NIPES-Journal of Science and Technology Research 6(10) 2024 pp 61-69. ISSN-2682-5821

NIPES

Journal of Science and Technology Research

Journal homepage: www.nipesjournals.org.ng

Short communication

Global Cumulative Installed Concentrated Solar Power Capacity with Thermal Energy Storage System and Cost Trend

Collins Chike Kwasi-Effah[a,b] & Martin Osikhuemhe[b]

[a]Department of Mechanical Engineering, University of Alberta, Edmonton, Canada
[b]Department of Mechanical Engineering, University of Benin Edo State Nigeria

Abstract

Thermal Energy Storage (TES) is essential for enhancing the dispatchability and efficiency of Concentrated Solar Power (CSP) systems. This short communication reviews recent advancements in TES technologies for CSP, focusing on novel storage materials, system designs, and implementation challenges. We explore innovations in molten salt formulations, solid-state storage media, and thermochemical storage systems. Key practical aspects such as system integration, cost considerations, and operational challenges are also discussed. Significant progress has been made in high-temperature TES systems, with potential for further cost reductions and efficiency improvements in the coming years. This review provides insights into the current state of TES in CSP and outlines future research directions for performance enhancement and cost reduction.

Keywords: *Thermal Energy Storage, Concentrated Solar Power, Molten Salts, Phase Change Materials, Thermochemical Storage, Renewable Energy*

*https://doi.org/10.5281/**zenodo.14033073***

1. Introduction

Concentrated Solar Power (CSP) with Thermal Energy Storage (TES) has emerged as a promising technology for providing dispatchable renewable energy. TES enables CSP plants to generate electricity during periods of low or no solar irradiance, significantly increasing their capacity factor and economic viability [1-35]. As of 2023, the global installed capacity of CSP plants with TES has reached approximately 5.6 GW, with projections indicating substantial growth in the coming years [1].

The integration of TES in CSP plants offers several key advantages:

Dispatchability: Enables electricity generation during periods of low or no solar irradiance.

Improved Capacity Factor: Increases from 20-25% without storage to 40-70% with storage.

Grid Stability: Provides valuable grid services, including frequency regulation and load following.

Economic Benefits: Allows shifting electricity production to periods of high demand, improving project economics.

Reduced Curtailment: Stores excess energy for later use in regions with high penetration of variable renewable energy sources.

This short communication provides insights into recent developments and practical aspects of TES for CSP applications, covering technological advancements, market trends, and future prospects

2. Current Status and Market Trends:

2.1 Global Deployment of TES in CSP

The global cumulative installed CSP capacity with TES has grown significantly over the past decade. Figure 1 illustrates this growth from 2010 to 2023. The chart shows a consistent increase in CSP capacity integrated with TES, growing from 0.6 GW in 2010 to 5.6 GW in 2023. This represents a Compound Annual Growth Rate (CAGR) of approximately 21.1%, which is a strong indicator of the increasing adoption of TES in CSP systems. The steady growth reflects an increasing demand for renewable energy sources that can provide dispatchable power, especially as grids integrate more intermittent renewables like solar PV and wind. TES allows CSP plants to generate electricity even when the sun is not shining, making them more reliable and attractive for grid.

The plateauing trend after 2017 could also suggest that CSP with TES has reached a level of technological maturity, where further growth is contingent on achieving significant cost reductions and overcoming technical challenges. As the technology matures, the focus will shift towards reducing costs to make CSP with TES more competitive with other forms of energy storage, such as batteries. The plateau could also reflect the need for further advancements in power cycles and system integration. The current generation of CSP plants typically operates at temperatures around 565°C using molten salts, but research is underway to increase operating temperatures beyond 700°C using advanced materials and power cycles (e.g., supercritical CO_2 cycles).

To sustain long-term growth, there will be a need for next-generation CSP systems that offer higher efficiencies and lower costs through innovations in TES materials (e.g., chloride salts or solid particles) and advanced power cycles. These advancements are part of initiatives like NREL's Generation 3 CSP systems.

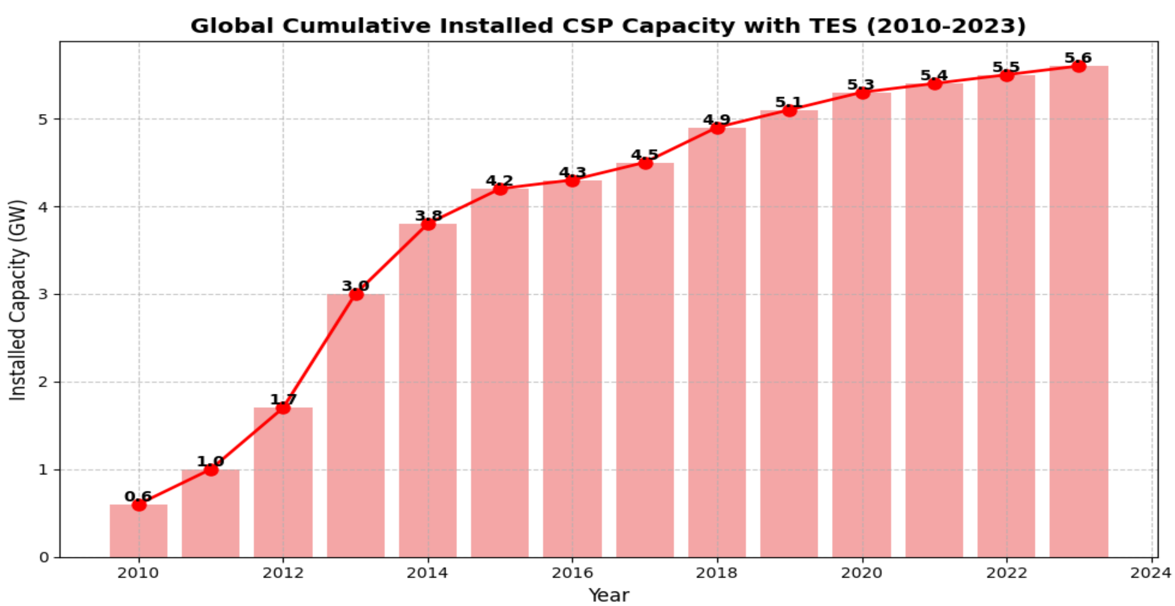

Figure 1: Global Cumulative Installed CSP Capacity with TES (2010-2023)

The market for TES in CSP plants has seen significant growth, driven by several factors:

1. Increasing demand for dispatchable renewable energy
2. Improved plant economics through higher capacity factors
3. Advancements in storage materials and system designs
4. Supportive policies and incentives in key markets

Table 1 presents the top 5 countries by installed CSP capacity with thermal storage as of 2023.

Table 1: Top 5 Countries by Installed CSP Capacity with Thermal Storage (2023)

Rank	Country	Installed Capacity with TES (MW)
1	Spain	2200
2	USA	1600
3	China	800
4	Morocco	510
5	UAE	400

2.2 Technology Adoption Trends

Sensible heat storage using molten salts has emerged as the dominant TES technology in operational CSP plants. The two-tank molten salt system, consisting of separate hot and cold storage tanks, has become the industry standard due to its proven performance and reliability.

Key trends in TES technology adoption for CSP include:

1. Increasing storage capacities: Recent CSP projects have incorporated larger storage capacities, with some plants achieving over 15 hours of full-load storage.
2. Higher operating temperatures: There is a trend towards higher temperature storage systems (> 565°C) to improve power cycle efficiencies and reduce costs.
3. Integration of TES in solar tower plants: Molten salt storage has been successfully adapted for solar tower plants, enabling higher operating temperatures and efficiencies.
4. Exploration of alternative storage media: Research and demonstration projects are investigating novel storage materials, including high-temperature concrete, ceramic particles, and advanced molten salt formulations.

3.0. Technological Advancements in Storage Media and System Designs

3.1 Advanced Molten Salt Formulations

Researchers have been developing new molten salt mixtures with improved properties to address some limitations of conventional solar salt (60% $NaNO_3$, 40% KNO_3). Key areas of improvement include:

1. Lower melting points: Novel salt mixtures incorporating calcium, lithium, or cesium nitrates have demonstrated melting points below 200°C, reducing the risk of salt freezing in pipes and heat exchangers.
2. Higher thermal stability: Efforts to increase the maximum operating temperature of molten salts beyond the current limit of about 565°C aim to enable higher power cycle efficiencies. Chloride-based salt mixtures have shown promise for high-temperature applications (>700°C).
3. Reduced corrosivity: The addition of corrosion inhibitors or the development of less corrosive salt formulations can extend the lifetime of system components and reduce maintenance costs.
4. Enhanced thermophysical properties: Research into salt mixtures with higher specific heat capacities and thermal conductivities aims to improve overall system performance and reduce storage volumes.

Table 2 compares the properties of conventional solar salt with some advanced molten salt formulations.

Table 2: Comparison of Conventional and Advanced Molten Salt Formulations

Salt Mixture	**Composition**	**Melting Point (°C)**	**Max. Operating Temp. (°C)**	**Specific Heat (kJ/kg·K)**
Solar Salt	60% $NaNO_3$, 40% KNO_3	220	565	1.5
Hitec XL	48% $Ca(NO_3)_2$, 45% KNO_3, 7% $NaNO_3$	120	500	1.4
LiNaK	30% $LiNO_3$, 20% $NaNO_3$, 50% KNO_3	120	600	1.6
Chloride Salt	32% NaCl, 24.5% KCl, 43.5% $ZnCl_2$	204	>700	0.8

3.2 Solid-State Storage Media

Alternative storage media are being investigated to overcome some limitations of molten salts:

1. High-temperature concrete: Specially formulated concrete mixtures have been developed for TES applications, offering advantages such as:
    - Lower cost compared to molten salts
    - Simplified system design (single-tank storage)
    - Reduced environmental and safety concerns

The DLR (German Aerospace Center) has demonstrated a high-temperature concrete storage system with operating temperatures up to 400°C.

2. Ceramic particles: Ceramic materials such as bauxite or silicon carbide particles are being explored for high-temperature applications (>1000°C) and direct solar absorption.

    Key advantages include:
    - Excellent thermal stability
    - Ability to act as both heat transfer and storage medium
    - Potential for direct irradiation in solar receivers

The U.S. Department of Energy's Gen3 CSP program is investigating particle-based systems for next-generation CSP plants [5].

3. Liquid metals: Metals with low melting points, such as sodium or lead-bismuth eutectic, offer advantages for high-temperature TES:
    - Excellent heat transfer properties
    - Wide operating temperature range
    - Compatibility with advanced power cycles (e.g., supercritical CO_2)

However, challenges related to safety and material compatibility need to be addressed for practical implementation.

3.3 Thermochemical Storage Systems

Thermochemical storage systems utilize reversible chemical reactions to store and release thermal energy. While still in the research phase, these systems offer potential for very high energy storage densities:

1. Metal oxide redox reactions: e.g., Co_3O_4/CoO
2. Carbonate decomposition: e.g., $CaCO_3/CaO$
3. Ammonia dissociation: $NH_3 \rightleftharpoons N_2 + 3H_2$

These systems could achieve energy densities up to 500 kWh/m³, significantly higher than current molten salt systems [6].

4.0. Practical Aspects of TES Implementation:

4.1 System Integration

Recent innovations focus on integrating TES more effectively with CSP plants:

1. Single-tank thermocline systems: These systems use a single tank with a temperature gradient, potentially reducing costs and complexity compared to two-tank systems
2. Direct thermal storage systems: Eliminating the need for heat exchangers by using the storage medium as the heat transfer fluid can improve efficiency and reduce costs.
3. Integration with advanced power cycles: TES systems are being designed to work with supercritical CO2 cycles, which offer higher efficiencies than conventional steam cycles [8]

4.2 Cost Considerations

The Levelized Cost of Storage (LCOS) for molten salt systems in CSP plants has decreased significantly in recent years. Figure 2 illustrates the trend in LCOS for molten salt storage systems from 2010 to 2023.

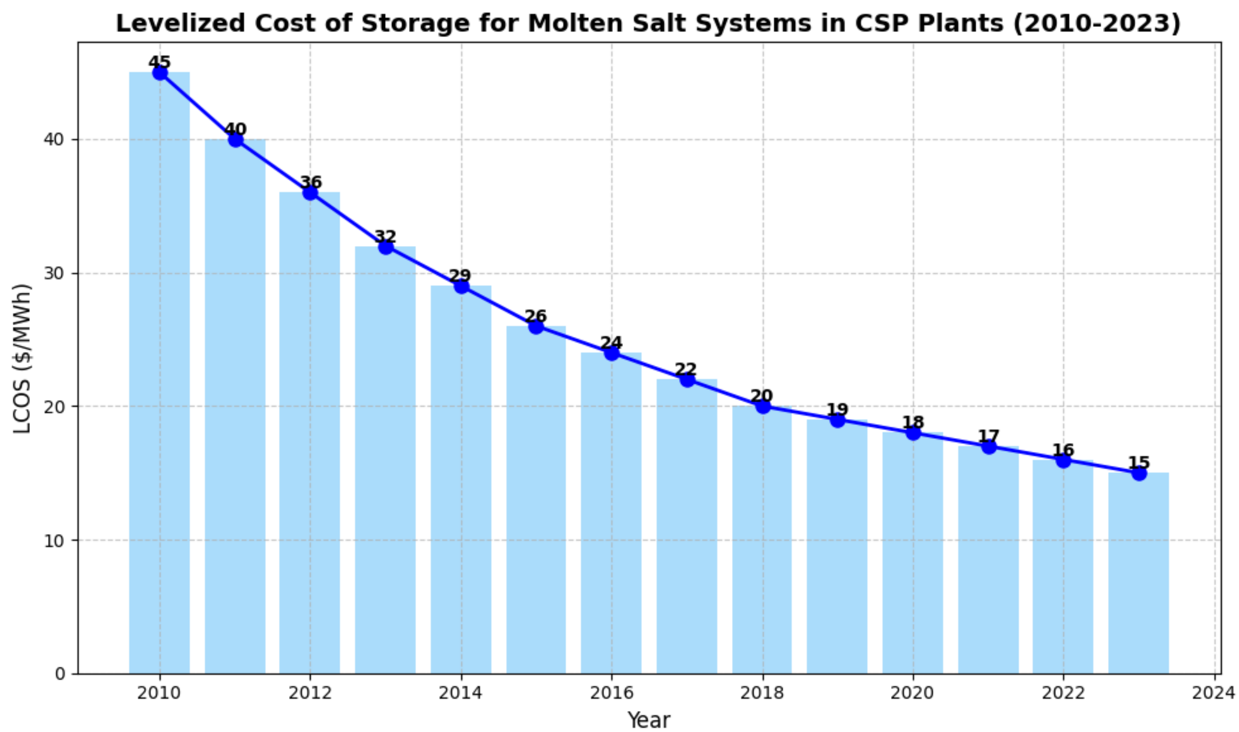

Figure 2: Levelized Cost of Storage for Molten Salt Systems in CSP Plants (2010-2023)

As of 2023, the LCOS for molten salt storage systems in CSP plants ranges from $15 to $30 per MWh, depending on the system size and location. Projections suggest potential for further cost reductions to $10-$15 per MWh by 2030.

4.3 Operational Challenges

Key challenges in TES operation include:

1. Managing thermal cycling and associated material fatigue
2. Optimizing charging and discharging strategies for maximum efficiency
3. Ensuring long-term stability of storage materials
4. Minimizing heat losses during storage periods
5. Addressing corrosion and material compatibility issues, especially at high temperatures

5.0. Future Prospects and Research Directions

5.1 Emerging TES Technologies

Several promising TES technologies are under development for future CSP applications:

1. High-temperature phase change materials (PCMs): Research is ongoing to develop PCMs with melting points above 500°C, which could offer higher energy densities than sensible heat storage.
2. Thermochemical storage using metal hydrides: These systems offer potential for long-duration, high-density energy storage with minimal thermal losses.
3. Hybrid storage systems: Combining different storage technologies (e.g., sensible + latent) to optimize performance and cost.

5.2 Integration with Advanced Power Cycles

The development of advanced power cycles, such as supercritical CO_2 Brayton cycles, is driving research into high-temperature TES systems capable of operating above 700°C. This integration has the potential to significantly increase overall plant efficiency.

5.3 Materials Research

Ongoing materials research focuses on:

1. Developing corrosion-resistant alloys for high-temperature applications
2. Improving the thermal stability and cycle life of storage materials
3. Exploring nanostructured materials for enhanced heat transfer and storage properties

5.4 System Optimization and Control

Advanced control strategies and predictive models are being developed to optimize TES operation, including:

1. Model predictive control for improved charging and discharging strategies
2. Machine learning algorithms for performance prediction and fault detection
3. Integration of weather forecasting for optimized plant operation

6.0. Conclusion

Thermal Energy Storage technologies play a crucial role in enhancing the performance, flexibility, and economic viability of Concentrated Solar Power systems. Significant advancements have been made in recent years, particularly in high-temperature storage systems and novel storage materials. The integration of TES with CSP has demonstrated the potential to provide dispatchable renewable energy, contributing to grid stability and supporting the transition to a low-carbon energy system.

Key areas for future research and development include:

1. Further cost reductions through improved materials and system designs
2. Development and scale-up of high-temperature storage technologies
3. Integration of TES with advanced power cycles for increased efficiency
4. Optimization of system operation through advanced control strategies

As these challenges are addressed, TES-integrated CSP systems are poised to play an increasingly important role in the global energy transition, providing reliable, dispatchable renewable energy to support a sustainable future.

References

[1] IRENA. (2020). Renewable Power Generation Costs in 2019.
[2] Mehos, M., et al. (2017). Concentrating Solar Power Gen3 Demonstration Roadmap. NREL/TP-5500-67464.
[3] Palacios, A., et al. (2020). Thermal energy storage in concrete tanks: Design and testing. Solar Energy, 206, 1-8.
[4] Fernández, A. G., et al. (2019). Thermal energy storage for CSP plants through the use of molten salt binary mixtures. Solar Energy Materials and Solar Cells, 201, 110082.
[5] U.S. Department of Energy. (2023). Generation 3 Concentrating Solar Power Systems.
[6] Prieto, C., et al. (2016). Review of technology: Thermochemical energy storage for concentrated solar power plants. Renewable and Sustainable Energy Reviews, 60, 909-929.
[7] González-Roubaud, E., et al. (2017). Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts. Renewable and Sustainable Energy Reviews,
[8] G. Alva, Y. Lin, G. Fang, et al, "Thermal energy storage materials and systems for solar energy applications," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 693-706, Feb. 2017.
[9] H. P. Garg, S. C. Mullick, and V. K. Bhargava, *Solar thermal energy storage*. Berlin, Germany: Springer Science & Business Media, 2012.
[10] Vignarooban, K., et al. "Heat transfer fluids for concentrating solar power systems – A review. Applied Energy", 146, 2015, 383-396.
[11] Benoit, H., et al. "Review of heat transfer fluids in tube-receivers used in concentrating solar thermal systems: Properties and heat transfer coefficients". Renewable and Sustainable Energy Reviews, 55, 2016, 298-315.
[12] H. O. Egware and C. C. Kwasi-Effah, "A novel empirical model for predicting the carbon dioxide emission of a gas turbine power plant," *Heliyon*, vol. 9, no. 3, Mar. 2023.
[13] C. C. Kwasi-Effah, O. O. Ighodaro, H. O. Egware, and A. I. Obanor, "Characterization and comparison of the thermophysical property of ternary and quaternary salt mixtures for solar thermal power plant applications," *Results in Engineering*, vol. 16, p. 100721, 2022.
[14] C. C. Kwasi-Effah, O. O. Ighodaro, H. O. Egware, and A. I. Obanor, "A novel empirical model for predicting the heat accumulation of a thermal energy storage medium for solar thermal applications," *Journal of Energy Storage*, vol. 56, p. 105969, 2022.
[15] C. C. Kwasi-Effah, H. O. Egware, O. O. Ighodaro, and A. I. Obanor, "Development and characterization of a quaternary nitrate-based molten salt heat transfer fluid for concentrated solar power plant," *Heliyon*, vol. 9, no. 5, May 2023.
[16] C. C. Kwasi-Effah, O. O. Ighodaro, et al., "Enhancing thermal conductivity of novel ternary nitrate salt mixtures for thermal energy storage (TES) fluid," *Progress in Engineering Science*, vol. 1, no. 4, p. 100020, 2024.
[17] I. Sarbu and C. Sebarchievici, "A comprehensive review of thermal energy storage," *Sustainability*, vol. 10, no. 1, p. 191, Jan. 2018.
[18] C. C. Kwasi-Effah, O. O. Ighodaro, and A. I. Obanor, "Recent progress in the development of thermal energy storage mediums for solar applications," *J. Eng. Dev.*, vol. 15, no. 1, pp. 146-170, 2023.
[19] A. Shukla, D. Buddhi, and R. L. Sawhney, "Solar water heaters with phase change material thermal energy storage medium: A review," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2119-2125, Oct. 2009.
[20] C. C. Kwasi-Effah, "Advancements in Heat Transfer Fluids for Concentrated Solar Power Systems: A Brief Review," 2024. [Online]. Available: https://doi.org/10.5281/zenodo.14020385
[21] C. C. Kwasi-Effah, "Heat Transfer Fluids in Solar Thermal Power Plants: A Review," *NIPES - Journal of Science and Technology Research*, 2024. [Online]. Available: https://journals.nipes.org/index.php/njstr/article/view/1109
[22] S. J. Wagner, "Environmental and Economic Implications of Thermal Energy Storage for Concentrated Solar Power Plants," Ph.D. dissertation, Carnegie Mellon University, Pittsburgh, PA, USA, 2011.
[23] C. C. Kwasi-Effah, "Economic Viability and Cost Analysis of Thermal Energy Storage in Concentrated Solar Power Systems," *NIPES - Journal of Science and Technology Research*, vol. 6, no. 10, 2024. [Online]. Available: https://doi.org/10.5281/zenodo.14020575
[24] M. Lambrecht, B. Wagner, F. Jost, and others, "Evaluation of the environmental impacts and economical study of Solar Salt in CSP-parabolic trough technology," *Materials at High Temperatures*, vol. 40, no. 4, pp. 331–337, 2023.
[25] C. C. Kwasi-Effah, "Environmental Impact and Sustainability of Thermal Energy Storage in Concentrated Solar Power Systems," *NIPES - Journal of Science and Technology Research*, vol. 1, no. 10, 2024. [Online]. Available: https://doi.org/10.5281/zenodo.14020637
[26] M. H. Esfe, et al., "Experimental study on thermal conductivity of DWCNT-ZnO/water-EG nanofluids," *International Communications in Heat and Mass Transfer*, vol. 68, pp. 248-251, 2015.

[27] O. Mahian, et al., "A review of the applications of nanofluids in solar energy," *International Journal of Heat and Mass Transfer*, vol. 57, no. 2, pp. 582-594, 2013.

[28] M. H. Esfe, et al., "Thermophysical properties, heat transfer and pressure drop of COOH-functionalized multi-walled carbon nanotubes/water nanofluids," *International Communications in Heat and Mass Transfer*, vol. 58, pp. 176-183, 2014.

[29] C. C. Kwasi-Effah, "Optimizing Heat Transfer Fluids for Enhanced Thermal Conductivity in Concentrated Solar Power Systems," *NIPES - Journal of Science and Technology Research*, 2024. [Online]. Available: https://doi.org/10.5281/zenodo.14020708

[30] T. Yousefi, et al., "An experimental investigation on the effect of Al_2O_3–H_2O nanofluid on the efficiency of flat-plate solar collectors," *Renewable Energy*, vol. 39, no. 1, pp. 293-298, 2012.

[31] R. D. Ayinla, C. C. Kwasi-Effah, and H. O. Egware, "Thermal Conductivity Enhancement of Quaternary Nitrate Salt Mixtures for Thermal Energy Storage with Al_2O_3 Nanoparticle Doping," *NIPES - Journal of Science and Technology Research*, vol. 6, no. 3, 2024. [Online]. Available: https://doi.org/10.5281/zenodo.14020924

[32] C. C. Kwasi-Effah. "Advancements in Hybrid Heat Transfer Fluids: Potential for Reduced Melting Points in CSP Applications". *NIPES - Journal of Science and Technology Research* vol 6, no. 10, 2024 https://doi.org/10.5281/zenodo.14026856

[33] M. Lambrecht, et al. "Evaluation of the environmental impacts and economical study of Solar Salt in CSP-parabolic trough technology. *Materials at High Temperatures*, *40*(4), 2023. https://doi.org/10.1080/09603409.2023.2182588

[34] C. C. Kwasi-Effah, M. Osikhuemhe. "Environmental and Economic Trade-offs in Heat Transfer Fluids for Concentrated Solar Power: A Brief Review." *NIPES - Journal of Science and Technology Research*. 2024 https://doi.org/10.5281/zenodo.14027127

[35] S.K.Tamilarasan, et al. "Recent Developments in Supercritical CO_2-Based Sustainable Power Generation Technologies" *Energies* **2024**, *17*, 4019. https://doi.org/10.3390/en17164019