Sustainability and Environmental Efficiency of Superconducting Magnetic Energy Storage (SMES) Technology

Ruoqian Lu

Faculty of Liberal Arts and Social Sciences, The Education University of Hong Kong, Hong Kong 999077, China

s1137322@s.eduhk.hk

Abstract. In recent decades, with global energy consumption increasing year by year, the issue of energy and the environment has become one of the hot issues of concern. In this paper, the superconducting magnetic energy storage (SMES) technology is selected as the research object, and its sustainability and environmental efficiency are discussed and analyzed based on the United Nations Sustainable Development Goals (SDGs). The results show that the characteristics and performance advantages of SMES technology and devices make it possible to fill the energy supply gap in a timely manner without polluting or disturbing the atmosphere and water environment. Through the study of the existing application direction, development status and policies of SMES technology, this paper also conclude that the current application of this technology is feasible and effective in renewable power generation systems, hybrid power systems and electric vehicles but still has the problems of high cost, which leads to incomplete scale up and low promotion rate. Therefore, this paper presents the outlook and prediction of its future trends, such as iterative superconducting materials and the introduction of monitoring systems. This paper expects to find and evaluate how SMES would meet sustainability goals and ecological requirements and the corresponding further development directions.

Keywords: Energy storage, Sustainability, Environmental efficiency, Superconducting magnetic energy storage.

1. Introduction

In recent years, the energy crisis has become a major international issue, meaning that it is one of the problems and challenges facing all of humanity and all of society, along with important issues such as climate change, global warming, and poverty. At the same time, the concept of sustainable development has become more and more important and has been recognized by the international community. It has been relatively widely accepted and promoted as a reliable and long-term development model. The close linkage between energy and the environment and related issues has also received considerable attention and discussion in this context. To address this issue in a practical way, many long-term studies have been conducted in the field of energy technologies and devices in order to find some new alternative or renewable energy sources, as well as to pursue energy storage technologies or devices with higher efficiency, lower energy consumption, and lower pollutant emissions. Therefore, this paper will focus on a relatively new type of energy storage technology, superconducting magnetic energy storage, and would be divided into four main sections for specific or detailed descriptions. First, the basic concepts and general perspective of the technology, such as definition, principles and classification, would be presented to explain its characteristics and development status. Then, the economic and environmental efficiency will be analyzed, evaluated, and discussed based on the perspective of sustainability. In addition, the main existing application directions of the technology will be compared and organized. In addition, the governmental and industrial policies related to the SMES technology, which has been scaled up to a certain extent, as well as the future development trend, are also worth discussing in a relatively concrete manner and providing feasible suggestions, including pointing out the existing problems and possible improvement directions and measures. The above is also the significance and importance of this study.

It is expected that this paper will discuss the comprehensive benefits of SMES technology in the field of sustainability and environment and provide relatively reliable references and evidence for possible further research or technology iterations and application directions in the future.

2. Overview of SMES System

2.1. Definitions and operating principles

A superconducting magnetic energy storage system, commonly referred to as a SMES system, is a technical facility that uses coils made of superconducting materials to generate a magnetic field when an electric current is passed through it, thereby directly storing electromagnetic energy and having the ability to release or feedback the stored electromagnetic energy to other equipment or facilities, such as the power grid [1]. It takes advantage of the fact that some metals and alloys drop to zero resistance at certain ultra-low temperatures, i.e., the principle of zero resistance effect. Therefore, by keeping the spiral wire made of superconductor wire in a deep cold state and combining the two ends of the solenoid, the effect of circulating current and storing electromagnetic energy can be achieved. This technology was first proposed in 1979 as a device whose main function was to balance the electrical load. In general, a typical SMES system consists of a superconducting magnet and its support structure, a cryogenic vessel or cryogenic system and cooling unit, a power conditioning system (PCS) and a measurement and control system, where the superconducting coil in the superconducting magnet can be considered as the core component of the entire SMES system [2].

2.2. Features and current situation

Based on the above constituent materials, operating principles, and structures, SMES systems have some relatively obvious and well-defined characteristics. Since the resistance of the superconductor could be zero or infinitely close to zero in the low-temperature environment, the energy storage of SMES system would be almost no lost and permanent. Moreover, it could support a relatively large capacity of energy storage with a large amount of energy discharge in a short period of time, and the short response time ensures its operational efficiency. Therefore, it is considered to have relatively high power density and high efficiency and has the ability to respond quickly. This means that it not only has a relatively complete and independent storage-discharge cycle but also is flexible and reliable enough [3]. At the same time, according to relevant studies, the energy conversion efficiency of SMES systems can reach or even exceed 96% under ideal conditions [2].

In addition, depending on the superconducting materials used in the electromagnetic coils of SMES systems, they can be divided into two types: low-temperature superconducting magnets (LTS) and high-temperature superconducting magnets (HTS). It seems that the development of SMES technology would have also gone through a process from LTS to HTS. For LTS, the superconducting niobium-titanium alloy (Nb-Ti) is utilized in the systems. Besides, this alloy requires being operated at 4.2 k. The technology is relatively conventional and requires a relatively high manufacturing cost. The technology is relatively conventional and requires relatively high manufacturing costs. In contrast, high-temperature Superconducting (HTS) coils would work at 70 K. And because they could have lower refrigeration cost and reduce eddy current loss and stray magnetic, it is still in the stage of development [4]. However, this type of SMES equipment would also be still in the stage of performance improvement, and the cryogenic refrigeration system used in superconducting technology would be complex to prepare and has high maintenance frequency [5].

3. Economic and Environmental Analysis

In the context of the global energy crisis in the current generation, the economic and environmental efficiency of an energy storage technology is gaining importance. Considering that the economic and environmental dimensions are also encapsulated under the umbrella of sustainability, this means that in a comprehensive or holistic assessment of the technology, its sustainability, and the expected sustainability goals should also be included accordingly as a benchmark or a requirement that can be used as a benchmark or basis, which will be of considerable importance. The author agrees that superconducting magnetic energy storage technology has some significance or value in this direction, although it would not be strictly recognized as an emerging technology in view of its decades-long development and research history. Therefore, for the superconducting magnetic energy storage technology that is the focus of this study, the extent to which it meets existing, relatively authoritative, generally accepted, and applicable sustainability goals are discussed below, along with an assessment and analysis of the economic and environmental benefits it has or can provide.

3.1. Sustainability and efficiency

SMES technology has gained attraction in society not only because of its technical advantages but also because of its sustainability in the current state of development. Based on the using of superconducting materials and related technologies, in SMES systems, electricity from the grid is stored in a magnetic field composed of superconducting wires, while the components and materials are placed below a low temperature cooled to their critical superconducting temperature, which means that the resistance encountered in DC power would be negligible, and the energy loss could be reduced to and controlled within a small range, theoretically almost zero, and could be stored for an unlimited period of time [6]. Although a certain degree of loss is inevitable during the conversion of DC to AC, the overall energy loss of the SMES system is relatively low and has a relatively high energy storage efficiency. Moreover, as mentioned above, the system has a fast response capability, which could support a longer lifetime and operation cycle of the whole system, allowing the energy storage and supply to be continuous and stable over a long time span while meeting the high energy supply demand. Related studies also show that the lifetime of SMES systems could even exceed around 20 years [7]. However, from a macroscopic perspective, the relatively high cost of manufacturing the superconducting components for operation may be a negative factor or limitation for the sustainability of SMES technology and achieving its own sustainability goals.

The relative sustainability of SMES technology itself needs to be further assessed in the context of existing specific United Nations Sustainable Development Goals (SDGs). Therefore, the author would select the SDGs, also known as the Global Goals, adopted by the United Nations in the year 2015 and consisting of 17 goals as a measure of their relatively wide global acceptance and consensus. Their overall content is comprehensive and aims to call for and advocate a development model that balances economic, social, and environmental sustainability [8].

SMES system and its technology would have an optimal performance in terms of energy saving. Since it does not require the use of fossil fuels or other types of fuel itself to keep it running, it can potentially reduce fuel consumption and emissions of greenhouse gases and harmful gases in a certain area, thus preventing the deterioration of water or air quality in the area to a considerable extent, which fits the requirements of the SDGs in terms of environmental dimension. Moreover, the high energy storage and high efficiency of SMES systems that can release a large amount of energy in a short period of time could reduce the cost per unit of energy. For some areas with a low level of economic and social development, such as towns and villages, if SMES technology is applied based on hydropower or wind power there, it would be possible for more residents and factories in them to afford clean energy more easily, and the 7th SDG would be practice. This also means that the old production and living patterns would be transformed and new industries would be developed, and new jobs could be created, and the benefits of this would be in line with the development patterns envisioned in the 8th and 9th SDGs. Not only would local industries and infrastructure be built with innovative elements and related capabilities, but more people or groups in the community could have access to decent jobs, leading to economic rebound or growth while regional development is stimulated. In the long run, the community and the city as a whole would be keeping on the way of sustainable development, and in the process, the market for research on SMES technologies and their related industries would be given opportunities for growth, expanding business, upgrading, or innovation.

3.2. Surroundings ecology and water environment

As a new energy storage technology that has emerged in the last decades, the environmental friendliness and low pollution of SMES technology make its application accompanied by several environmental benefits, as the above elaboration shows. The installations could be virtually harmless to the surrounding environment. Moreover, the system does not generate much noise during operation, making it not pollute or disturb the surrounding area [9]. In some areas where dams or hydroelectric plants are built, SMES units could also be used to help improve the water environment. With its large energy storage capacity and discharge power, some dams could have a moderate amount of water removed for power generation, and even some small, old dams could be considered for removal to lower the water level, which means that the flow of rivers and watersheds previously cut off by dams would be enhanced, and riverbeds raised by slowing water flow and sediment deposition would be gradually lowered and flattened by scouring, restoring the environment suitable for the growth of native aquatic plants and animals [3]. In addition, the energy stored in the SMES system would not be lost in heat dissipation or evaporation, which could allow the habitat ecology around the installation not to be negatively affected locally by the additional heat dissipated into the air.

3.3. Reducing carbon emissions and energy consumption

Additionally, in a related study, it was noted that the SMES technology and its applications would also contribute to the sustainable development goal of poverty reduction [7]. Such facts or situations may deserve attention and emphasis: residents often use solar power technology in some urban or developing rural areas, which could result in electricity surpluses and wasted power. With SMES technology, this excess power can be pre-stored and avoids the large power losses caused when fed directly into the grid, which means that not only could undeveloped or developing areas use the stored power for self-sufficient development and reduce some of their electricity expenses but also the stored power surpluses in other areas could be used to support and assist in the development of them when there may be facing a shortage or failure of electricity. Hence, moving one step further, within the framework of the United Nations Sustainable Development Goals (SDGs), SMES technology and its application would contribute to the achievement of improvements in the economy, society, environment, and energy, as well as their related aspects.

4. Application of SMES Systems

4.1. Application of SMES in the renewable power generation system

SMES technology was originally proposed as an electrical load balancing device, as mentioned above. Thus, one of the main applications of this technology today is in power generation systems. For example, in a microgrid, SMES equipment can act as a backup power source or a constant current source, with the ability to feed the grid with the different electrical forces required [10]. It would be directly connected to the grid through a power conditioning system, which means that it is itself equivalent to a pole-conducting coil, thus ensuring a certain degree of maximum energy storage time and avoiding the influence of undesirable external disturbances or energy leakage.

In recent years, the use of SMES systems has been expanding, especially in some non-traditional power generation systems [11]. The results can be seen to be relatively promising and promising, and as a virtually non-polluting, environmentally friendly, flexible, and controllable energy storage technology, SMES technology also enhances the overall sustainability of the power generation system it serves to some extent. Therefore, even if it is separated from the traditional grid, it still has considerable adaptability and compatibility with renewable power generation systems such as wind energy systems, solar photovoltaic systems, and biofuel cells.

It provides a reliable alternative and solution to the problem of intermittent power output from these sources by releasing energy in a timely manner to mitigate power fluctuations and keep the power system stable.

These SMES systems themselves need to be relatively fine-tuned for adaptation to the appropriate facility size, materials and generation capacity. Moreover, their overall performance would be largely related to the configuration or design of their internal superconducting coils [11].

4.2. Application of SMES in hybrid power system

As more new and renewable energy types are being developed or adopted, some regions are beginning to apply hybrid power system models. The penetration of traditional local power grids and generation systems, such as wind power and photovoltaic power, is increasing, and there are models that directly combine the two [12]. In such hybrid power systems, SMES technologies can be applied in addition to, or in conjunction with, other technologies. As an example, in a practical case study, a coordinated control strategy combining load frequency control (LFC) and SMES technologies has shown relatively optimistic results [13]. The strategy was used to address frequency deviations in the power system between peak and low periods at a given time while mitigating power fluctuations in wind farms, preventing damage to generators that exceed their rated power and leading to the risk of sudden interruptions in industrial processes and power supply in local plants. In this model, the SMES system acts as a conventional frequency stabilizer, and although the performance is generally satisfactory, it has been noted that it may take too long to stabilize when the frequency deviation is large.

4.3. Application of SMES in electrical vehicle systems

At present, not only in Europe and the United States but also in some major countries and regions in Asia, such as Japan, China, Hong Kong, and Singapore, electric and new energy vehicles are being introduced in the hope of gradually replacing gasoline or diesel-powered vehicles and reducing air pollution and carbon emissions. Although the future of electric vehicles is predicted to become the mainstream of civil and commercial transportation, at this stage, the battery capacity and range problems, as well as the load fluctuation of the main generator (MG) during charging, have, in fact, become obstacles to the promotion of electric vehicles and their marketization [10]. The introduction of the SMES system is expected to solve these concerns. In the internal system of an EV, the SMES device will be directly connected to a DC-DC converter or DC-AC converter, which would then be connected to a voltage and current controller [3]. The SMES system would then function as a load regulator and a voltage and current source converter, forming a relatively large overall network of systems that will extend the range and battery life of the EV on a single charge [14].

5. Policy Analysis and Future Perspectives of SMES System

As one of the most widely used SMES systems in the world, some major governments in North America, such as the United States government, have enacted policies and regulations to support and regulate the development of SMES technology and its related companies, research institutions, and markets [15]. In addition, SMES technology development plans have been introduced with specific and actionable development goals for a limited number of years. In contrast, China, one of the major countries in Asia, also has official support policies, but the local SMES technology market and applications are still in the initial development stage or not large enough. Apart from that, a report on the status of the SMES market in China and corresponding guidance would be published yearly or every several years.

While having a relatively broad prospect and potential, the development of SMES technology also needs to avoid some pitfalls caused by its own problems. Undoubtedly, the cost of maintaining a continuous low-temperature superconducting environment is high, and this is one of the most significant shortcomings of SMES technology. However, as technology and the economy evolve, the cost of technology and superconducting materials used in SMES devices would be pulled down further, which means that it is expected that the price of SMES devices would be reduced to a more generally acceptable range in the coming decades. Moreover, the range of applications, fields, and markets for SMES technology would be further broadened, and the combination with other emerging energy technologies would receive more attention as a target or research direction for testing, experimentation, as well as technology adaptation in the laboratory at this stage. It also has a more sophisticated and complex cooling and temperature control system with a high maintenance frequency, which means that based on the trend, HTS may gradually replace LTS in the future [16]. It could be necessary to introduce monitoring components and related sensing systems in the whole SMES system to meet the demand for timely feedback on the status of the device and smooth operation to meet the standards and strengthen the self-risk detection capability of the system itself.

6. Conclusion

In general, SMES technology offers considerable sustainability and many environmental benefits. It could help the public and businesses to have more affordable access to electricity and provide more options for environmentally sound energy storage at this stage and in the future. When it replaces traditional energy storage and related equipment in specific scenarios, the native ecology and species communities previously affected will be restored and protected to a certain extent as it will not pollute or disturb the surrounding atmosphere or water environment. In addition, the application of SMES devices can contribute to economic growth, reduce carbon emissions in the region and indirectly contribute to poverty reduction, which will help build sustainable industrial models and communities. At the same time, the relatively high degree of fit and effectiveness of SMES systems with renewable power generation, hybrid power generation, and new energy vehicles mainly driven by electric power also reflects its promising and potential application directions and can support its sustainability and environmental friendliness. In addition, this study has some limitations or shortcomings; for example, in the elaboration and analysis of relevant policies and future development trends of HTS, due to the limitation of the focus of this paper, no more specific data and clear comparisons are given, which could be further discussed in future studies.

References

[1] Naderi P, Alizadeh Pahlavani M R, Azizian Fard M. A novel controlling method for the superconducting magnetic energy storage system as a distributed generation source; full modelling, design and simulation [J]. International Journal of Sustainable Energy, 2014, 33(4): 766-782.

[2] Al Zaman M A, Ahmed S, Monira N J. An overview of superconducting magnetic energy storage (SMES) and its applications [C]. International Conference on Nanotechnology and Condensed Matter Physics. 2018.

[3] Shaqsi A Z A L, Sopian K, Al-Hinai A. Review of energy storage services, applications, limitations, and benefits [J]. Energy Reports, 2020, 6: 288-306.

[4] Kumar A, Jeyan J V M L, Agarwal A. Electromagnetic analysis on 2.5 MJ high temperature superconducting magnetic energy storage (SMES) coil to be used in uninterruptible power applications [J]. Materials Today: Proceedings, 2020, 21: 1755-1762.

[5] Mukherjee P, Rao V V. Design and development of high temperature superconducting magnetic energy storage for power applications-A review [J]. Physica C: Superconductivity and its applications, 2019, 563: 67-73.

[6] Acar C. A comprehensive evaluation of energy storage options for better sustainability [J]. International Journal of Energy Research, 2018, 42(12): 3732-3746.

[7] Huang Y, Ru Y, Shen Y, et al. Characteristics and Applications of Superconducting Magnetic Energy Storage [C]. Journal of Physics: Conference Series. IOP Publishing, 2021, 2108(1): 012038.

[8] The SDGs in Action, United Nations Development Programme, 2022. Accessed date: 21 September. Retrieved from: https://www.undp.org/sustainable-development-goals.

[9] Hawsey R A, Morozumi S. The energy and environmental benefits of superconducting power products [J]. Mitigation and adaptation strategies for global change, 2005, 10(2): 279-306.

[10] Vulusala G V S, Madichetty S. Application of superconducting magnetic energy storage in electrical power and energy systems: a review [J]. International Journal of Energy Research, 2018, 42(2): 358-368.

[11] Mukherjee P, Rao V V. Superconducting magnetic energy storage for stabilizing grid integrated with wind power generation systems [J]. Journal of Modern Power Systems and Clean Energy, 2019, 7(2): 400-411.

[12] Magdy G, Mohamed E A, Shabib G, et al. SMES based a new PID controller for frequency stability of a real hybrid power system considering high wind power penetration [J]. IET Renewable Power Generation, 2018, 12(11): 1304-1313.

[13] Mohammad Rozali N E, Wan Alwi S R, Manan Z A, et al. A process integration approach for design of hybrid power systems with energy storage [J]. Clean Technologies and Environmental Policy, 2015, 17(7): 2055-2072.

[14] Zhou X S, Lu B, Ma Y J. A Review on Superconducting Magnetic Energy Storage [J]. Advanced Materials Research, 2013, 614: 825-828.

[15] Van der Linden S. Bulk energy storage potential in the USA, current developments and future prospects [J]. Energy, 2006, 31(15): 3446-3457.

[16] Schoenung S M, Bieri R L, Meier W R, et al. Cost savings and prospects for applications of micro superconducting magnetic energy storage (SMES) using high temperature superconductors [J]. IEEE transactions on applied superconductivity, 1993, 3(1): 200-203.