

Thermal Energy Storage Options: Comparisons between Molten Salt, Liquid Air, and Liquid Nitrogen Technologies

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Abstract. Thermal energy storage is crucial for the transition to a low-carbon, renewable energy future. This literature review critically compares and contrasts three sustainable thermal energy storage technologies: molten salt, liquid air energy storage (LAES), and the liquid nitrogen engine (LNE). Molten salt systems have a high energy density and long thermal stability, but are restricted by their high cost and maintenance needs. LAES has a high energy density and low environmental impact, yet suffers from low efficiency. LNE is highly efficient but limited to low-power applications and needs a high-pressure storage tank. Each technology has its benefits and drawbacks, and the most appropriate technology will depend on the specific application. Molten salt may be suitable for large-scale projects, LAES for urban environments and LNE for low-power applications. Therefore, research and development in thermal energy storage should focus on improving efficiency, and cost-effectiveness and exploring new technologies to aid in the transition to a low-carbon, renewable energy future.

Keywords: Thermal Energy Storage, Sustainable Technology, Molten Salt.

1. Introduction

Sustainable thermal energy storage technologies will play a crucial role in allowing the grid integration of intermittent renewable energy sources as the world moves closer to a future with low carbon emissions and renewable energy sources. There have been many different approaches to the problem of storing excess thermal energy, each of which has its own unique set of advantages and drawbacks[8][9]. As part of this review of the relevant literature will examine the similarities and differences between molten salt, liquid air energy storage (LAES), and liquid nitrogen engine (LNE).

High-temperature liquid salt is used in the molten salt technique of thermal energy storage, which involves both the storage and transfer of heat via the salt at high temperatures. The heat from renewable sources, such as the sun or the wind, is used to heat the salt, and then the salt is used to store the heat until it is needed. When there is a need for energy, salt is converted into steam, which is then utilised to turn a turbine and produce electricity. Molten salt systems are well suited for applications that need a consistent energy supply due to their high energy density and extended thermal stability [14] [15] [16]. Despite this, molten salt systems are often reserved for usage in large-scale applications because of the significant costs associated with both their construction and their upkeep [11] [12] [13].

The LAES is a technique for the storage of energy that utilises air that has been compressed and cooled. When there is a need for energy, liquid air is heated, which causes it to expand. This expansion then drives a turbine, which produces electricity. Because it does not emit any emissions while it is operating, LAES has a high energy density while having little impact on the surrounding environment [20] [21]. In addition, the LAES may be powered by a diverse range of energy sources, including environmentally friendly ones such as wind and solar [10] [20]. Despite this, LAES is inefficient since the process of expansion results in the loss of a significant amount of energy. In addition to this, the system requires a pricey high-pressure tank to store the liquid air, which may be expensive both to create and maintain over time.

A liquid nitrogen engine (LNE) is a kind of external combustion engine that uses liquid nitrogen as its working fluid. The engine produces mechanical power by heating liquid nitrogen, which causes it to vaporise and expand. This expansion drives a piston or a turbine, depending on the kind of engine

[4] [5]. LNE is very effective because liquid nitrogen has a boiling point that is not too high and because it can easily be evaporated with just a little amount of heat. Despite this, LNE devices are often only suitable for low-power applications since the expansion process is not optimal for producing high-power outputs [4]. LNE requires a high-pressure tank to store the liquid nitrogen, which may be expensive to build and maintain over the course of its lifetime.

The review will compare and contrast these technologies, with a focus on their challenges and aims. For example, molten salt systems aim to provide a cost-effective and reliable way to store thermal energy on a large scale, while LAES aims to provide a high-density and low-cost way to store energy, particularly in urban environments [1]. LNE, on the other hand, aims to provide a high-efficiency and low-emission way to generate power, particularly for low-power applications [19]. The review will also examine the scalability of each technology, as well as their integration with renewable energy sources and their environmental impact. Overall, the review aims to provide a comprehensive comparison of these three technologies and to identify the most suitable technology for a particular application.

2. Molten Salt

Molten salt storage is a well-established technology that involves using molten salt as a heat transfer fluid to store excess energy in a tank. The salt is circulated through a heat exchanger to release the stored energy when needed. This technology is often used in concentrated solar power plants due to its ability to store energy at high temperatures and its relatively low cost.

One of the main advantages of molten salt storage is its high energy density. Molten salt has a high specific heat capacity and a high latent heat of fusion, which means it can store large amounts of energy in a relatively small volume. In addition, molten salt storage systems can operate at high temperatures, which makes them well-suited for use with high-temperature heat sources such as concentrated solar power plants. A study by Kim et al. (2018) found that molten salt storage systems can store energy at temperatures up to 600°C, which is much higher than the maximum temperature of other thermal energy storage technologies such as sensible heat storage or phase change materials [13][17][18]. This high-temperature capability allows molten salt storage systems to achieve a high energy density and efficiency, as more energy can be stored per unit volume at higher temperatures. A study by Hui et al. (2018) found that molten salt storage systems can have energy densities of up to 200 MJ/m³, which is significantly higher than other technologies such as compressed air storage (20-30 MJ/m³) or pumped hydro storage (30-70 MJ/m³) [9]. This high energy density makes molten salt storage an attractive option for large-scale energy storage applications.

Another advantage of molten salt storage is its relatively low cost. Molten salt is a widely available, abundant, and inexpensive material, and the technology required to store energy in the molten salt is well-established and relatively simple. This makes molten salt storage an attractive option for large-scale energy storage applications. A study by Chen et al. (2020) found that molten salt storage systems have a lower Levelized cost of storage (LCOS) compared to other technologies such as compressed air energy storage or liquid air energy storage [21]. The LCOS is a measure of the overall cost of a storage system, including the cost of the storage material, the storage tanks, and the heat exchangers, as well as the cost of operation and maintenance. Cai et al. (2019) quantitatively estimated the LCOS of all the technologies studied, among which molten salt storage systems have an LCOS of \$40/MWh [2]. This was significantly lower than the LCOS of other technologies such as compressed air storage (\$80/MWh) or liquid air energy storage (\$100/MWh).

However, molten salt storage also has some potential drawbacks. For example, the high temperatures required for molten salt storage can cause corrosion of the storage tanks and heat exchangers, which can be expensive to repair or replace. In addition, molten salt storage systems require careful temperature management to ensure that the salt does not solidify or boil, which can be challenging to achieve in some cases. A study by Zhang et al. (2019) found that the corrosion resistance of molten salt storage tanks and heat exchangers is an important factor to consider when

designing a molten salt storage system [23]. The authors found that corrosion can be minimized by using corrosion-resistant materials such as stainless steel or nickel-based alloys, or by applying corrosion-resistant coatings to the tanks and heat exchangers. However, these measures can increase the cost of the storage system. A study by García et al. (2017) found that corrosion of the storage tanks and heat exchangers in molten salt storage systems can be a significant issue, and can lead to significant maintenance costs and reduced system lifetime [7]. In addition, the authors found that proper temperature management is critical to the performance of molten salt storage systems and that temperature control systems can be complex and costly to implement.

Another potential drawback of molten salt storage is the risk of leaks or spills. Molten salt is a corrosive material that can cause damage to the environment if it is released, and the high temperatures associated with molten salt storage systems can make spills or leaks more likely to occur [7] [23]. In addition, molten salt storage systems may require specialized safety measures to ensure that they are operated safely.

Despite these potential drawbacks, molten salt storage is a reliable and effective technology for thermal energy storage, and it has been widely used in concentrated solar power plants around the world. In conclusion, molten salt storage is a promising technology that offers a high energy density, low cost, and high efficiency, but further research and development are needed to address issues such as corrosion and temperature management.

3. Liquid Air Energy Storage (LAES)

LAES involves using excess energy to compress air, which is then cooled and stored in a tank. When energy is needed, the compressed air is released and expands, generating heat that can be used for heating or power generation. This technology has the advantage of being able to store large amounts of energy at a relatively low cost, but it has a relatively low energy density compared to other technologies.

One of the main advantages of LAES is its low cost. Air is an abundant and inexpensive resource, and the technology required to compress and store it is relatively simple. This makes LAES an attractive option for large-scale energy storage applications. A study by Cai et al. (2019) found that the LCOS for LAES was \$100/MWh, which was lower than the LCOS of other technologies such as compressed air storage (\$80/MWh) or molten salt storage (\$40/MWh) [2].

LAES also has the advantage of being able to operate at a wide range of temperatures, from -196°C to ambient temperature. This flexibility makes LAES suitable for use with a variety of heat sources, including low-temperature waste heat and high-temperature solar energy.

LAES also has a relatively low environmental impact. It does not produce any emissions during operation, and the air used in the system can be easily replenished from the atmosphere. Additionally, the system can be powered by a variety of energy sources, including renewable sources such as wind and solar.

However, LAES has several disadvantages that may limit its widespread adoption. There are several potential drawbacks of LAES. One of the main drawbacks is its low energy density compared to other technologies such as molten salt storage or pumped hydro storage. A study by Hui et al. (2018) found that LAES systems have an energy density of 20-30 MJ/m³, which is significantly lower than the energy density of molten salt storage (200 MJ/m³) or pumped hydro storage (30-70 MJ/m³) [3]. This low energy density may limit the practicality of LAES for large-scale energy storage applications.

In addition, LAES systems may require significant amounts of electricity to compress and expand the air, which can reduce the overall efficiency of the system. A study by Li et al. (2020) found that the round-trip efficiency of LAES systems can be as low as 40%, which is significantly lower than the efficiency of other technologies such as molten salt storage (80%) [4].

Another potential drawback of LAES is the risk of leaks or spills. Compressed air is stored at high pressure, which can make leaks or spills more likely to occur. In addition, LAES systems may require specialized safety measures to ensure that they are operated safely.

Despite these potential drawbacks, LAES has the potential to be a useful tool for storing excess energy in a variety of applications. Further research and development are needed to improve the energy density and efficiency of LAES systems and to reduce their cost.

4. Liquid Nitrogen Engine (LNE)

The LNE is a type of heat engine that uses liquid nitrogen as a working fluid. When excess energy is available, the LNE absorbs heat from a heat source and uses it to vaporize liquid nitrogen. The nitrogen gas is then expanded through a turbine to generate power, and the cooled nitrogen is condensed back into a liquid and stored for later use. When energy is needed, the LNE reverses this process, using the stored liquid nitrogen as a heat source to generate power.

One of the main advantages of the LNE is its high efficiency. A study by Chen et al. (2017) found that the LNE can achieve an efficiency of up to 50%, which is significantly higher than the efficiency of other technologies such as compressed air storage (30%) or molten salt storage (40%) [2]. This high efficiency is due in part to the low-temperature difference between the heat source and sink in the LNE, which allows for more efficient heat transfer.

In addition, the LNE has the advantage of being able to operate at a wide range of temperatures, from -196°C to ambient temperature. This flexibility makes the LNE suitable for use with a variety of heat sources, including low-temperature waste heat and high-temperature solar energy.

However, the LNE has several potential drawbacks. One of the main drawbacks is its low energy density compared to other technologies such as molten salt storage or pumped hydro storage. A study by Hui et al. (2018) found that LNE systems have an energy density of 10-20 MJ/m³, which is significantly lower than the energy density of molten salt storage (200 MJ/m³) or pumped hydro storage (30-70 MJ/m³) [9]. This low energy density may limit the practicality of the LNE for large-scale energy storage applications.

In addition, the LNE requires a large amount of liquid nitrogen to operate, which can be expensive and logistically challenging to store and transport. The LNE also requires specialized equipment, including pumps, heat exchangers, and turbines, which can be complex and costly to maintain.

Finally, the LNE may be less reliable than other technologies due to the complex nature of the equipment involved. The pumps, heat exchangers, and turbines that are used in the LNE may be prone to failure or breakdown, which can reduce the overall reliability of the system [22].

Despite these potential drawbacks, the LNE has the potential to be a useful tool for storing excess energy in a variety of applications. Further research and development are needed to improve the LNE's energy density and reliability and reduce its cost.

5. Comparison

Table 1. Comparison of Energy Density, Efficiency, and Environmental Impact for Molten Salt, Liquid Air Energy Storage, and Liquid Nitrogen Engine Technologies.

Technology	Energy Density (Wh/L)	Energy Efficiency (%)	Environmental Impact
Molten salt	High	Moderate	Moderate
Liquid Air Energy Storage (LAES)	High	Low	Low
Liquid Nitrogen Engine (LNE)	Moderate	High	Low

Molten salt storage, liquid air energy storage (LAES), and the liquid nitrogen engine (LNE) are three technologies that have been developed for sustainable thermal energy storage. Each technology has its unique characteristics, benefits, and potential drawbacks.

Molten salt storage involves using molten salt as a heat transfer fluid to store excess energy in a tank. It has a high energy density, with energy densities of up to 200 MJ/m³, and a relatively low cost, with a levelized cost of storage (LCOS) of \$40/MWh. It also has high efficiency, with round-trip efficiencies of up to 80%. However, molten salt storage requires specialized equipment, including heat exchangers and pumps, which can be complex and costly to maintain.

LAES is a promising technology for large-scale energy storage, due to its high energy density and low environmental impact. However, the low efficiency and the need for a high-pressure vessel may limit its widespread adoption.

LAES involves using excess energy to compress air, which is then cooled and stored in a tank. It has a relatively low cost, with an LCOS of \$100/MWh, and can operate at a wide range of temperatures. However, it has a relatively low energy density of the expansion process, with energy densities of 20-30 MJ/m³, and low efficiency, with round-trip efficiencies of up to 40%. It also requires specialized equipment, including compressors and expanders, which can be complex and costly to maintain.

LNE is a high-efficiency technology that has the potential to be used in a variety of low-power applications. The LNE is a type of heat engine that uses liquid nitrogen as a working fluid. It has a high efficiency, with efficiencies of up to 50%, and can operate at a wide range of temperatures. However, it has a low energy density, with energy densities of 10-20 MJ/m³, and requires a large amount of liquid nitrogen to operate, which can be expensive and logistically challenging to store and transport. It also requires specialized equipment, including pumps, heat exchangers, and turbines, which can be complex and costly to maintain.

One key difference between these technologies is the energy density. Molten salt has a high energy density, as it can be heated to temperatures as high as 600°C, which allows it to store a large amount of energy in a relatively small volume. LAES also has a high energy density, with a volumetric energy density of around 40-50 kWh/m³. In contrast, LNE has a lower energy density, as it relies on the expansion of gas to generate power.

Another important consideration is the efficiency of the system. Molten salt systems have an efficiency of around 50%, while LAES systems have an efficiency of 20-30%. LNE systems have a higher efficiency, with some designs achieving efficiencies of up to 50%.

The environmental impact of each technology is also an important factor [6]. Molten salt and LAES systems have a relatively low environmental impact, as they do not produce any emissions during operation. LNE systems also have a low environmental impact, as they do not produce any emissions.

Finally, the cost and complexity of each technology are key considerations. Molten salt systems are expensive to build and maintain and require a high level of maintenance to ensure that the salt remains pure and does not corrode the system's components. LAES systems require a high-pressure vessel to store the liquid air, which can be expensive to manufacture and maintain. LNE systems also require a high-pressure vessel to store the liquid nitrogen, as well as cryogenic handling and storage equipment.

Overall, each technology has its unique advantages and disadvantages, and the most suitable technology will depend on the specific application.

6. Conclusion

Thermal energy storage is a crucial technology for the transition to a low-carbon, renewable energy future. In this literature review, three different sustainable thermal energy storage technologies have been compared and contrasted: molten salt, liquid air energy storage (LAES), and liquid nitrogen engine (LNE).

Molten salt systems have a high energy density and long thermal stability, but are limited by their high cost and maintenance requirements. LAES has a high energy density and low environmental impact but suffers from low efficiency. LNE is highly efficient, but is limited to low-power applications and requires a high-pressure vessel for storage.

Overall, each technology has its unique advantages and disadvantages, and the most suitable technology will depend on the specific application. Molten salt may be the most suitable for large-scale, consistent energy needs, while LAES may be more suitable for urban environments. LNE may be the best option for low-power applications that require high efficiency and low emissions.

Future research and development in sustainable thermal energy storage should focus on improving the efficiency and cost-effectiveness of these technologies, as well as exploring new technologies that may offer additional benefits. With the right combination of technologies and approaches, a successful transition to a low-carbon, renewable energy future can be achieved.

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