Solar Thermal Energy Storage Technology: Current Trends

Pravin Prabhu and Sanjay Sawant

Abstract Energy security has major three measures: physical accessibility, economic affordability and environmental acceptability. For regions with an abundance of solar energy, solar thermal energy storage technology offers tremendous potential for ensuring energy security, minimizing carbon footprints, and reaching sustainable development goals. Global energy demand soared because of the economy's recovery from the COVID-19 pandemic. By mitigating the adverse effects of solar energy uncertainties, solar thermal energy storage provides an opportunity to make the power plants economically competitive and reliable during operation. Solar thermal power plant technology is still in the early stages of market introduction, with about six gigawatts of installed capacity globally in 2020 compared to PV technology. In a developing economy, the potential for cost reduction through invention, mass production, and growing competitiveness is far from being exhausted. The objective of this review paper is to access the progress of solar thermal energy technology in India compared to world and its potential to accomplish the clean energy goals.

Keywords Solar energy · Thermal energy storage · Concentrated solar power · Phase change materials · Carbon emission

1 Introduction

The goals outlined in the 2030 Agenda for Sustainable Development are under threat as the globe deals with interrelated and cascading global crises and wars. The war in Ukraine is intensifying the food, energy, humanitarian, and refugee problems while also contributing to the COVID-19 epidemic, all against the context of a declared

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climate emergency. The world is moving further toward its sustainable energy goals. However, with the current rate of development, Goal 7 of affordable and sustainable energy cannot be met by 2030 [1].

Economic growth has always been highly linked to growing energy use and GHG emissions. Solar energy breaks up this link, promoting sustainable development and climate action. Three important technological breakthroughs are required for such separation: shifting to solar energy in place of fossil fuels; reducing energy consumption on the demand side, and increasing electrical generation efficiency. An indicator of diminishing poverty and improved economic growth, in emerging countries, is increased together with power consumption. Renewable solar energy enhances rural poor people's ability to access electricity and reduces poverty.

One of the most significant challenges confronting humanity today is global warming. To address the problem of global warming, solar thermal systems (STSs) have seen a surge in the recent two decades on the international market. Solar thermal systems would be a better choice to replace existing energy systems. By functioning as thermal storage batteries, phase change materials (PCMs) have emerged as an alternative to improve the efficiency of solar heating systems [2] (Fig. 1).

Utilizing thermal energy storage (TES) enables the efficient use of clean energy sources, reduction of energy consumption, and improvement of energy system performance. The primary step to minimize the effects of climate change is now generally acknowledged to be reducing carbon emissions into the atmosphere. As a result, the majority of countries invested many resources in search of effective techniques for reducing energy usage and the amount of energy generated by fossil fuels [4].

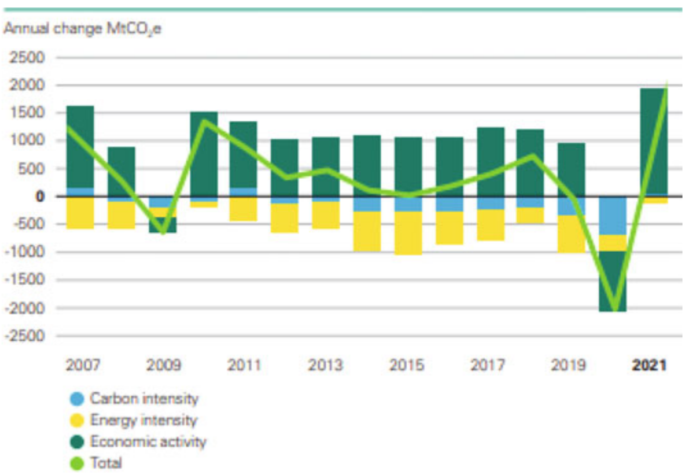

Fig. 1 Increase in carbon emissions in 2021, driven by the rebound in economic growth [3]

2 Thermal Energy Storage

Thermal energy storage is a technique that stores thermal energy by heating or cooling a storage medium so that the energy can be used later for power generation, heating and cooling systems, and other purposes. In order to balance energy demand and supply on a daily, monthly, and even seasonal basis, Thermal energy storage systems are used. They can also improve the overall effectiveness of energy systems by minimizing peak demand, energy consumption, carbon dioxide emission, and cost [5].

There are two distinct types of TES systems: (A) sensible heat storage, which utilizes heating or cooling a solid or liquid storage medium (such as water, rock, sand, or molten salts), and (B) latent heat storage, which utilizes phase change materials or PCMs. Energy storage system prefers to utilize PCM with the latent heat of fusion of 300 kJ/kg and higher at operating temperatures of 180 °C [6].

It is predicted that India receives more than 5000 trillion kWh of solar energy each year, with the majority of areas receiving 4–7 kWh/m2. Presently, India consumes over 1.13 trillion kWh per year while producing roughly 1.38 trillion kWh per year, indicating that production capacity is just a little bit more than actual demand. India now has roughly 40 GW of installed solar capacity out of 100 GW of installed renewable energy potential [7].

2.1 World

The world has installed 6313.9 MW by the end of 2021, with Spain and the United States dominating the market. Figure 2 represents the total installed CSP capacity globally from 2011 to 2021 and illustrates the percentage of CSP capacity across all nations as of the end of 2021. The completion and operation of numerous large-scale commercial CSP plants in developing nations like China, Morocco, South Africa, India, Israel, and UAE significantly increased the installed capacity of CSP globally in 2021 [8].

More than 35% of the world's total energy consumption is made up of process heat in industrial applications. Fossil fuel is used for industrial process heat applications, providing 10% of the energy for the metal industry, 23% for the refining of petroleum, 80% for the pulp and paper industry, and 60% for the food processing industry. Applications for industrial process heating account for 32% of overall energy consumption in countries like India. Flat plate collectors and evacuated tube collectors may be employed for low-temperature applications (120 °C), whereas concentrated solar power technology is appropriate for medium- and high-temperature applications (400 °C) [9]. For regions with an abundance of solar resources, solar thermal technology is extremely promising for ensuring energy security, minimizing carbon footprints, and ultimately achieving sustainable development goals. The introduction of

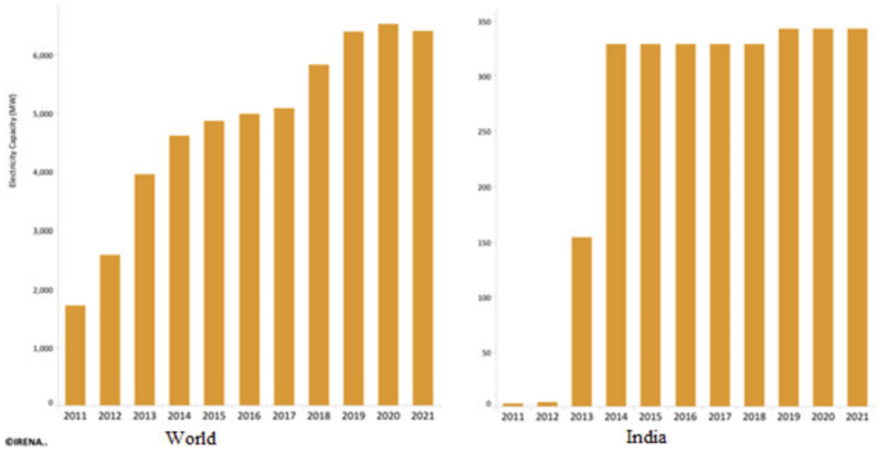

Fig. 2 Electricity capacity (MW)–CSP technology [14]

thermal energy storage (TES) to CSP plants could balance the supply and demand of energy by minimizing the adverse effects of solar energy intermittency [10].

Increased use of irregular RES has an impact on grid stability. Systems for storage of electricity (EES) offer a potential solution for grid stability problems [11] (Table 1).

Table 1 WORLD: percentage of renewable technologies [12]

Parent-technology	Sub-technology	Percentage (%)	Generation: GWh
Bioenergy	Biogas	1.3	96,564.82
Solar	Concentrated solar power	0.2	13,113.42
Geothermal	Geothermal energy	1.3	94,949.10
Bioenergy	Liquid biofuels	0.1	7932.64
Marine	Marine energy	0.0	957.47
Renewable hydropower	Mixed hydro plants	0.0	115.29
Wind	Offshore wind energy	1.3	1,00,114.07
Wind	Onshore wind energy	19.9	14,88,471.96
Renewable hydropower	Renewable hydropower	58.3	43,55,819.74
Bioenergy	Renewable municipal waste	1.0	73,239.19
Solar	Solar photovoltaic	11.1	8,30,741.44
Bioenergy	Solid biofuels	5.4	4,06,038.84

2.2 India

In India, Solar power generation has grown at an accelerating rate from 0.07 GW in 2010 to 50 GW in 2021. India is in an active position to accelerate toward its goal of 280 GW by 2030, a six-fold increase over present levels. As a result of solar Power generation, India has saved US$4.2 billion in fuel expenditures in the first half of 2022. It also eliminated the requirement for 19.4 million tonnes of extra coal, which would have put even more burden on the already constrained domestic supply [13].

According to the Global Trends in Renewable Energy Investment 2020 report, India's renewable energy projects and programs attracted investments of US$64.2 billion between 2014 and 2019. (Rs 4.7 lakh crore). Since April 2014, solar tariffs have also dropped significantly, from Rs. 6.47 per kilowatt-hour in 2013–14 to Rs. 1.99 in December 2020 [15] (Table 2).

India's Nationally Determined Contributions (NDC) under the Paris Agreement for the period 2021–2030 include the following goals: To achieve about 40% of the total installed capacity of electric power from non-fossil fuel-based energy resources by 2030 with the aid of technology transfer and inexpensive international financing. By 2030, India aims to reduce the emissions intensity of its GDP by 33 to 35% from 2005 levels. India is on track to accomplish these goals.

India has a total installed capacity for renewable energy of 92.54 GW (excluding large hydro), of which 5.47 GW was added from April 2020 to January 2021. India's installed RE capacity expanded by two and a half times between April 2014 and January 2021, while installed solar energy capacity increased by 15 times within the same time frame. India currently ranks fourth in the world for RE power capacity, fourth for wind power, and fifth for solar power capacity. One of the world's fastest rates of growth for renewable energy is seen in India.

In order to ensure the objectives of energy security and climate protection, there is a need for definite policies. In order to fulfil peak electricity demand and ensure grid stability without any severe environmental impact, solar thermal energy storage is an important step forward in sustainable energy production [17] (Table 3).

The most effective option for India is to implement a system that is entirely dependent on renewable energy. India's future energy system will be mostly comprised of

Table 2 INDIA: percentage of renewable technologies [12, 16, 17]

Parent-technology	Sub-technology	Percentage (%)	Generation: GWh
Bioenergy	Biogas	0.01	31.89
Solar	Concentrated solar power	0.10	360.3
Wind	Onshore wind energy	21.20	63,522.27
Renewable hydropower	Renewable hydropower	53.30	1,59,728.81
Bioenergy	Renewable municipal waste	0.30	931.62
Solar	Solar photovoltaic	18.10	54,305.90
Bioenergy	Solid biofuels	7.00	21,023.86

Table 3 INDIA: list of solar thermal plants [8]

No	Power_station	Capacity (MW)	CSP technology	Owner
1	ACME solar tower	2.5	Power tower	ACME Group
2	National solar thermal power facility	1	Parabolic trough	IIT Bombay
3	Godawari solar project	50	Parabolic trough	Godawari Green Energy
4	Dhursar	125	Linear fresnel	Reliance power
5	Megha solar plant	50	Parabolic trough	Megha Engg. and Infra
6	Dadri ISCC plant	14	Linear fresnel	NTPC
7	KVK energy solar project	100	Parabolic trough	KVK Energy Ventures Ltd

solar PV and batteries, with other technologies acting as a control mechanism [18]. India's constructive and cooperative climate commitment is reflected by the foundation of the International Solar Alliance (ISA) in November 2015. The alliance was established during the Paris Agreement negotiations jointly by India and France. It is a treaty-based, member-driven forum aimed at trans-regional solar energy cooperation to both minimize the reliance on fossil fuels and create a more just and sustainable energy system.

The ISA was established during the 2015 UN Conference of Parties 21 (COP21) in Paris as a result of Indian Prime Minister Narendra Modi's ambitious "One World, One Sun, One Grid" initiative. The establishment of ISA underlined India's position as a major global player in the difficult issues of climate change. On December 6, 2017, ISA's multilateral treaty status, as granted by the UN, became effective. A multi-country partnership organization called ISA was proposed, with members from the "sunshine belt" nations located entirely or in part between the Tropics of Cancer and Capricorn [19].

3 Discussion

India's power sector is the largest contributor to its CO_2 emissions, and coal-fired power plants are responsible for the great majority of power sector emissions [20].

The key reasons for the moderate growth of the CSP technologies are a number of constraints, including inadequate DNI data, inappropriate policies, a complex system of land acquisition, a scarcity of water, approval complications, low investor confidence, and a lack of long-term planning. A key challenge to promoting CSP is the lack of funding and the rapid decline in the price of PV modules.

Table 4 summarizes the results of a SWOT analysis that has been conducted based on the opinions of various researchers.

In addition to this, several technical factors are listed below.

Table 4 SWOT analysis of CSP technology [21]

Strength	Weakness	Opportunity	Threats
Significant efficiency	Excessive investment cost	Room for high concentration ratio	Remarkable reduction in PV price
Completely recyclable working medium	Production cost of a reflector	More efficient reflector	Focused radiation, harmful for flying species
Storage	Heat transfer losses	New material for storage	Possibilities of leakage may hamper the system
Longer duration span than batteries	Controlling high-temperature working medium	Thermochemical storage with minimum loss of heat	Environmental pollution by chemicals

Capacity factor

Traditional thermal power plants have a capacity factor of 90%. The majority of CSP power plants have capacity factors of under 25% and can reach up to 80% with an expensive storage system.

High capital cost

The capital cost of the CSP-based technology is multiplied due to the necessity of highly complicated components and land. Based on a lifecycle study, the lifespan of CSP-based power plants is longer than that of traditional thermal power plants.

Low level of technological development

CSP technology is still in its initial phases. The industrial infrastructure for the production of components has not yet been built to meet the demand for CSP deployments in DNI-exposed countries like India.

Materials and component availability

The CSP includes components like absorbers and reflectors. Due to the lack of a developed market for the availability of these components, they are costly. The addition of a unique design and sun tracking so the deployment of CSP is complicated.

The development of heat and power generation employing Rankine cycles, research on supercritical CO_2 power cycles in CSP plants, performance analysis of calcium looping, and thermochemical energy storage on CSP systems are further study topics [22]. In India, a country with typically 300 bright days per year and 220 MW of solar radiation per square kilometer, coal-fired power plants produce enormous amounts of carbon dioxide emissions. As a result, solar-based power generation has the ability to both reduce emissions and meet the growing demand for energy [23]. The government of India has set an ambitious goal of increasing the contribution of manufacturing output to 25% of gross domestic product (GDP) by 2025, which would be a 9% increase from the current level of 16%. The International Solar Alliance (ISA), a platform initiated by the government of India, encourages trade among its 121 members positioned in tropical regions with abundant solar radiation [24].

4 Conclusion

India is now the third-largest carbon dioxide emitter in the world when combined with the industry, transportation, and service sectors. The National Solar Mission has encouraged future growth of the solar thermal sector with ambitious goals in terms of installation targets. India's solar business has extensive experience with large-scale projects; approximately 78,000 m^2 of concentrating projects have been implemented.

Barriers to the growth of renewable energy sources include a lack of transmission infrastructure, land availability, overvalued resource assessments, and, policy instability brought on by various political interests. In a competitive market, low-cost imports and inadequate standards might constrain market expansion.

Solar thermal energy storage technology is a promising field with advancements and setbacks in a national scenario. Although this technology currently involves some technical risks and high electricity costs, with ongoing technological advancements and the gradual localization of core equipment, it will undoubtedly become the sustainable energy solution of the future. Further technological advancements are required to overcome the stated hurdle and a comprehensive policy encouraging solar thermal power generation is essential for the deployment of solar thermal energy storage-based CSP power plants in India. CSP technology is expected to grow quickly because of its numerous benefits, including efficiency, a long life cycle, negligible environmental effects, etc. By 2024, it is estimated that CSP's total installed capacity would increase to 1.3 GW.

References

1. The sustainable development goals report: 2022
2. Palacios, A., Barreneche, C., Navarro, M. E., & Ding, Y. (2020). Thermal energy storage technologies for concentrated solar power—A review from a materials perspective. *Renewable Energy, 156*, 1244–1265. https://doi.org/10.1016/j.renene.2019.10.127
3. BP. Statistical Review of World Energy 2022.
4. Cabeza, L. F., de Gracia, A., Zsembinszki, G., & Borri, E. (2021). Perspectives on thermal energy storage research. *Energy, 231*. https://doi.org/10.1016/j.energy.2021.120943
5. Solar thermal power plants Heat, electricity and fuels from concentrated solar power, German Aerospace Center (DLR) Institute of Solar Research. www.dlr.de/sf/en/
6. Kalidasan, B., Pandey, A. K., Shahabuddin, S., Samykano, M., Thirugnanasambandam, M., & Saidur, R. (2020). Phase change materials integrated solar thermal energy systems: Global trends and current practices in experimental approaches. *Journal of Energy Storage, 27*. https://doi.org/10.1016/j.est.2019.101118
7. Pandey, A., Pandey, P., & Tumuluru, J. S. (2022). Solar energy production in India and commonly used technologies—An overview. *Energies*, *15*(2). https://doi.org/10.3390/en15020500
8. https://solarpaces.nrel.gov/
9. Ravi Kumar, K., Krishna Chaitanya, N. V. V., & Sendhil Kumar, N. (2021). Solar thermal energy technologies and its applications for process heating and power generation—A review. *Journal of Cleaner Production, 282*. https://doi.org/10.1016/j.jclepro.2020.125296

10. Achkari, O., & el Fadar, A. (2020). Latest developments on TES and CSP technologies—Energy and environmental issues, applications and research trends. *Applied Thermal Engineering, 167*. https://doi.org/10.1016/j.applthermaleng.2019.114806
11. Shyam, B., & Kanakasabapathy, P. (2018). Large scale electrical energy storage systems in India- current status and future prospects. *Journal of Energy Storage, 18*, 112–120. https://doi.org/10.1016/j.est.2018.04.018
12. Global Energy Perspective 2022 Executive Summary. 2022.
13. The sunny side of Asia, Centre for Research on Energy and Clean Air (CREA) Institute for Energy Economics and Financial Analysis (IEEFA), Publication date: November 10, 2022.
14. https://www.irena.org/Energy-Transition/Technology/Solar-energy
15. G. of I. Ministry of New and Renewable Energy. Annual Report 2020–21. [Online]. Available: https://www.mnre.gov.in/
16. Cea Annual Report 2020–21 Central Electricity Authority Ministry of Power Government of India.
17. https://mnre.gov.in/solar/current-status
18. Gulagi, A., Bogdanov, D., & Breyer, C. (2018). The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India. *Journal of Energy Storage, 17*, 525–539. https://doi.org/10.1016/j.est.2017.11.012.91
19. Issue Brief speech or electronic media without prior written approval from ORF. India and the Global Commons: A Case Study of the International Solar Alliance OluwaseunOguntuase. 2022.
20. I. Energy Agency. (2021). India Energy Outlook 2021 World Energy Outlook Special Report. [Online]. Available: www.iea.org/t&c/
21. Bijarniya, J. P., Sudhakar, K., & Baredar, P. (2016). Concentrated solar power technology in India: A review. *Renewable and Sustainable Energy Reviews, 63*, 593–603. https://doi.org/10.1016/j.rser.2016.05.064
22. Shahabuddin, M, Alim, M. A., Alam, T., Mofijur, M., Ahmed, S. F., & Perkins, G. (2021). A critical review on the development and challenges of concentrated solar power technologies. *Sustainable Energy Technologies and Assessments, 47*. https://doi.org/10.1016/j.seta.2021.101434.915
23. Akhtar, I., Kirmani, S., Jameel, M., & Alam, F. (2021). Feasibility analysis of solar technology implementation in restructured power sector with reduced carbon footprints. *IEEE Access, 9*, 30306–30320. https://doi.org/10.1109/ACCESS.2021.3059297
24. Solar heat for industry, Solar Payback INDIA, German Solar Association, Solar Thermal Federation of India (STFI).