by the HPH reduction or termination in the discharge regime. The accumulator tank pressure in the discharge mode is maintained by its connection with the primary steam pipeline, which prevents the water from boiling.

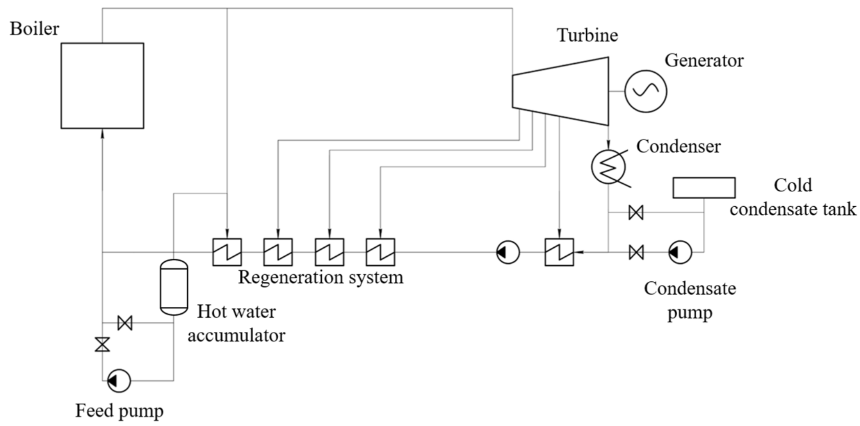


Figure 11. Heat flow chart of TPP with feed water accumulator.

Besides the feed water accumulation, a thermal power plant (TPP) may use the heated water accumulation that is storage and release of the district heat supply water (Figure 12).

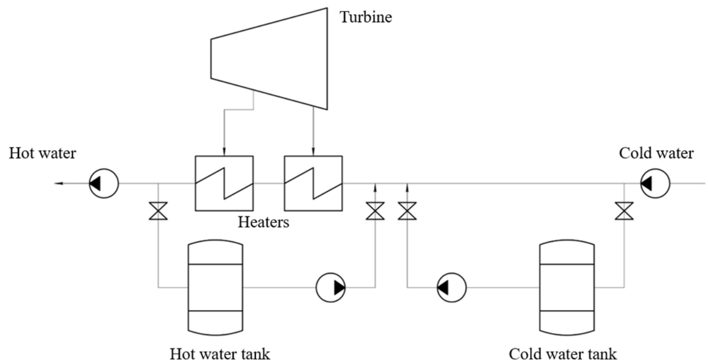


Figure 12. Heat flow chart of TPP with heating water accumulator.

The accumulation of water heat carriers in atmospheric type tanks is limited by the 95 °C fluid temperature that prevents the water from boiling. The manufacturing and operation of high-pressure tanks is complicated, and their price is significantly higher than that of atmospheric tanks. To achieve heat accumulation at a higher temperature, it is necessary to use an intermediate accumulating heat carrier, for example, of oil (Figure 13). This method's higher boiling temperature allows for accumulation at a higher potential heat, but this requires additional heat exchangers to transfer heat from the steam–water heat carrier.

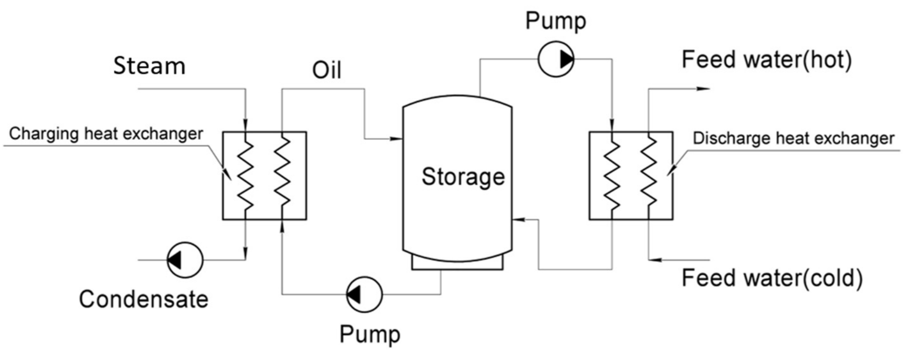


Figure 13. Heat flow chart with an intermediate heat carrier.

In addition to heat carrier accumulation, energy may be stored by using a phase transformation accumulator. During the low demand period, a portion of the produced heat is used for the phase transformation of a low melting agent, for example, salt alloy. During the peak load period, the heat is usually released by the crystallization of the agent, and the energy is used, for example, in a special peak turbine that covers the peak loads (Figure 14).

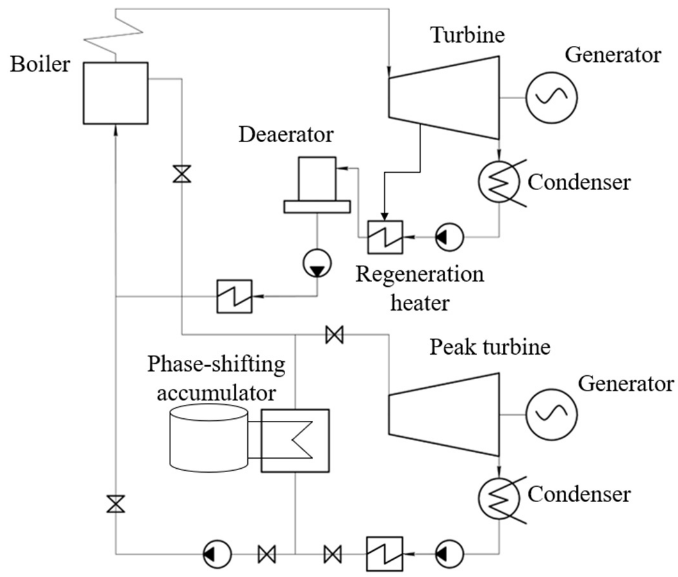
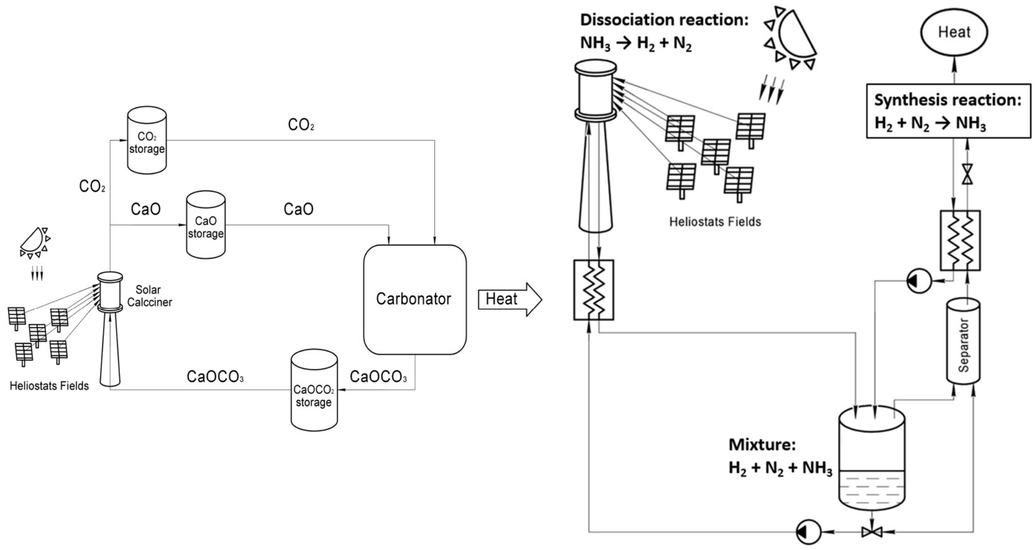


Figure 14. Heat flow chart of a TPP with phase transformation accumulator.

Another prospective power block scheme featuring thermochemical heat accumulation is energy transformation based on a thermochemical reaction with heat consumption and release.

Papers [43–45] describe the accumulation of the heat obtained from renewable heat sources by reversible reactions based on calcium. The cycle charge involves the reaction of $CaCO_3$ synthesis with heat consumption in a carbonator. In the discharge, it dissociates into carbon dioxide and calcium oxide, with the heat release occurring in a calciner (Figure 15a). Another example of this is the application of ammonia synthesis and dissociation (Figure 15b) [46,47].



(**a**) (**b**)

Figure 15. Thermochemical accumulation in a solar power plant: (**a**) calcium carbonate synthesis cycle; (**b**) ammonia synthesis cycle.

Papers [48,49] considered heat transportation and storage via methane reversible reactions, carbon dioxide, and steam reforming (Figure 16). The reforming catalytic reaction produces a synthesis gas that enters a reactor where it produces methane, carbon dioxide, and water and releases heat that is supplied to a customer. This released heat may be also used in a traditional steam turbine cycle.

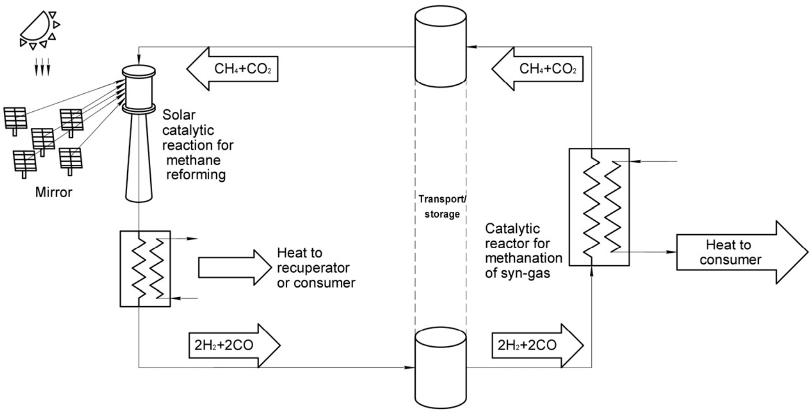


Figure 16. Thermochemical accumulation in a solar power plant.

In addition to reversible chemical reactions, a thermochemical accumulation systems may employ synthesis gas from methane for direct combustion and the feeding of a gas turbine (Figure 17) [50,51]. A portion of the combined cycle facility flue gas heats the methane, reforming and synthesizing gas production. During the discharge period, the accumulated synthesis gas is burned in a gas turbine for additional electricity production.

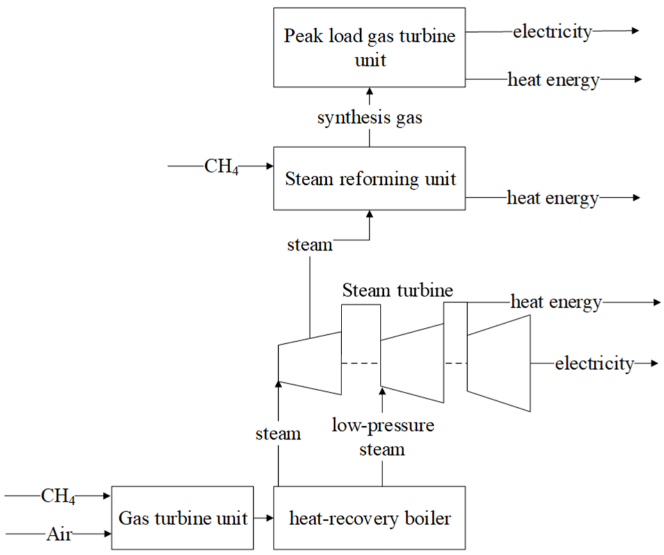


Figure 17. Combined cycle facility equipped with methane steam conversion.

Electrochemical accumulation systems with electrolyzers may produce additional fuel by superheating wet steam for low-pressure turbines in thermal or nuclear power plants [52]. The electrolyzers take power from a grid or from NPP auxiliar consumption and uses it for the dissociation of water into hydrogen and oxygen. During discharging, the fuel burns in a hydrogen combustion chamber, and the generated steam mixes with the wet steam, with the high-pressure turbine increasing its temperature and dryness (Figure 18). Another application of accumulated hydrogen is in reversible fuel cell power production [53]. A hydrogen production and storage system can be up to 30% of the total capital intensity of a station [54].

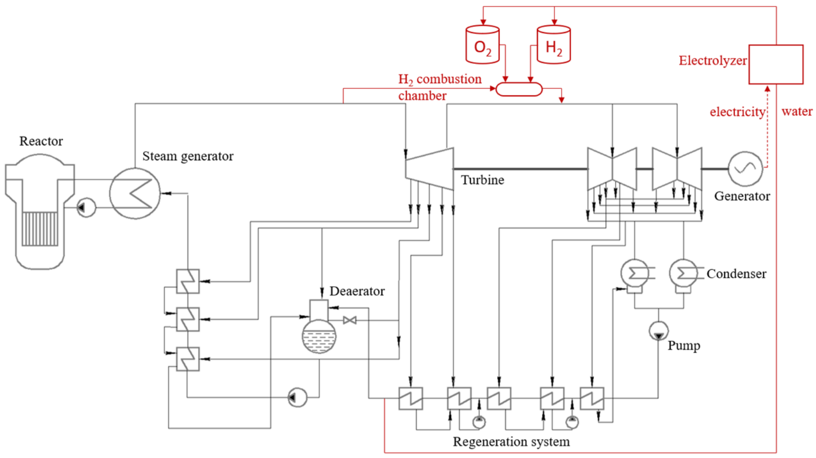
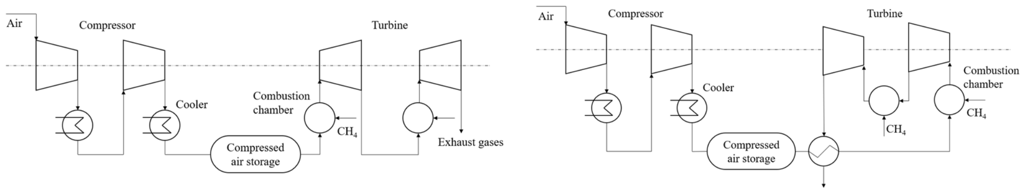


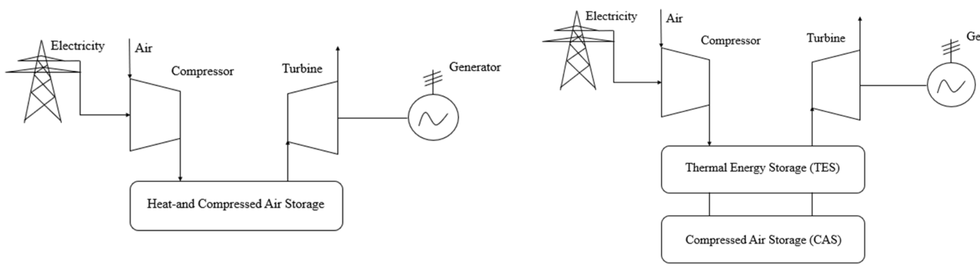
Figure 18. Power plant facility equipped with hydrogen accumulation.

One more prospective method in gas turbines is the compressed air energy storage system (CAES). A small number of CAES facilities operate such systems successfully. Built in 1978, the CAES facility in Huntorf (Germany) was the first and simplest possible facility, with minimal power production equipment in the form of an air compressor, combustor, and gas turbine (Figure 19a). The facility efficiency was below 42%. The CAES facility in McIntosh, USA included a heat recuperation system which increased the facility efficiency up to 50–55%. In both facilities, the combustor increased the turbine inlet temperature (Figure 19b). This solution may be reasonable in the case of cheap fuel. Otherwise, it is reasonable to apply fuel-free adiabatic CAES schemes (Figure 20) [55].



(**a**) Huntorf plant (**b**) McIntosh plant

Figure 19. Compressed air energy storage systems: (**a**) Huntorf plant, Germany; (**b**) McIntosh plant, Alabama, USA.



(**a**) Without thermal energy storage (**b**) With thermal energy storage

Figure 20. Systems with adiabatic CAES.

The accumulation of compressed air heat is the key problem in adiabatic CAES systems. The simplest solution to this is the storage of thermal energy in the air heated by its compression (Figure 20a). This requires efficient heat insulation in terms of the storage systems. The high storage temperature reduces the volumetric storage density and increases the compression power. These shortages lower the prospects of such system in comparison to systems with additional buildup accumulation (Figure 20b). In these systems, the compressed air releases its energy into a heat accumulation system, usually a heat capacity system, and the cooled air enters the compressed air storage [56]. During discharge, the compressed air is heated by the heat accumulated in thermal energy storage and expands in a turbine, producing electricity.

The capacity of the compressed air energy storage systems is mostly determined by the subterranean cave, or some other cavity volumes and the maximal compressed air pressure. The system capacity may be increased by a liquation system installed downstream compression (Figure 21). This allows a remarkable reduction in the stored fluid volume [57] and increase in the system total capacity.

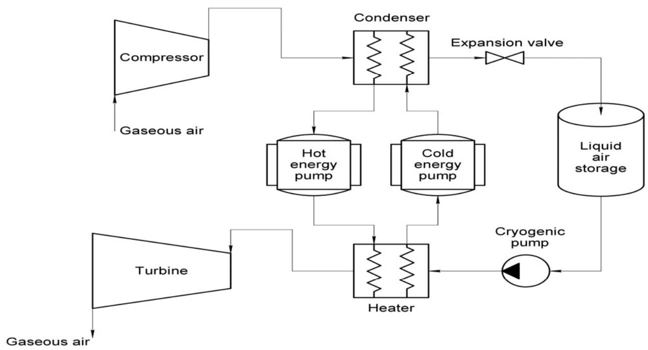


Figure 21. Energy accumulation with air liquation.

Table 3 shows the main financial indicators of certain energy complexes with promising energy storage systems. The addition of storage systems significantly increases the capital intensity of the complex; however, the flexibility of power units increases, and it becomes possible to regulate the load level over a larger range.

Table 3. Main characteristics of energy complexes with energy storage systems.

Energy Complex	Unit Power, MW	Unit Specific Capital Cost, $/kW	Accumulation System Specific Capital Cost, $/kW	Energy Complex Specific Capital Cost, $/kW
TPP with feed water accumulation	50–300	1200	200	1400
Steam turbine CHP plant with heated water accumulation	50–300	1200	100	1300
TPP with phase transition accumulation	50–300	1200	400	1600
Concentrating solar power plant	50–390	5600	2000	7600
CCPP CHP with steam reforming	200–500	1100	1400	2500
NPP with hydrogen superheating	1000–1200	5000	1500	6500
CAES	60–300	700	600	1300

5. Conclusions

This paper presents a review of energy accumulation methods and their application in power production facilities and plants.

1. In the large-scale power production industry, the most promising accumulation methods for energy systems and complexes (systems characterized by the best capacities and costs/performances) are the following:

- Pumped hydroelectric energy storage systems are widely used and approved as a storage technology. The associated large volumes of stored energy and relatively low cost of supplying electricity determined the applicability of this technology.
- Thermochemical accumulation is a promising method that allows for large amounts of accumulation and prompt energy release. The use of this technology can help increase the flexibility of power units.

- Thermo-capacity accumulation includes feed water heat supply tanks and phase transition accumulators. The main advantage of such systems is their low capital costs.

Electrochemical accumulatio, especially electrolysis systems including hydrogen systems, are currently being actively developed. This technology promises a large amount and power, which makes these methods prospective.

2. Accumulation systems may be integrated into power production plants, steam and gas turbine facilities, and renewable power sources. Accumulation systems smooth electricity consumption peaks and supply power in the case of insufficient equipment power due to weather or conditions, etc.

3. Possible options for the use of energy storage systems in energy complexes to increase the possible level of load regulation have been considered. Thermochemical storage systems for concentrating solar power plants, water accumulators for thermal power plants, hydrogen storage at nuclear power plants, and methane reforming at combined cycle power units are an important direction in the development of power generation technologies.

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Nomenclature

CAES	compressed air energy storage
CCPP	combined cycle power plant
CHP	combined heat and power
HPH	high-pressure heater
NPP	nuclear power plants
PHES	pumped hydroelectric energy storage
PTA	phase transition accumulators
SMES	superconducting magnetic energy storage
TCES	thermochemical energy storage
TPP	thermal power plant

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