

Molecular Solar Thermal Energy Storage: Can Sunlight Really Be Stored in a Liquid?

*G. Sindhuja¹ and C. Aparna²

¹Teaching Associate, College of Agri. Engineering, Sangareddy, PJTAU, Hyderabad

²Teaching Assistant, Vikas college of Engineering and Technology, Vijayawada

*Corresponding Author's email: gonessindhu295@gmail.com

Solar energy is one of the most abundant renewable energy resources available to humanity. Every day, enormous amounts of solar radiation reach the Earth's surface, offering a clean alternative to fossil fuels. Yet one fundamental problem remains: sunlight is not available continuously. Solar-energy production varies with the time of day, weather conditions and season, while energy demand may occur at any time. This mismatch between energy generation and energy demand makes energy storage one of the most important challenges in the transition towards renewable energy. Conventional batteries can store electricity, but they are not always the most suitable solution when the final requirement is heat. An interesting alternative is therefore emerging from chemistry: instead of converting sunlight into electricity and then storing it, why not store solar energy directly as chemical energy inside molecules? This is the basic idea behind **Molecular Solar Thermal Energy Storage (MOST)**. In a MOST system, specially designed molecules absorb sunlight and transform into a higher-energy form. The energy can then remain stored in the molecule and be released later as heat when required.

What exactly is MOST?

Molecular Solar Thermal Energy Storage is a technology in which a specially designed molecule acts as a molecular energy carrier. When exposed to sunlight, the molecule absorbs solar energy and undergoes a structural transformation known as photoisomerization. The resulting molecule is a metastable, higher-energy form that can retain the absorbed solar energy. As illustrated in Fig. 1, the process involves sunlight absorption, formation of a higher-energy molecular state, storage of the absorbed energy, controlled heat release and regeneration of the original molecular form. The stored energy is not released immediately. Instead, it can remain stored until an appropriate trigger such as heat, a catalyst or an electrochemical stimulus is provided. The high-energy molecule then returns to its original, lower-energy form and releases the stored energy as heat. Ideally, the original molecule can subsequently be recharged using sunlight, creating a closed molecular energy-storage cycle.

A molecule that behaves like a tiny solar battery

The concept becomes easier to understand when we think of the molecule as a tiny rechargeable solar battery. A conventional battery stores energy through electrochemical processes involving electrodes and ions. In a MOST system, energy is stored through a reversible change in the structure of a molecule. One of the most extensively studied molecular systems is based on **norbornadiene (NBD) and quadricyclane (QC)**. Norbornadiene absorbs sunlight and is converted into the more energetic quadricyclane form. During this transformation, solar energy becomes stored as chemical energy in the strained molecular structure. When the stored energy is required, quadricyclane can be converted back into norbornadiene, releasing the stored energy as heat. The parent molecule can then be used again for another charging cycle. The molecular energy-storage mechanism of the NBD/QC system is illustrated in Fig. 2.

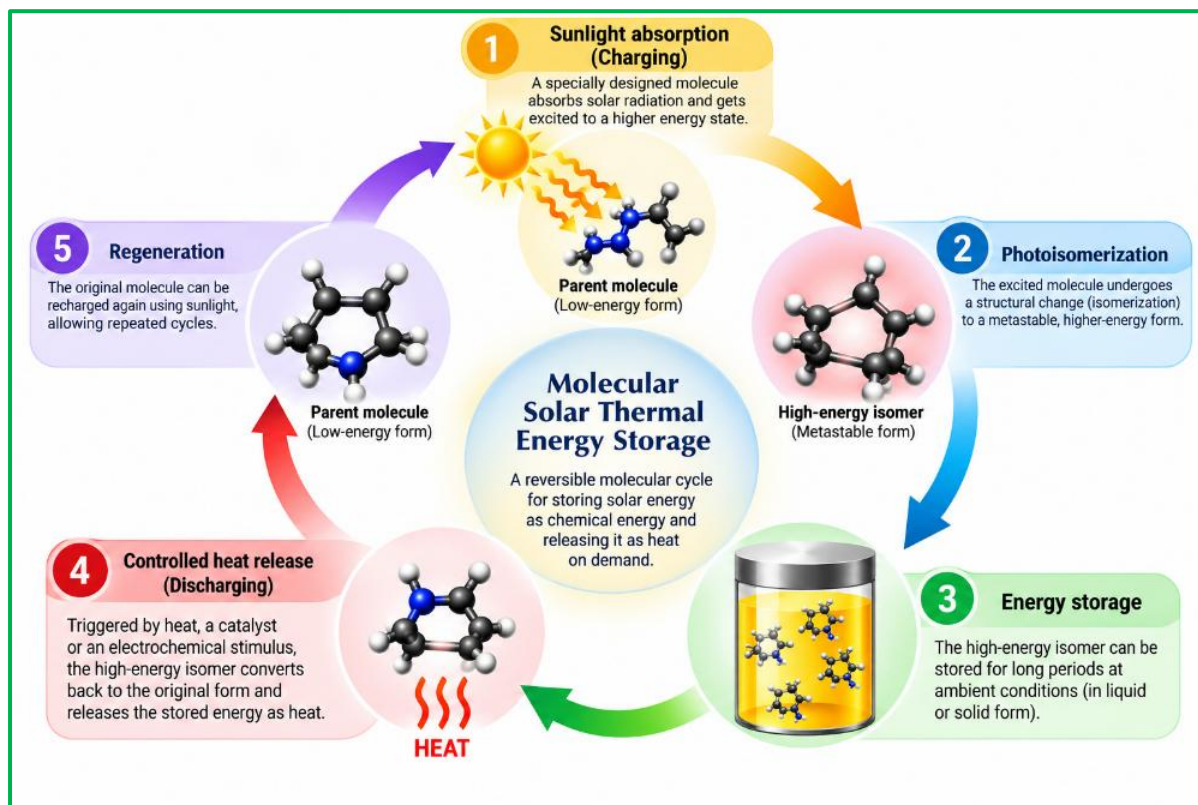


Fig 1. Basic working principle of Molecular Solar Thermal Energy Storage

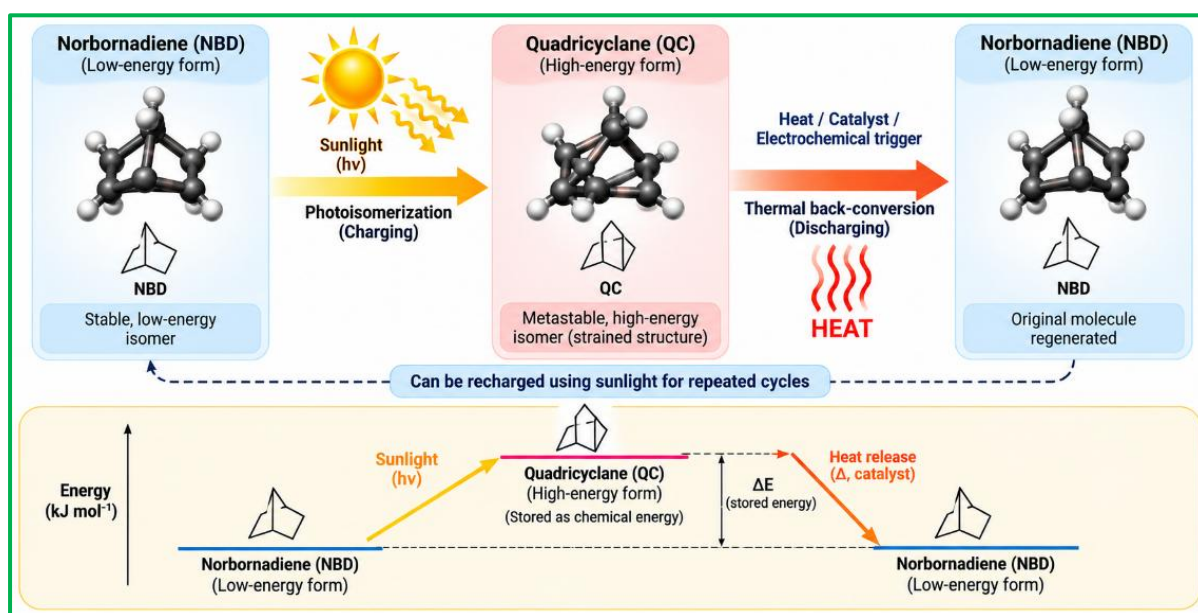


Fig 2. Molecular energy-storage mechanism based on the norbornadiene/quadracyclane (NBD/QC) system

Why store energy in a molecule?

The attraction of MOST technology lies in the possibility of storing energy within chemical bonds and molecular structure rather than simply storing it as sensible heat. This creates the possibility of storing solar energy during periods of strong sunlight and releasing it later when sunlight is unavailable. The stored molecular energy could potentially be transported and released at a location where thermal energy is required. This opens an interesting possibility: sunlight collected at one time and place could provide useful heat at another time and potentially another location. However, MOST should not simply be described as a replacement for batteries. It is more accurately viewed as a chemical method for storing solar energy, particularly for thermal-energy applications.

How much energy can these molecules store?

Energy density is one of the most important parameters for any energy-storage technology. Studies on NBD/QC systems have demonstrated energy-storage densities in the range of several hundred kilojoules per kilogram. **Dreos *et al.* (2017)** reported NBD/QC compounds capable of storing approximately 354–396 kJ kg⁻¹, corresponding to about 86.5–103 kJ mol⁻¹ for the investigated compounds. These values demonstrate why researchers are interested in MOST. However, energy density alone is not enough. A successful molecular energy-storage system must combine efficient sunlight absorption, high energy density, long storage stability, rapid heat release and repeated charging and discharging.

From a molecule in the laboratory to useful heat

A major challenge is converting the molecular concept into a practical device. It is not enough for a molecule to store energy; researchers must also be able to release that energy rapidly and efficiently when required. This problem was addressed in an important study by **Wang *et al.* (2019)**. They developed a MOST system using a specially designed NBD derivative and demonstrated macroscopic heat release from stored molecular energy. The researchers used a heterogeneous catalyst based on cobalt phthalocyanine supported on carbon to promote the conversion of the high-energy molecular form back to its original form. The system was operated under flow conditions, allowing stored molecular energy to be converted into a measurable temperature increase. Fig. 3 shows how the molecular concept can be integrated into a practical flow-based energy-storage system, including solar charging, molecular storage, catalytic heat release and regeneration.

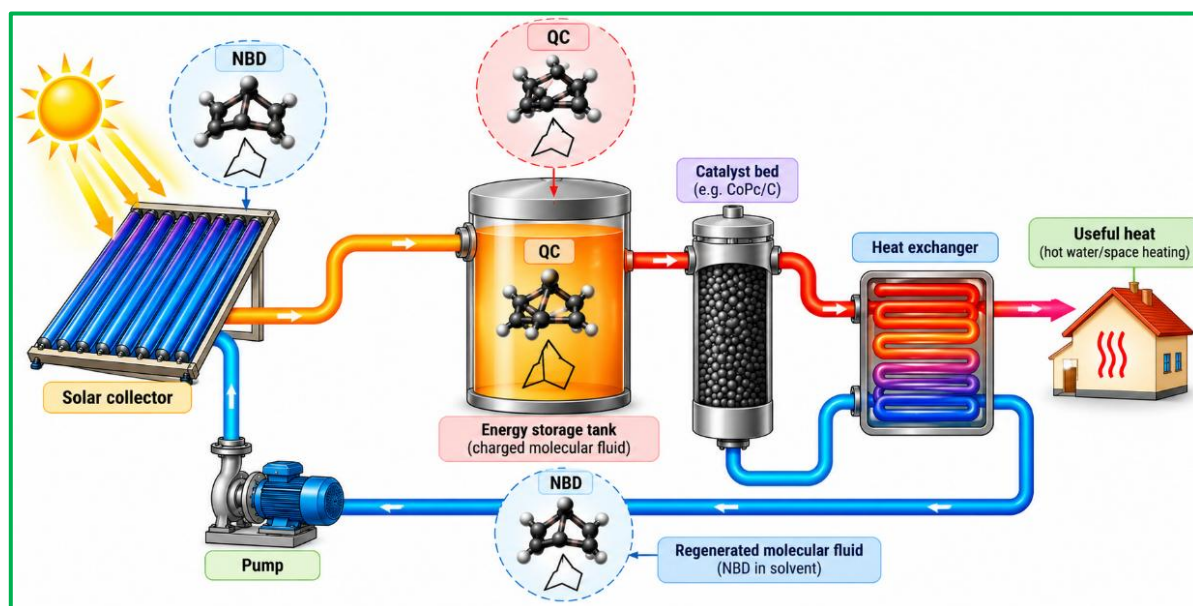


Fig. 3. Concept of a practical MOST system showing solar charging, molecular storage, catalytic heat release and regeneration

A remarkable demonstration of stored heat

The work of **Wang *et al.* (2019)** provided an important demonstration of the practical potential of MOST technology. Their system produced a temperature increase of approximately 63 °C across the catalytic heat-release stage, with an outlet temperature reaching about 83 °C under the reported experimental conditions. This was significant because it demonstrated that molecular solar thermal storage could move beyond the scale of individual molecules and produce macroscopic heat. The researchers also demonstrated outdoor operation, providing an important proof-of-concept for integrating molecular solar thermal storage with real solar radiation. The study reported an energy-storage density of approximately 0.4 MJ kg⁻¹ for the investigated NBD derivative. The result showed that carefully designed molecules, suitable catalysts and appropriate reactor configurations can work together to convert molecularly stored solar energy into useful heat.

Combining MOST with solar water heating

MOST does not necessarily have to compete with conventional solar-thermal technologies. Another interesting approach is to combine molecular storage with existing solar-water-heating systems. **Dreos *et al.* (2017)** investigated a hybrid system combining solar water heating and molecular solar thermal energy storage. In their study, the solar collector could simultaneously provide useful heat for water heating while a fraction of the incoming solar energy was stored chemically in the MOST system. The researchers reported that approximately 1.1% of the incoming solar energy was stored in the molecular system without significantly compromising the solar-water-heating function. The combined solar-water-heating and storage system achieved efficiencies of up to approximately **80%** under the investigated conditions. As shown in Fig. 4, this hybrid concept allows solar energy to serve two purposes: providing immediate useful heat and storing a fraction of the energy for later use.

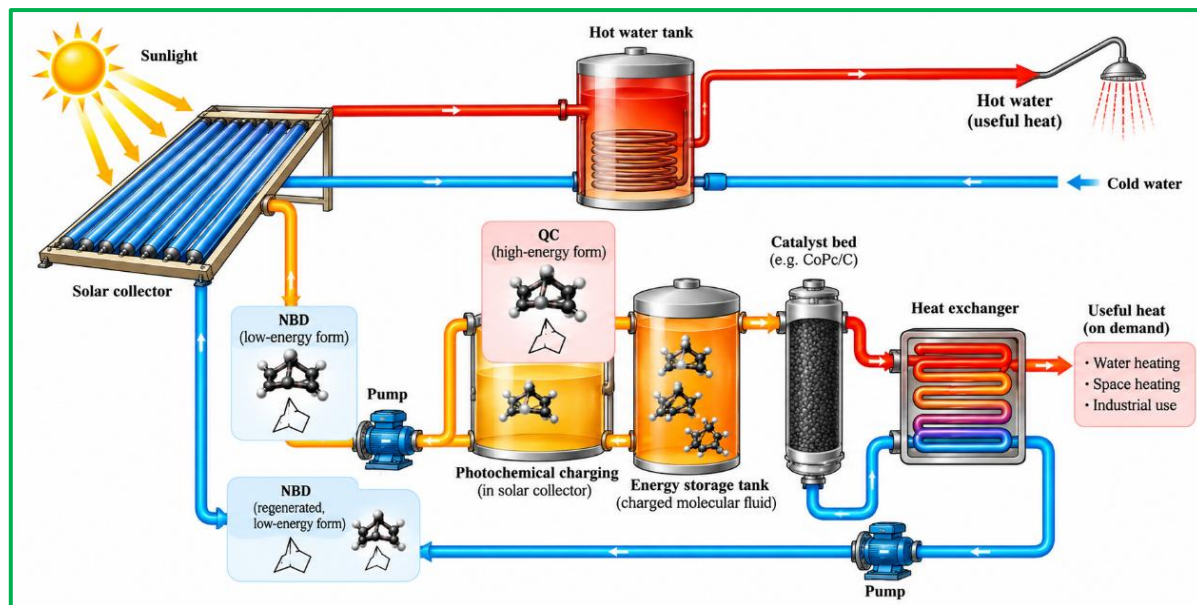


Fig. 4. Hybrid solar water-heating and molecular solar thermal energy-storage concept

The secret is not just the molecule

Developing a good MOST molecule is a balancing act. The molecule must absorb an appropriate portion of the solar spectrum, efficiently undergo photoisomerization, store a large amount of energy, remain stable during storage and return to its original state when energy is needed. One particularly important parameter is the quantum yield, which describes how efficiently absorbed photons produce the desired molecular transformation. A high quantum yield is desirable because not every photon absorbed by a molecule necessarily results in useful energy storage. The molecule must also have a sufficiently long lifetime in its high-energy state. If the stored molecule spontaneously returns to its original form too quickly, the stored energy can be lost before it is used. At the same time, the reverse reaction must be sufficiently rapid when heat is demanded. Thus, the development of a practical MOST molecule requires a balance between efficient charging, long-term storage stability and controlled energy release.

How long can sunlight remain stored?

One of the most fascinating aspects of MOST is the possibility of storing solar energy without continuously maintaining a high temperature. Unlike conventional thermal storage, where heat gradually escapes to the surroundings, MOST stores energy in a molecular configuration. However, storage time is not a universal fixed value. It depends on the molecular structure, solvent, temperature and stability of the metastable isomer. Therefore, MOST systems should not generally be described as being capable of storing sunlight for a particular number of years. Research has demonstrated storage over periods ranging from weeks to months for particular molecular systems, while researchers continue to design molecules with longer lifetimes and

improved stability. The challenge is to retain the energy for as long as necessary without sacrificing the ability to release it efficiently.

From buildings to industry and agriculture

The potential applications of MOST extend beyond laboratory experiments. If the technology can be developed economically and at sufficient scale, it could provide stored thermal energy for buildings, industrial processes, chemical processing and off-grid applications. For buildings, stored solar energy could potentially provide hot water or space-heating assistance after sunset. In industry, where many processes require moderate-temperature heat, MOST could provide another method of matching intermittent solar energy with continuous thermal demand. Agriculture is another area where thermal energy is frequently required. Solar heat can be useful for crop drying, seed drying, food processing, greenhouse applications and water heating. A MOST-based system could potentially collect solar energy during periods of strong sunlight and release stored heat when the crop-drying or processing operation requires it. However, agricultural applications should currently be regarded as future possibilities rather than established commercial applications. More research is needed to determine whether the cost, durability, safety and thermal output of MOST systems can meet agricultural requirements.

What is stopping MOST from becoming mainstream?

Despite its promise, MOST technology is still under development. Several challenges must be solved before large-scale commercialization becomes realistic. First, the molecular system must absorb sunlight efficiently. Second, the photoisomerization process must have a high quantum yield. Third, the high-energy isomer must be sufficiently stable during storage. Fourth, the system must release the stored energy rapidly when required. Finally, the molecules, solvents, catalysts, reactors and supporting equipment must be affordable and environmentally acceptable. Researchers must also improve the number of charging and discharging cycles that can be achieved without significant loss of performance. A practical energy-storage technology must survive repeated operation rather than simply demonstrate good performance during a limited number of laboratory cycles.

The future: from molecular chemistry to energy technology

Recent research shows that the field is gradually moving from studying individual molecules towards developing functional MOST devices. Reviews by **Hemauer, Steinrück and Papp (2024)**, **Giménez-Gómez *et al.* (2024)**, and **Xu *et al.* (2025)** highlight both the progress and the remaining challenges in converting MOST chemistry into practical energy-storage systems. Future developments are likely to focus on improving solar-spectrum utilization, molecular stability, energy density, quantum yield, catalyst performance and device integration. Researchers are also exploring ways to reduce dependence on solvents and develop systems that are more suitable for practical operation. The ultimate objective is not simply to create a molecule that stores sunlight. It is to create an integrated device in which sunlight can be collected, stored and converted into useful heat whenever it is needed.

References

1. Dreos, A., Börjesson, K., Wang, Z., Roffey, A., Norwood, Z., Kushnir, D. and Moth-Poulsen, K., 2017. Exploring the potential of a hybrid device combining solar water heating and molecular solar thermal energy storage. *Energy & Environmental Science*, 10(3): 728-734.
2. Giménez-Gómez, A., Magson, L., Merino-Robledillo, C., Hernáez-Troya, S., Sanosa, N., Sampedro, D. and Funes-Ardoiz, I., 2024. State-of-the-art and challenges towards a Molecular Solar Thermal (MOST) energy storage device. *Reaction Chemistry & Engineering*, 9(7): 1629-1640.
3. Hemauer, F., Steinrück, H.P. and Papp, C., 2024. The norbornadiene/quadracyclane pair as molecular solar thermal energy storage system: surface science investigations. *ChemPhysChem*, 25(9): e202300806.

4. Wang, Z., Roffey, A., Losantos, R., Lennartson, A., Jevric, M., Petersen, A.U., Quant, M., Dreos, A., Wen, X., Sampedro, D. and Börjesson, K., 2019. Macroscopic heat release in a molecular solar thermal energy storage system. *Energy & Environmental Science*, 12(1): 187-193.
5. Xu, X., Li, C., Li, W., Feng, J. and Li, W.Y., 2025. Molecular solar thermal energy storage devices: toward a more sustainable future. *Energy & Environmental Science*, 18(20): 8990-9017.