2020 Ural Smart Energy Conference (USEC)

Assessment of Thermal Storage Technologies in Energy Sector

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***Abstract*—The paper deals with a pressing issue of intensive development of thermal energy storage. This task is especially relevant for modern and promising technologies, for example, alternative energy, electric and hydrogen fuel cell vehicles, etc. The work considers the topical technologies of thermal energy storage systems. A detailed description of several implemented projects related to heat storage (Drake Landing Solar Community and Ice Bear) are represented. It has been shown that the main problems of development and widespread implementation of thermal energy storage are high capital and operating costs. From the brief review of the existing thermal energy projects, it was found that they mainly aimed at solving the problems of air conditioning, heating, reducing peak energy consumption, and supporting renewable energy generation. An impact of the current politics on the development of innovative technologies in the energy sector was considered. It was shown that the most significant factors affecting the R&D and scaling of thermal energy storage technologies are stimulating instruments (grants, privileges, etc.) and customs instruments.**

Keywords—energy storage, heating, air conditioning, peak power

I. INTRODUCTION

Worldwide trends in efficiency, energy savings, and security of power systems ensure an urgent task of R&D for energy storage (ES) technologies [1]–[3]. This task's solution has the potential to significantly decrease the operating expenses for various technologies, including alternative energy, electric and hydrogen fuel cell vehicles, etc. [4]. At the moment, there are numerous technological solutions in the field of ES, among which supercapacitors and flow batteries, electrochemical batteries, thermal batteries, and others). Depending on the form that energy is stored, the general ES technologies are divisible into the following categories:

- mechanical energy storage;
- electromagnetic energy storage;
- chemical energy storage;
- thermal energy storage (TES).

Mechanical energy can be stored as the kinetic energy of linear or rotational motion of bodies and their particles, as the potential energy in a lifted object, as the strain energy of any elastic material, or as the compression energy in a gas [5]. Besides, mechanical energy storage systems can be coupled with solar and wind energies in terms of their utilization [6]. Electromagnetic energy device stores energy in the electromagnetic field with the direct current into a coil unit [7], e.g., super magnetic energy stores and supercapacitor energy stores, which store energy in the magnetic and electric fields, respectively. In chemical ES, energy is stored by using the heats of chemical reactions, which are carried out at both low and high temperatures [8]. For example, the process is based on multi-cycle carbonation – calcination of CaO – $CaCO_3$ system [9]. Moreover, authors [10] presented a new hybrid energy storage system composed of compressed air ES cycle as mechanical storage and amine assisted carbon dioxide capture cycle as chemical ES.

Thermal energy storage is a simple and most environmentally friendly technology. TES is designed for periodic accumulation of heat, and it is taking from it when necessary. The role of TES is likely to grow given it's ability to assist manage the costs and overall system efficiency of HVAC systems during periods of peak and off-peak demand [11]. From an economic point of view, TES is relevant both for the household sector and for the industrial sector. In particular, electric storage heaters in conjunction with a two-tariff meter are widely used in European houses, which allow, due to high-density ceramic bricks and good insulation, to store thermal energy at night, when the cost of electricity is cheaper. In industry, TES devices are in most common use in the store of solar energy and heat in rock caverns, in district-heating (or cooling) networks, etc. [12]–[14]. Heat stores are also widely used in housing and communal services, industrial power plants, transport and construction sectors, renewable energy, and other facilities [15]–[19]. Moreover, TES can be used in various processes at thermal power stations, for example, when cleaning gas [20], [21].

The purpose of this work is to analyze the development of thermal storage technologies in sectors of the energy system.

II. CLASSIFICATION OF TES CONCEPTS

According to the energy conversion method, three types of TES systems are most commonly distinguished: sensible, latent, and thermochemical thermal storages [22]. It should be noted that some researchers in [23], [24] classify TES only into sensible and latent ones. However, the advances in new technologies for the storage and transfer of thermal energy require a more extensive classification. Therefore, within the framework of this paper, TES is divided into three categories (Fig. 1). The sensible heat storages operate on the principle of accumulating energy that is transferred to the storage material during the heating and cooling processes. The stored energy is proportional to the difference in temperature of the used materials. The simplest example of this type of TES is a bed that is warmed before bedtime by a heater. It should be noted that the thermophysical properties of materials (density, heat capacity, thermal diffusivity, et al.) are essential for sensible TES. Sensible heat storages in some cases are subclassified into solid (metals, stones, concrete, etc.), liquid (water, oil, etc.), and solid/liquid (water/pebbles, oil/cast iron, etc.).

The reported study was funded by the grant of the President of the Russian Federation, project number MK–616.2020.8.

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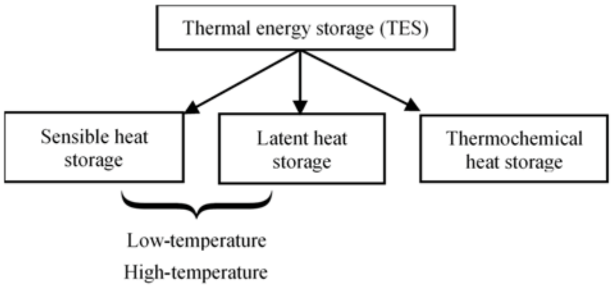

Fig. 1. Classification of thermal energy storage.

Latent heat storages are based on the principle of energy conversion during phase change materials, as a rule, changing from solid to liquid and vice versa. The phase transformation of the storage materials is always associated with the absorption or release of heat under isothermal conditions. An example of latent TES can be given ice production during off-peak hours and using it after for air-conditioning purposes [25], [26]. Stored energy is equal to the enthalpy for melting or freezing. Thermochemical heat storage depends for its operation on the reversible thermochemical reactions. This energy storage systems are substantially more complex than sensible and latent TES because it comprises in addition to heat transfer the mass transfer phenomena and the kinetics of the chemical reactions. Moreover, the stored and released heat is equal to the enthalpy of the reaction.

Sensible and latent heat storages are also classified into low-temperature and high-temperature systems. At the same time, the temperature range characterizing a specific system (low-temperature or high-temperature) differs for sensible and latent TES. So, the category of low-temperature sensible heat storages includes the processes at temperatures up to 100 °C, whereas to latent heat storages – up to 120 °C. Respectively, the category of high-temperature sensible heat storages includes the processes at temperatures above 100 °C to latent heat storages – above 120 °C.

III. APPLICATIONS OF TES IN POWER SYSTEMS

The current trends in the world towards energy saving, energy efficiency, and green energy indicate that the energy balance is shifting from traditional forms of energy generation to thermal energy storage. This is evidenced by TES projects developed and partially or fully implemented, such as Crescent Dunes Solar Energy Project (SolarReserve, LLC, USA), Concentrating Solar Power (Terrafore Technologies, LLC, USA), thermodynamic energy storage (Caspian Energy Group, Russia), etc. In recent years, many global projects relating to TES and its further use have been realized. Note that the most intensive development of thermal storage technologies was obtained in Western countries due to their geographical location and climatic characteristics.

One of the most unprecedented implemented projects is the Drake Landing Solar Community. It is a master-planned neighborhood in the Town of Okotoks (Canada), consisting of 52 single houses. The essence of the project is to use boreholes as long-term storage and tanks as short-term storage of thermal energy received in summer from 798 flat plate solar panels located on garage roofs. On average, the indoor heating system emits about 6 to 7 tons of greenhouse gas emissions (GHG) per household annually into the environment. The main objectives of the Drake Landing project were to reduce GHG by eliminating the burning of fossil fuels and creating a living area that almost wholly provides itself with thermal energy. An array of solar collectors can generate up to 1.5 MW of heat over a single summer day. Average monthly maintenance costs 60–70 $ [27]–[29].

Solving the peak power problems, Ice Energy (California, USA) developed large-scale industrial power technology of TES called the Ice Bear. The principle of operation is as follows: to freeze water in ice chillers into an ice block at night (off-peak hours) and to melt it during the day to cool the air. Ice Energy investigated that blocks of ice reduced total electrical system demand by 30 % and excluded the use of generating plants. Nowadays, the Ice Energy company executes the contract for Orange County (South California, USA), providing 26 MW over 5 years through 1800 Ice Bear units for 3600 roof AC. Storage of the electric power in the form of ice becomes more regular technology [30].

From the TES projects mentioned above, it can be concluded that new technologies in the form of energy storage are being realized everywhere, are economically beneficial and environmentally friendly. However, the main negative factor in scaling such projects is the high start-up cost.

Nowadays, the energy sector, particularly the development of thermal energy storage, is highly dependent on politics both in a particular country and in the world. The past years have shown that political conflicts between various countries can destroy their research, production, communications, etc. This fact significantly slows down the progress of any given innovation tasks. Furthermore, some countries have imperfect local laws and poor energy politics, which in some cases prevent innovations from reaching local markets and being competitive with traditional technologies. The paper also considers the influence of political regulators on the development of TES technologies such as stimulating instruments and customs instruments.

As a rule, a new scientific idea of R&D, including TES systems, requires stimulating tools of partial or full funding (grants, privileges, etc.). Also, the companies can work on projects for the practical application of the developed systems in the networks and get regulatory approval for their realization. International experience proves that the majority of the countries (USA, Germany, etc.) successfully use this method in the last decade. In particular, a large number of projects related to the systems of heat storage have been financed. This procedure has proven to be effective and of practical importance, for example, to improve the operational characteristics of new technologies and reduce production costs. In this way, we can gradually decrease the start-up costs of the developed TES systems. Thus, investment in research projects leads to the creation of new products. Of equal importance in the development of TES systems is the legal regulation of international purchase and sale of energy resources through customs and tax legislation. Import duties for raw materials and the equipment for the power industry from other countries are necessary for the production of TES systems. Barriers to the import of necessary materials complicate the competitive position of local producers of TES systems in comparison with producers from developed countries. In paper [31], authors analyzed more than 1687 TES projects according to Global Energy Storage Database from 2015 to 2020. It turned out that most of the projects are related to ES with phase change (74 %), then sensible (24 %), and thermochemical heat storages (2 %) (Fig. 2).

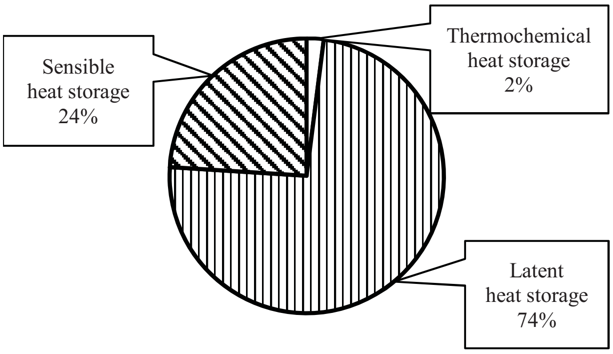

Fig. 2. Percentage distribution of heat storage technologies.

Consequently, the hitherto majority of TES are utilized for ice storage systems (water–ice and ice–water phase changes) and cooling of technological equipment during peak load periods (Fig. 2–3). Thermochemical heat storages have the smallest distribution due to the complexity of the unit design and, accordingly, the higher cost.

The projects under consideration were classified according to the focus areas: air conditioning, heating, reducing energy consumption during peak hours, and supporting the capacity of renewable energy sources. The projects related to sensible TES, in contrast to latent and thermochemical ones, cover all the identified tasks. The percentage is as follows: air conditioning – 9 %, heating – 59 %, reduction in peak power consumption – 16 %, and support for renewable energy generation – 16 %. This scattering of projects by areas is caused by the fact that sensible heat storage systems have the most uncomplicated technical and technological implementation plans.

Latent heat storage projects have the following percentage distribution by areas: air conditioning – 78 % and heating – 22 %. It is notable that in some cases, air conditioning tasks are associated with reducing peak electricity consumption demand as well as supporting renewable energy generation. All thermochemical heat storage devices are oriented towards heating (Fig. 3).

Following the classification of TES presented in Fig. 1, the projects were also subdivided into two groups: low-temperature – 78 % and high-temperature – 22 %. Simple technologies of TES are predominant are noted, which convert energy at low temperatures up to 100 and 120 °C heat storage devices of sensible and latent types, respectively (Fig. 4). This statement is confirmed by the classification of low-temperature and high-temperature TES devices according to focus areas (Fig. 5). All projects of low-temperature TES aim to solve problems related to air conditioning – 72 % and reducing peak energy consumption – 28 %, while high-temperature TES to cover heating – 72 %, supporting renewable energy generation – 19 % and reducing peak demand – 9 % (Fig. 5).

Thus, the projects implemented in recent years on thermal energy storage, in most cases, are focused on solving problems related to air conditioning and heating. This fact can be explained that thermal energy storage technologies for solving these problems are quite simple and require relatively low capital and operating costs.

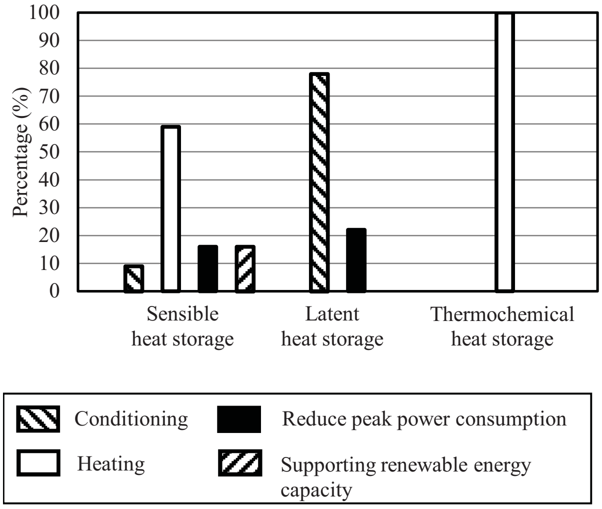

Fig. 3. Percentage of areas in heat storage technologies.

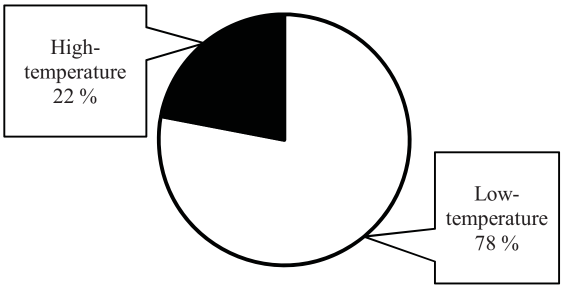

Fig. 4. Percentage of low-temperature and high-temperature TES.

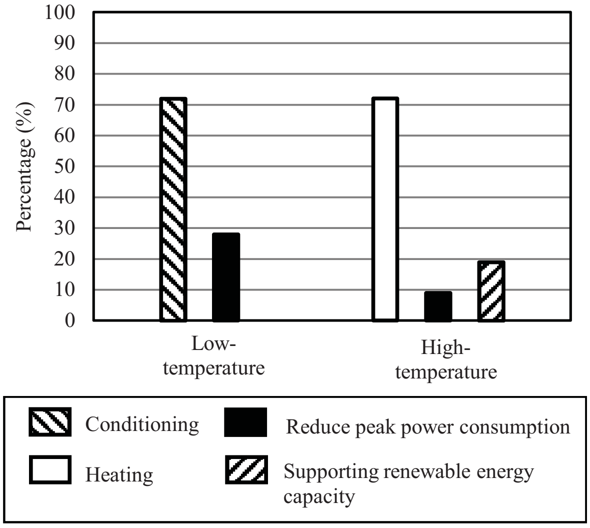

Fig. 5. Percentage of areas in heat storage technologies divided into low-temperature and high-temperature.

IV. CONCLUSION

Based on the analysis presented in the paper, the following conclusions can be drawn:

- the development of TES has a great prospect soon for various technologies. Numerous research projects are almost ready for implementation in many industries;

- high-tech TES projects are complicated by their high start-up cost and payback period;
- development of innovative TES asks complex and transparent work between interdepartmental services;
- development of TES systems requires the legal regulation of international purchase and sale of energy resources through customs and tax legislation;
- stimulating tools of partial or full funding (grants, privileges, etc.) are important factors affecting the development and scaling of TES;
- projects implemented in recent years on TES are focused on solving problems related to HVAC systems.

Based on our analysis of thermal storage technologies globally, we plan to proceed with research efforts in terms of existing and future projects in Russia taking into account the best experience.

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