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Large Scale Applications of Solar Thermal Energy

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As a vital component of the renewable energy sector, solar thermal utilization plays a crucial role in the global transition to sustainable energy. This paper examines a range of large-scale solar thermal technologies, including solar thermal power generation, solar cooling, solar desalination, solar drying, and solar district heating, from the perspectives of energy quality, technological maturity, and economic feasibility. These technologies have already been deployed in various regions, demonstrating significant potential in reducing carbon emissions and mitigating energy shortages. However, challenges remain, such as high capital costs, efficiency limitations, and constraints related to geographic and climatic conditions. With ongoing technological innovations, such as the development of high-efficiency solar absorbers, advanced thermal energy storage, and integrated multi-energy systems, solar thermal utilization is expected to play an increasingly important role in the future energy mix. Its incorporation into carbon trading mechanisms may further enhance its adoption. Ultimately, solar thermal technology holds promising prospects for contributing to a sustainable energy supply on a global scale.

INTRODUCTION

Under the influence of global climate change, the challenges related to energy and the environment have intensified. In 2023, global energy-related carbon emissions reached 36.8 billion tons. The green and low-carbon transformation of the energy system has become an international consensus. In 2015, the Paris Agreement set the goal of limiting the temperature increase to 2 °C and striving for 1.5 °C. China proposed the Dual Carbon strategy in 2020, and calculations show that it will lead to a reduction of approximately 18 % in global carbon emissions. Together, these initiatives are the core driving forces of the new energy revolution.

In the energy transition, the transportation, industrial, and construction sectors account for approximately 75 % of global energy-related carbon emissions. The electrification path for the transportation sector is clear. In 2024, the global penetration rate of electric vehicles exceeded 15 %, and in some European countries, it exceeded 30 %. In the residential building sector, heat demand accounts for more than 60 % of the total energy consumption. While in industries such as steel and chemicals, the usage of process heat accounts for 70-80 %. The electricity and heat demand in these two sectors are huge. Whether the demands of heat and electricity can be met determines the success or failure of the energy transition.

Solar energy technology is mature and has great potential. By the end of 2024, the cumulative installed capacity of photovoltaic power exceeded 2 terawatts globally, and the annual power generation accounted for more than 5 % of the global total power generation. Solar energy can not only serve as the main force for power supply, but also replace fossil energy for heating purposes. Besides solar photovoltaic power generation, the solar low-temperature thermal utilization technology (≤ 200 °C) has a heat collection efficiency of up to 70-85 %, which can meet 0-50 % of the heating needs of northern urban buildings in winter and also provide process heat for industries such as the chemical industry.[1] Calculations show that for every million square meter of solar collectors installed, 20,000 tons of standard coal can be replaced annually and a reduction of 55,000 tons of carbon emissions can be achieved. This is one of the most efficient and affordable ways to achieve the goals of energy conservation and carbon reduction.

ANALYSIS FROM THE PERSPECTIVE OF ENERGY QUALITY

Compared with technologies such as wind power and photovoltaics, solar thermal utilization mainly outputs thermal energy. Although the energy grade is low, it has significant advantages in terms of high matching between production and consumption, high conversion efficiency, and low cost for heating applications. In the process of the green and low-carbon transformation of the entire society, this characteristic should be fully exploited, enabling the efficient applications of solar thermal utilization technologies in various civil and industrial sectors such as heating, drying, cooling, and seawater desalination.[2] Relevant products such as flat plate collectors, vacuum tube collectors, parabolic trough collectors, and solar tower are already relatively mature. The current bottlenecks in their development mainly lie in the reduction of capital cost, the improvement of system efficiency, and the integration with the existing energy systems. Especially in areas with low irradiation resources and less developed economies, the applications of solar thermal energy are still very challenging. However, it is still of great significance to systematically review and improve the existing solar thermal utilization technologies. Its energy-quality matching advantages should be further leveraged to ensure a more pivotal role in the global energy system, and its contribution to energy substitution should be continuously enhanced through technological innovation and iterative development.

APPLICATION STATUS OF LARGE-SCALE SOLAR THERMAL UTILIZATION

This article presents the status quo of various types of solar thermal power generation, solar cooling, solar thermal drying, solar seawater desalination, and solar centralized heating, as shown in Figure 1. For low-temperature applications, water is heated to 50-100°C by solar collectors, which can be used for space heating, domestic hot water, solar thermal cooling, and seawater desalination. Although the energy quality is not high, the application scale is extensive. For medium-temperature applications, using concentrating or non-concentrating collectors, air or fluids are heated to 80-300 °C, which are suitable for agricultural drying, industrial processing. A high energy utilization efficiency can be achieved. For high-temperature applications, solar energy is concentrated by reflectors/mirrors, and the concentrated solar energy is converted into heat of above 300 °C. The heat can be used to drive steam turbines for power generation. Thus, solar thermal utilization has

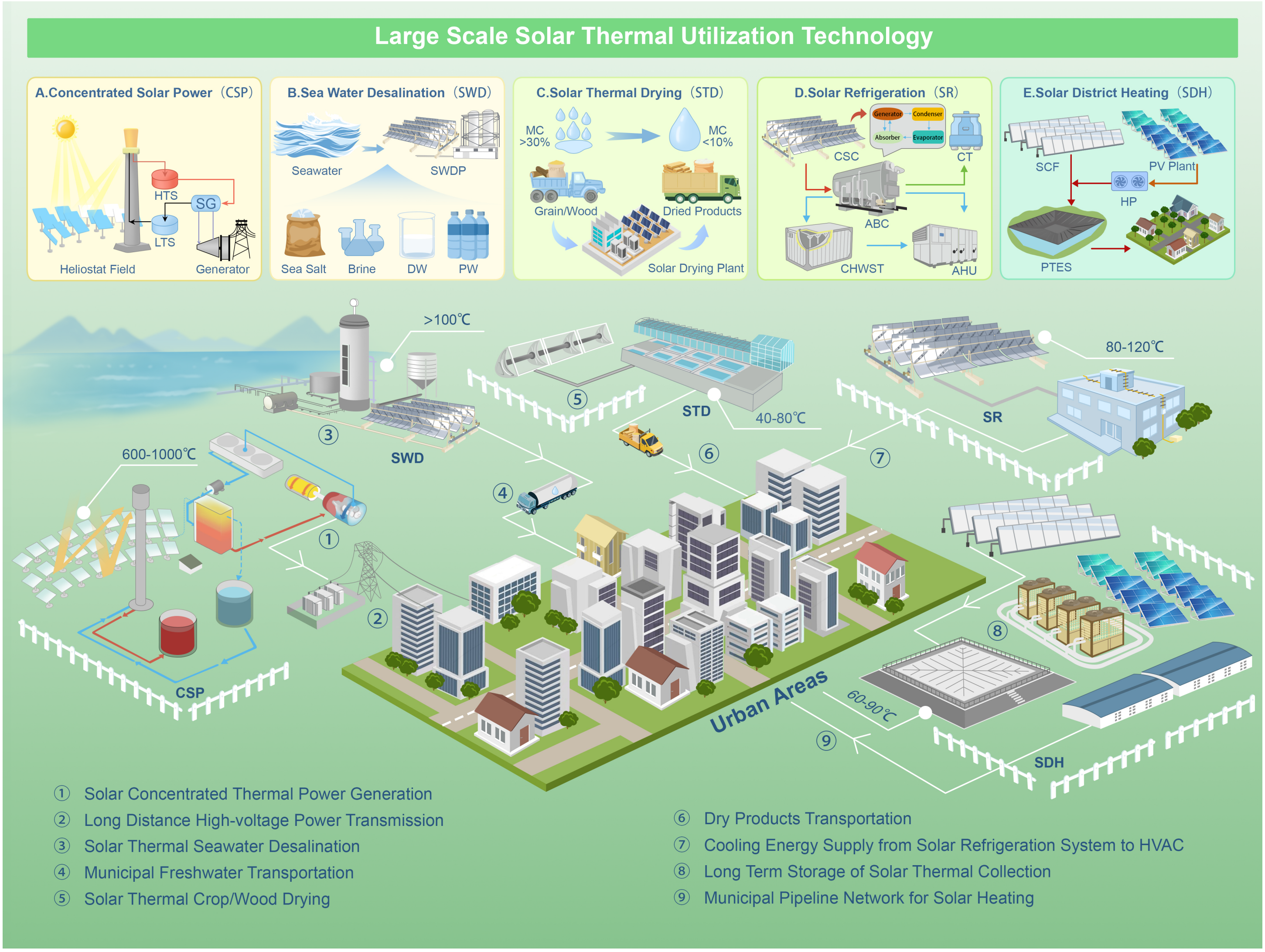

Figure 1. Large scale solar thermal utilization technologies

the ability to output energy in multiple grades and dimensions, and can flexibly match different levels of industrial and domestic heat demands.

(1) Commercial solar thermal power plants mainly adopt trough-type and tower-type collectors. It has the advantage of decoupling heat and power and ensuring a stable electricity power output. To enhance power generation efficiency and scheduling capabilities, solar thermal power is developing towards higher operating temperatures and more efficient heat transfer media. However, its development is still limited by factors such as high requirements for direct solar irradiance, large land area, high initial investment, and long construction period. Therefore, solar thermal power plant is often constructed in combination with photovoltaic or wind power plant to reduce overall power generation costs, increase utilization hours, and enhance system economy and stability.[3] China has built several demonstration projects, such as the Delingha solar power plant with parabolic collectors and the Dunhuang solar power plant with a solar tower. These demonstration projects gradually promote the large-scale application of solar thermal power generation. Internationally, there are also well-known projects, such as the DEWA Phase IV project in Dubai integrating solar thermal, photovoltaic and heat storage, and the Noor composite project in Morocco (cooperative operation of solar thermal and photovoltaic), which have demonstrated the feasibility and prospects of solar thermal hybrid systems.

(2) Solar thermal drying is an efficient and environmentally friendly method for material dehydration, widely used in processing agricultural products, food and industrial raw materials.[4] This technology mainly uses solar collectors to heat up the air by forced ventilation through fans. Since temperature and humidity of the air can be precisely controlled, it is suitable for large-scale applications. Multiple demonstration projects have been constructed in China and abroad, such as the solar tea drying system in Xishuangbanna, China, and the solar sludge treatment project in Jinan. These demonstration projects have demonstrated excellent energy-saving effects and application potential.

(3) Solar thermal cooling mainly employs absorption and adsorption cooling methods. Absorption cooling typically uses lithium bromide-water or ammonia-water as the working medium, suitable for district cooling and medium-sized air conditioners, but requires a heat source above 80 °C. Adsorption cooling can utilize a low-temperature heat source ranging from 50 to 85 °C, making it more suitable for decentralized and small-scale applications. The current research at Shanghai Jiao Tong University[5] includes improving heat collection and cooling efficiency, developing new working fluids and adsorption materials, promoting system integration and combining with heat pumps, thermal storage, and energy management systems. There are several demonstration projects both domestically and internationally, such as the Day Moon Temple in China and the cooling system of the Southeast Asia Joint World College in Singapore, which have verified the technical feasibility and accumulated operational experience. However, this technology still faces challenges such as high capital investment, long payback period, intermittent solar energy, and low system stability.

(4) Solar seawater desalination is a sustainable technology that utilizes solar energy to extract fresh water from seawater or brackish water, especially suitable for coastal, arid, and off-grid areas, providing a green solution to address the shortage of fresh water. Currently, multiple demonstration projects have been established domestically and internationally, such as the solar multi-stage flash evaporation device in Saudi Arabia, and the solar reverse osmosis seawater desalination demonstration projects in Hainan and

Zhoushan in China. These projects have accumulated important experience for large-scale promotion. However, certain issues still hinder its wider applications, for example, high water production costs and insufficient performance stability under conditions with low solar irradiation.

(5) Solar district heating utilizes large-scale solar collector field, combined with steel water tanks or water pit heat storage, to achieve centralized heating for towns or cities through district heating networks.[6,7] It has significant scale benefits, such as, low heating costs, and high solar energy guarantee rates, and is particularly suitable for areas with high winter heating demands. This technology has been widely promoted in China (Qinghai-Tibet Plateau), Denmark, Finland and other European countries. For instance, the solar district heating system in Silkeborg, Denmark has an area of 156,000 square meters of solar collectors, with a large water storage tank, meeting approximately 40 % of the city's annual heating needs. The solar district heating system in Langkazi, China, uses a 23,000 m[2] solar collector field and a 15,000 m[3] water pit heat storage, achieving a solar fraction of almost 100 % for the town with 80,000 m[2] floor area. The project become the flagship demonstration project in high-altitude and high-altitude areas. The EU Horizon project TREASURE (https://www.treasure-project.eu/) has further advanced the development and deployment of water pit heat storage, including demonstrations of seven large-scale water pit systems across Europe, providing valuable experience for broader implementation and integration of this technology. Currently, the key bottlenecks of solar district heating mainly lie in reductions of costs for design, construction, operation and management of the system, as well as the research and development of key components of the system, such as large water pit and water tanks, high efficiency solar collector fields.[8,9]

PERSPECTIVES OF THE LARGE-SCALE UTILIZATION OF SOLAR THERMAL ENERGY

It is firmly believed that in the context of the global response to the energy crisis and climate change, the strategic position and unique value of solar thermal utilization technologies should be highly emphasized. The main recommendations are given as follows:

(1) For heating of civil and industrial buildings, large-scale solar thermal utilization is an important part of the future low-carbon energy system. For building heating and cooling, industrial drying, and seawater desalination, the medium and low-temperature heat demands can be precisely met by directly and efficiently converting solar energy into heat. Thus, it avoids the energy-grade waste associated with first converting solar energy into high-grade electricity and then using it for low-grade heating, while also minimizing the losses from multiple energy conversions. Therefore, large-scale solar thermal utilization clearly demonstrates significant advantages in both economic viability and energy efficiency.

(2) In remote counties or cities with limited fossil energy but abundant solar energy, large-scale centralized solar heating systems offer an effective way to address both heating needs and livelihood challenges in these regions. For instance, in the Qinghai-Tibet Plateau region of China and similar climate zones along the Belt and Road Initiative routes, where conventional energy infrastructure is underdeveloped but solar energy resources are abundant, large-scale solar thermal utilization technologies can enable county or city level zero-carbon heating.

(3) In large-scale solar thermal utilization, the low-cost large-scale heat storage is essential for balancing the intermittency of energy supply with the volatility of energy demand. Among the available options, the large water pit heat storage, due to its excellent thermal stratification property, relatively low construction and operation costs, and high system reliability, has become one of the widely used heat storage technologies.[10] Water pit heat storage can achieve thermal energy storage on both diurnal and seasonal scales, and ca be applied across a wide range of scenarios, including district heating, agricultural drying, and industrial processes.

(4) Systematic policy frameworks should be established to promote the large-scale application of solar thermal utilization. It is recommended that solar thermal utilization projects be included in the carbon market trading system, and explore the determination and trading mechanism of their carbon reduction amounts. Market measures should be utilized to enhance the economic feasibility of the projects. At the same time, the integration of solar heating system requirements into green building evaluation standards and urban planning guidelines should be clearly specified, thereby promoting the adoption of the technology from the outset.

CONCLUSIONS

In response to the urgent demands of global climate governance and the transition to low-carbon energy, large-scale solar thermal utilization, due to its direct energy quality matching, diverse application scenarios and significant emission reduction benefits, has become one of the core paths for building a new energy system. This technology directly meets medium and low-temperature heating demands through solar-to-heat conversion, avoiding the waste of energy grade in electric heating, and has irreplaceable economic and energy efficiency advantages in industrial process heating and district heating. Especially, the breakthrough of large-scale heat storage technology provides key support for coping with the intermittency of solar energy and achieving continuous and stable heating. In the future, through continuous technological innovation to reduce costs and improve system efficiency, and by incorporating policy measures such as the carbon market trading and higher application standards, its large-scale application should be accelerated. In conclusion, solar thermal utilization is not only a crucial pathway for achieving carbon peaking and carbon neutrality, but also a strategic option for advancing energy system transformation and strengthening energy security.

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DECLARATION OF INTERESTS

The authors declare no competing interests.