*batteries*

*Review*

# Comparative Review of Thermal Management Systems for BESS

**Nixon Kerwa Mdachi and Chang Choong-koo ***

KEPCO International Nuclear Graduate School (KINGS) Ulju-gun, Ulsan 45014, Republic of Korea; kerwa2@gmail.com
* Correspondence: ckchang@kings.ac.ke

**Abstract:** The integration of renewable energy sources necessitates effective thermal management of Battery Energy Storage Systems (BESS) to maintain grid stability. This study aims to address this need by examining various thermal management approaches for BESS, specifically within the context of Virtual Power Plants (VPP). It evaluates the effectiveness, safety features, reliability, cost-efficiency, and appropriateness of these systems for VPP applications. Among the various hybrid cooling options, two notably promising combinations are highlighted. First, the integration of heat pipes with phase change materials, which effectively conduct heat away from sources with minimal temperature differences, enabling swift heat transfer. Second, the combination of heat pipes with liquid passive cooling, which utilizes the efficient heat transfer properties of heat pipes and the steady cooling offered by liquid systems. This study offers recommendations for choosing the best thermal management system based on climate conditions and geographic location, thereby enhancing BESS performance and sustainability within VPPs.

**Keywords:** active liquid cooling; battery energy storage systems; hybrid systems; passive cooling; thermal management systems; virtual power plants

## 1. Introduction

The integration of renewable energy sources and decentralized power generation necessitates innovative methods for managing energy. VPPs represent a novel approach, combining multiple energy sources into a single, adaptable power generation and distribution system using advanced technologies. As the shift towards renewable energy continues, VPPs play a crucial role in enhancing grid stability, dependability, and efficiency.

Efficient thermal management systems (TMSs) are essential for controlling the temperature of energy storage systems, particularly BESS, within VPPs. These systems ensure the optimal performance and long-term health of BESS by effectively managing heat dissipation and mitigating temperature fluctuations. Despite advancements in TMS technologies, critical knowledge gaps remain, hindering the smooth integration and operation of VPPs.

One significant knowledge gap pertains to the optimization of phase change materials (PCMs) and natural convection, which are cost-effective passive cooling techniques. While these methods are affordable and straightforward, their effectiveness in high-energy consumption scenarios is not well understood, necessitating further research to enhance their reliability and performance. Additionally, challenges associated with the complexity and potential hazards [1] of heat pipes and liquid cooling TMS must be addressed. Despite their excellent thermal performance, issues such as leaks and short lifespans pose significant obstacles that require innovative solutions.

Active cooling techniques like liquid active cooling and air-forced convection also present challenges due to their high energy consumption. Balancing energy efficiency with accurate temperature control is a complex task, underscoring the need for research aimed at maximizing energy use without compromising thermal regulation capabilities. Furthermore, designing robust cooling technologies capable of withstanding harsh operating conditions and temperature fluctuations is a top priority. The resilience of TMS in

check for updates

**Citation:** Mdachi, N.K.; Choong-koo, C. Comparative Review of Thermal Management Systems for BESS. *Batteries* **2024**, *10*, 224. https://doi.org/10.3390/batteries10070224

Academic Editor: Carlos Ziebert

Received: 6 May 2024
Revised: 14 June 2024
Accepted: 18 June 2024
Published: 24 June 2024

VPP [2] is crucial for minimizing downtime and ensuring uninterrupted power supply, necessitating further research to enhance system durability and dependability.

In light of these knowledge gaps, this study aims to explore and assess different TMS technologies for BESS in VPP. By addressing significant obstacles and advancing innovations in thermal management within contemporary energy systems, the research contributes to filling critical gaps in TMS for VPPs. This introduction underscores the importance of addressing these knowledge gaps and sets the stage for the research goals and methodologies outlined in subsequent sections.

The study begins with an extensive literature review in Section 2, discussing current advancements and challenges. Section 3 employs a multi-criteria decision-making (MCDM) approach using the analytical hierarchy process (AHP-OS), combined with a detailed comparative analysis in Section 4, to assess various TMS options alongside their metrics. Section 5 summarizes these findings, recommending the most suitable TMS for optimizing BESS performance in VPP. In addition, it suggests future research directions to further the field of renewable energy integration and grid stability.

## 2. Literature Review

### 2.1. Heat Generation

Heat generation within a battery is a critical factor that can affect its performance and safety. It arises from various sources, including internal resistance, which converts electrical energy into heat as current flows through the battery's components. Electrochemical reactions, which are the fundamental processes of charging and discharging, also contribute to heat production. Additionally, external electrical loads can impose further thermal stress on the battery. The total heat generation (Qgen) [3] in a battery is the sum of these effects, which can be expressed as shown by Equation (1):

$$Q_{gen} = I^2 R_{int} + Q_{reac} \tag{1}$$

where:

$I$ is the current flowing through the battery (A).
$R_{int}$ is the internal resistance of the battery (Ω).
$Q_{reac}$ is the heat generated from electrochemical reactions (W).

### 2.2. Heat Transfer Process

Heat transfer in batteries is governed by conduction, convection, and radiation. These mechanisms can be mathematically described by the heat Equation (2), which models the overall thermal behavior and ensures efficient battery operation [3].

$$\frac{\partial T}{\partial t} = \propto \nabla^2 + \frac{Q_{gen}}{\rho_{C_p}} \tag{2}$$

where:

$T$ is the temperature (K).
$t$ is the time (s).
$\alpha$ is the thermal diffusivity of the material ($\alpha = \frac{\hbar}{\rho_{C_p}}$) ($m^2/s$).
$\hbar$ is the thermal conductivity (W/m·K).
$\rho$ is the density ($kg/m^3$).
$C_p$ is the specific heat capacity (J/kg·K).
$\nabla^2$ is the Laplace operator, representing the spatial derivatives.

i. Conduction refers to the transfer of heat within the materials of a battery. This process can be quantified using Fourier's law, which describes the rate of conductive heat transfer as directly proportional to the temperature gradient and the material's thermal conductivity, as shown by Equation (3) [4]:

$$q_{cond} = -\hbar \nabla T \quad (3)$$

where:

$q_{cond}$ is the heat flux due to conduction (W/m$^2$).

ii. Convection is the transfer of heat between the battery surface and the surrounding fluid (air or liquid). The convective heat transfer rate is given by Newton's law of cooling in Equation (4) [4,5]:

$$q_{conv} = hA\left(T_{surface} - T_{fluid}\right) \quad (4)$$

where:

$h$ is the convective heat transfer coefficient (W/m$^2$·K).
$A$ is the surface area through which heat is being transferred (m$^2$).
$T_{\text{surface}}$ is the temperature of the battery surface (K).
$T_{fluid}$ is the temperature of the surrounding fluid (K).

iii. Radiation involves the transfer of heat through electromagnetic waves. The rate of radiative heat transfer is governed by the Stefan-Boltzmann law, which states that the power radiated per unit area of a surface is proportional to the fourth power of its absolute temperature, as shown in Equation (5) [5]:

$$q_{rad} = \epsilon\sigma A\left({T^4}_{surface} - {T^4}_{ambient}\right) \quad (5)$$

where:

$\epsilon$ is the emissivity of the battery surface (dimensionless).
$\sigma$ is the Stefan-Boltzmann constant (5.67 × $10^{-8}$ W/m$^2$·K$^4$).
$T_{ambient}$ is the ambient temperature (K).

### *2.3. Cooling for a Static BESS in VPPs*

Batteries used in BESS generate heat during charging and discharging cycles, making a cooling system essential [6]. If the heat is not effectively dispersed, it can adversely affect the batteries' lifespan, safety, and performance. One of the most critical risks is thermal runaway, a hazardous situation where the battery temperature rises uncontrollably, potentially leading to fires or explosions. A cooling system can prevent thermal runaway by maintaining the batteries' optimal temperature range. Additionally, cooling systems enhance battery capacity and efficiency by reducing internal resistance and boosting electrochemical reactions. Various types of lithium-ion battery cooling systems exist, including liquid, air, and PCM systems, each with unique benefits and drawbacks regarding cost, complexity, reliability, and efficiency.

This study focuses on BESS operating within VPPs. Unlike traditional centralized power plants, VPPs consist of geographically dispersed networks of medium-sized power generators, such as solar farms, wind turbines, and co-generation units, along with flexible consumers and BESS, all managed from a central control station [7]. The BESS units can be stationed anywhere within the network. VPPs are primarily used for demand control [8], efficiently distributing generated power during peak load periods to alleviate strain on the grid. Furthermore, the combined generated and consumed power is traded on the energy exchange, offering frequency and voltage regulation to help stabilize the grid.

### *2.4. Classifications and Characteristics of TMS*

Natural convection, a passive cooling technique, operates without mechanical components, leveraging the fundamental principle of heat rising and cold air descending. Its inherent simplicity reduces the risk of component failure or leakage, ensuring safety. Recent TMS advancements emphasize combining composite cooling solutions and air, liquid, and phase change materials to optimize heat dissipation [5]. This approach aligns with the industry's pursuit of performance, cost-effectiveness, and environmental sustainability.

Air-forced convection, an active cooling technique, employs blowers or fans to enhance heat dispersion. This method, while effective, introduces mechanical components like fans that require careful maintenance to prevent hazards. Recent advancements suggest incorporating microchannel heat sinks (MCHS) for improved performance [5]. MCHS are compact heat exchangers with a high heat transfer area-to-volume ratio, offering enhanced thermal management for electronic devices.

Liquid passive cooling falls under the category of passive cooling, where heat is transferred and dispersed using a liquid, typically water or a specialized coolant, instead of relying on active cooling systems or mechanical pumps [9]. The cooling process employs passive techniques, such as natural convection, to circulate the liquid and remove heat from a source. Relying on passive fluid movement reduces the likelihood of component failures, making it generally safe. Proper fluid maintenance is essential to ensure safety and prevent leaks. Liquid passive cooling is characterized by low energy usage and environmental friendliness. The choice of cooling fluid can influence the system's overall environmental impact.

Liquid active cooling utilizes both primary and secondary loops as active cooling circuits. The primary loop operates similarly to a passive liquid system but circulates heat using a pump. Instead of a cooler, a high-performance heat exchanger acts as a bridge between the primary and secondary loops, enabling the air conditioning system to function as the secondary loop and provide cooling through evaporation [10]. Pump malfunctions and fluid leaks are potential risks, highlighting the importance of regular maintenance. Its significant power consumption worsens its environmental impact. However, new research indicates that incorporating advanced battery thermal management systems, such as a double S-channel [11] cold plate design, enhances the cooling performance of prismatic LiFePO4 batteries compared to a single S-channel design. This design reduces temperature differences within the battery and minimizes pressure drop and pumping power by 73.88%, thereby increasing battery efficiency and safety in demanding environments.

Heat pipes are passive cooling devices that transfer heat between two solid interfaces using a phase transition. They operate without external energy, making them environmentally friendly, inherently safe, and highly reliable due to their sealed systems, which reduce the likelihood of fluid leakage. This enables heat pipes to maintain stable temperatures efficiently while minimizing energy consumption. Consequently, they enhance safety and reduce environmental impacts. Pulsating heat pipes (PHPs) [12], a specific type of heat pipe, have gained attention for their simple structure and improved thermal performance. They do not require a porous wick and function effectively under a two-phase flow regime, where oscillating gas bubbles and liquid plugs facilitate efficient heat transfer.

PCMs are integral to passive thermal management, utilizing materials that absorb or release heat during phase transitions, such as melting and solidifying. These materials are lauded for their low energy consumption and passive operation, which eliminates the need for mechanical parts, enhancing safety and environmental sustainability. However, their efficacy can diminish at extreme temperatures, potentially impacting performance and safety. Recent advancements have focused on enhancing PCM performance through nano-enhancements and composite formulations, which improve thermal conductivity and stability, ensuring consistent operation across a broader temperature range [13]. These innovations aim to maintain the benefits of PCMs while addressing their limitations in high-temperature scenarios.

Thermoelectric cooling, utilizing the Peltier effect, has seen significant advancements, making it an ideal solution for precise temperature control in electronic components. Recent innovations also include the integration of nanotechnology to enhance material efficiency and the development of new composite materials that improve thermal conductivity and durability [14]. These improvements address previous limitations, such as scalability and heat dissipation, ensuring that thermoelectric coolers can maintain performance under varying conditions. Additionally, the incorporation of advanced heat sinks and careful material handling further mitigates overheating risks, solidifying thermoelectric cooling as a reliable and efficient technology for modern applications.

Hybrid cooling systems, which combine passive and active techniques, are at the forefront of thermal management innovation. They offer tailored solutions for heat dissipation, balancing safety and environmental considerations. The integration of advanced materials like nano-enhanced PCM and liquid cooling technologies has significantly improved their efficiency and scalability [15]. These systems are designed to adapt to various operational conditions, ensuring optimal performance while minimizing environmental impact. The strategic selection of cooling components and the configuration's adaptability are key to achieving a sustainable thermal management solution.

### *2.5. TMS Metrics and Their Assessment*

Combined, these metrics provide a comprehensive view of a BESS's performance and its ability to meet its objectives. By considering these metrics, stakeholders can make informed decisions about the installation, use, and investment in BESS. An important metric is heat dissipation, which measures the effectiveness of the cooling system in removing excess heat from battery cells [16]. Another metric, cost-effectiveness, evaluates the expenses associated with implementing a specific TMS approach. This includes the cost of materials, technology used, maintenance and servicing of additional devices and equipment, electricity costs, and considerations for safety, security, and environmental interventions [17,18].

Moreover, the response to dynamic loads, a metric that evaluates how swiftly and accurately a BESS can adapt its power generation in reaction to changes in grid supply or demand [19], should be considered. The last aspect to consider is safety and environmental concerns, encompassing various precautions to mitigate risks such as fires, explosions, and exposure to hazardous liquids and gases arising from battery operation [20]. This also encompasses measures aimed at safeguarding the environment against potential pollution and waste products that could result from subsequent releases or accidents. Safety and the environment are intertwined aspects due to their interdependence, regulatory requirements, long-term impacts, resource conservation, public perception, and ethical responsibilities.

### *2.6. Case Studies and Practical Applications*

i. Liquid active cooling, as shown in Figure 1, is widely utilized in BESS to control the temperature of lithium-ion batteries [21]. Notable examples include the Hornsdale Power Reserve in Australia [22], the Mira Loma BESS in California [23], the Noor Power Station in Morocco [24], the Hokkaido Tomatoh-Atsuma BESS in Japan [25], and the Big Battery Eland project in South Africa [26]. These installations serve as key components of their respective energy grids, providing stability, managing renewable energy fluctuations, and ensuring continuous power supply during peak demand hours and emergencies.
ii. Natural convection finds useful application in smaller-scale home energy storage systems, as shown in Figure 2, prioritizing ease of use and energy efficiency [27]. Examples include the Tesla Powerwall [28], LG Chem RESU [29], Sonnen Eco [30], and Enphase Encharge [31]. These systems utilize lithium-ion or lithium-iron-phosphate battery technology to store excess energy from solar panels or the grid, offering homeowners greater energy independence, flexibility, and the ability to optimize energy usage. Additionally, they provide backup power capabilities during grid outages, contributing to enhanced reliability and resilience for residential energy needs.

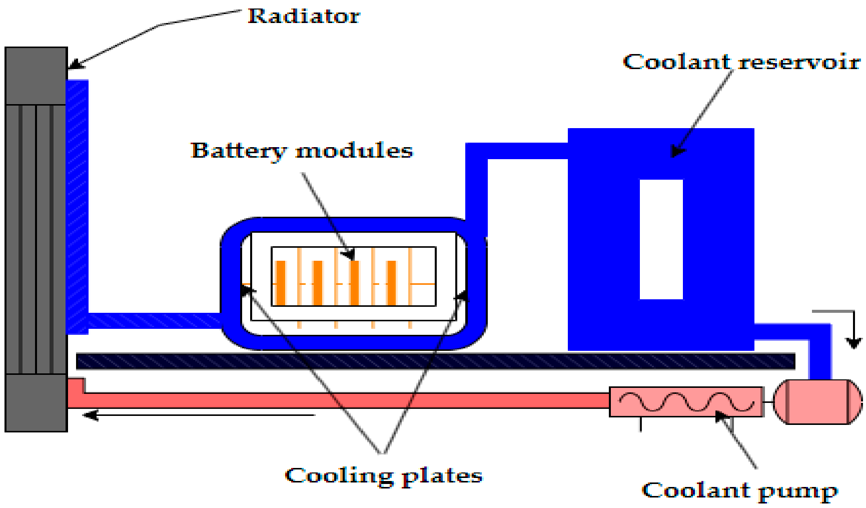



**Figure 1.** Schematic of liquid-active cooling.

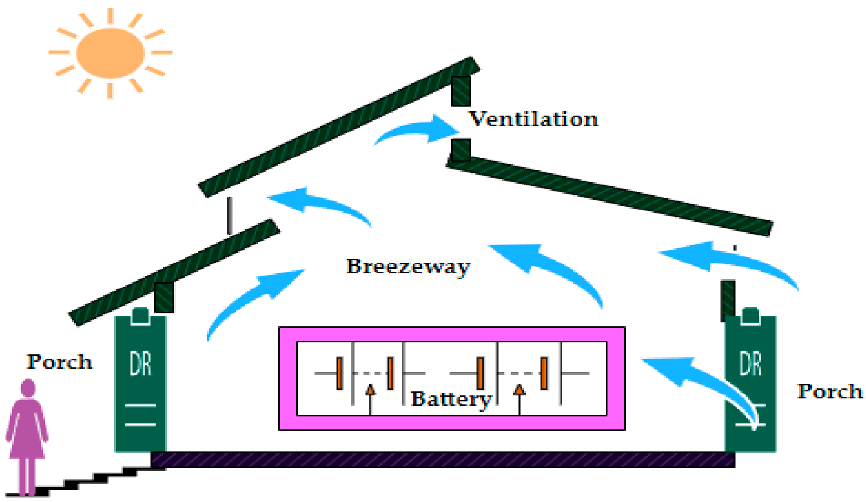



**Figure 2.** Schematic of natural convection cooling.

iii. Heat pipes are extensively utilized in electric vehicles (EVs) [32], with examples such as the Tesla Model S/X/3/Y, Nissan Leaf, Chevrolet Bolt EV, BMW i3, BYD e6, Audi e-tron, and Hyundai Kona Electric. These vehicles incorporate various types of lithium-ion batteries supplied by manufacturers such as Tesla, LG Chem, Samsung SDI, BYD Auto, and SK Innovation [33]. Figure 3 displays a summarized arrangement of the heat pipe cooling TMS.
iv. Hybrid cooling with both liquid and air as cooling media, as shown in Figure 4, represents a unique method for TMS in BESS [34]. These systems are particularly valuable in grid-scale BESS operations, especially those integrated with renewable energy sources, as they effectively manage variable climatic conditions and load fluctuations.

For instance, the CryoBattery in the United Kingdom, located in Manchester [35], supports the local electricity network by storing excess renewable energy from wind and solar sources, ensuring grid stability during extreme weather events. Similarly, the Wattway Solar Panel BSS in France [36] combines solar PV panels with battery energy storage to efficiently harness solar energy, providing backup power and offsetting grid demand as needed. Additionally, Hecate Energy's grid-scale battery storage projects in the United States integrate with renewable sources such as solar and wind, mitigating intermittency and stabilizing the grid under varying climatic conditions and load circumstances. These examples highlight the versatility and effectiveness of hybrid cooling systems in enhancing the performance and resilience of grid-scale BESS integrated with renewable energy generation.

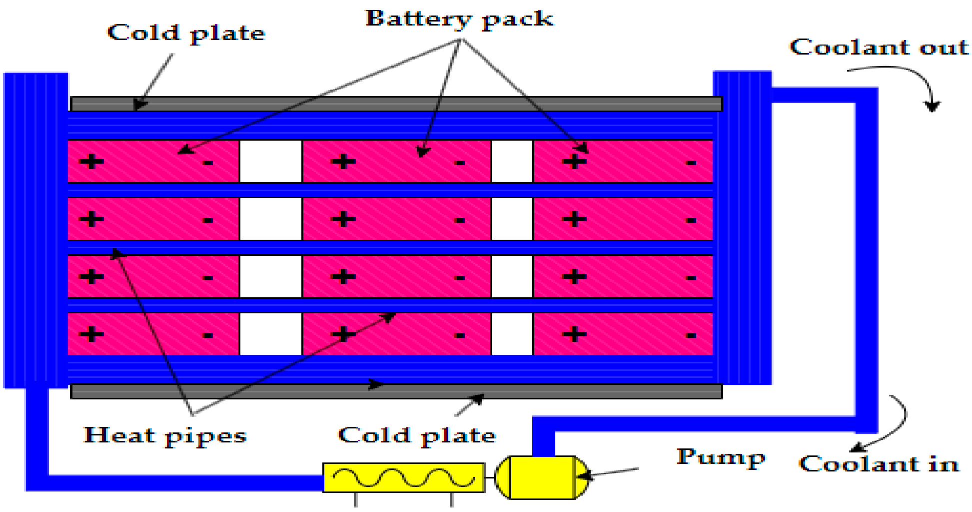



**Figure 3.** Schematic of heat pipe cooling.

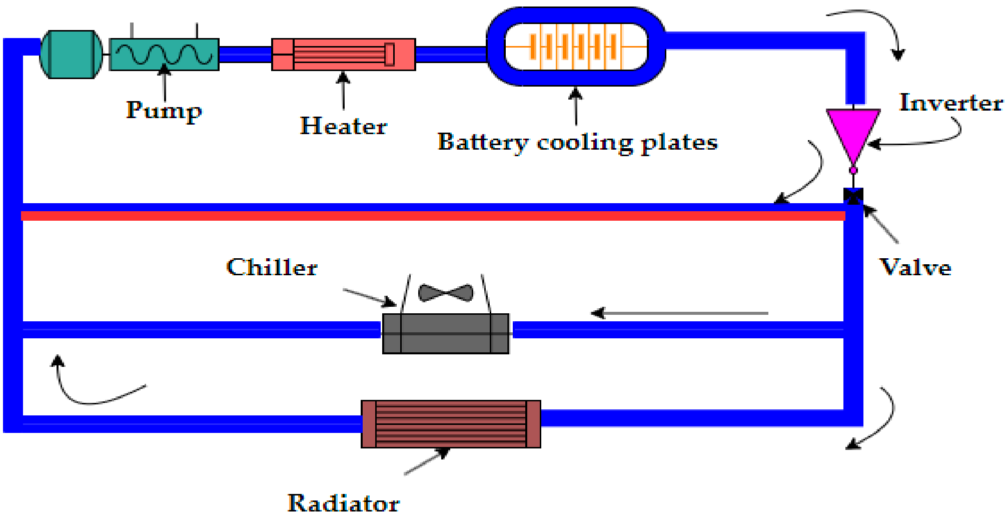



**Figure 4.** Schematic of liquid/air hybrid cooling.

v. Practical applications of PCM-based TMS in lithium-ion batteries include electric vehicles (EVs), grid-scale energy storage systems, and portable electronic devices [37]. By effectively managing battery temperature, PCM-based TMS contributes to improved battery performance, efficiency, and safety, ultimately enhancing the overall reliability and longevity of lithium-ion battery systems. Figure 5 provides a schematic arrangement of PCM TMS. One of the key advantages of PCM-based TMS is its passive nature, requiring no active components such as fans or pumps. This leads to simplified system design, reduced complexity, and lower energy consumption compared to traditional active cooling methods. Additionally, PCMs offer high thermal stability, reliability, and compatibility with lithium-ion batteries.

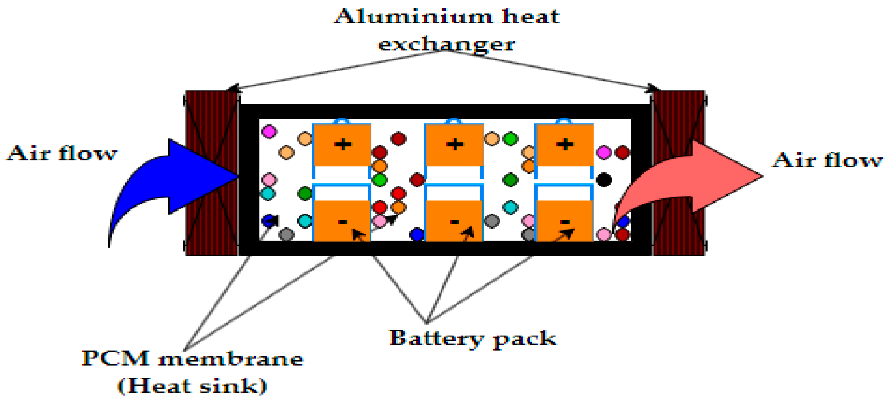



**Figure 5.** Schematic of PCM cooling.

vi. Liquid-passive TMS are extensively utilized in Vanadium Redox Flow Batteries (VRFB) to enhance their efficiency and reliability [38]. Ions of Vanadium in different oxidation states serve as the active materials, and they are contained within external electrolyte chambers. Moreover, it offers temperature regulation without the addition of labor-intensive or energy-intensive cooling equipment. As a result, heat is automatically released from this system by making use of the characteristics that the flowing vanadium electrolyte has to offer. Liquid passive TMS is particularly well-suited for VRFBs due to their large-scale and stationary nature. The simplicity and effectiveness shown in Figure 6 contribute to the overall efficiency and dependability of VRFB systems, enabling them to operate reliably under various operating conditions.

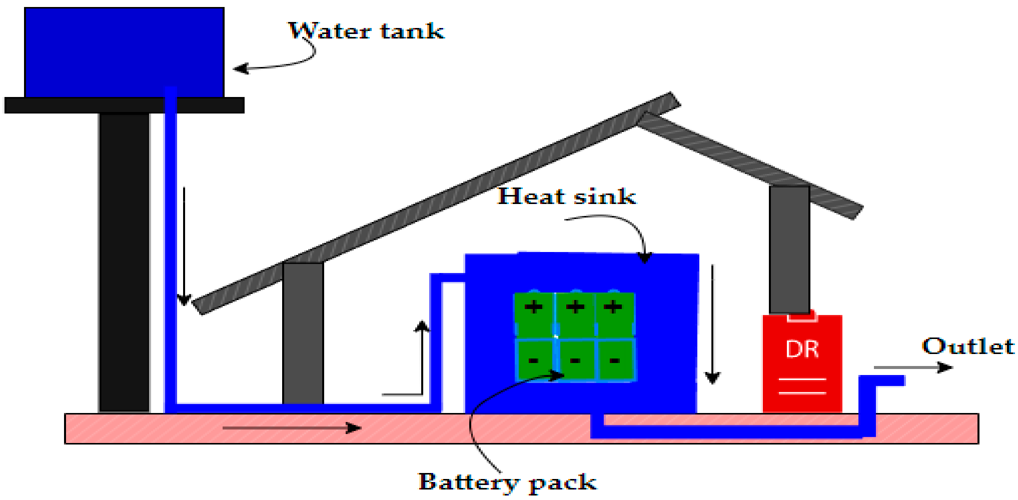



**Figure 6.** Schematic of liquid passive cooling.

vii. Air-forced TMS, as illustrated in Figure 7, is crucial for prolonging the lifespan and enhancing the performance of lead-acid batteries. These batteries are extensively utilized for energy storage in various applications, such as backup power, telecommunications, and automotive. Air-forced TMS is an active way to keep lead-acid batteries at the right temperature during their charging and discharging cycles [39], whether flooded or valve-regulated (VRLA).

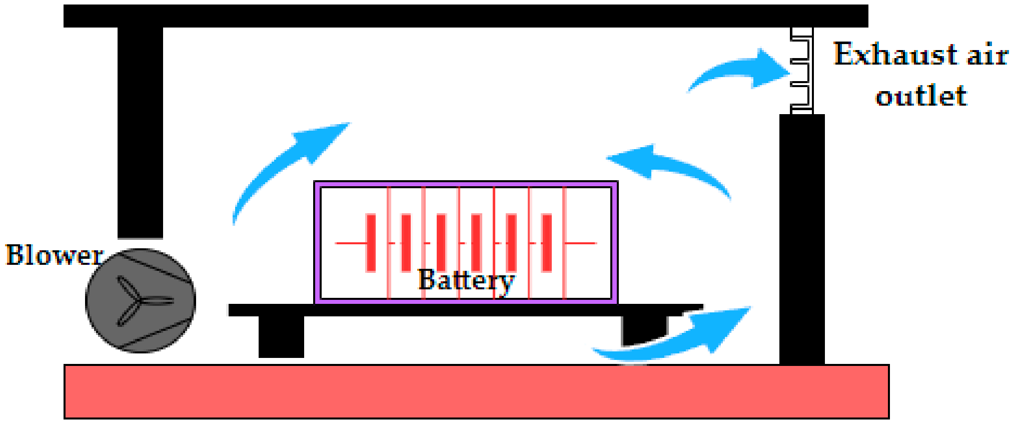



**Figure 7.** Schematic of air-forced cooling.

One of the primary benefits of air-forced TMS in lead-acid batteries is its ability to maintain a steady temperature profile, even under varying load conditions. By continuously circulating air, these systems prevent overheating during charging cycles and maintain optimal operating temperatures, thus preserving battery performance and extending their lifespan.

## 3. Methodology

This study employed the AHP-OS method to evaluate the metrics that constitute the TMS criteria parameters and systems, based on their determined importance and weights from comparative analyses in existing literature and data. The AHP-OS is a statistical tool designed for multi-criteria decision-making [40]. It also accommodates minor judgmental errors and produces ratio scales based on comparisons of paired criteria. It can process both subjective assessments and exact measurements as inputs, leading to the calculation of a consistency ratio and priority weights [41]. Although the parameters chosen were not quantitatively exact, they were essential in identifying the most suitable TMS for BESS in VPPs.

### *3.1. TMS Metrics Comparison*

The study identified the four key TMS metrics: heat dissipation efficiency, cost-effectiveness, response to dynamic loads, and safety and environment. These metrics were given weights reflecting their significance. Utilizing the Saaty scale [42], a method within AHP, two factors were juxtaposed, with their corresponding values ranging from 1 to 9. This scale is used to gauge the comparative importance of one option over another, as illustrated in Table 1.

**Table 1.** Modified comparative scale for TMS metrics.

| Preference Level | Preference Score | Description |
|---|---|---|
| Extremely preferred | 9 | One factor is overwhelmingly more important than the other. |
| Very strong to extremely | 8 | The preference is very strong, almost reaching an extreme level. |
| Very strongly preferred | 7 | One factor is strongly preferred over the other. |
| Strongly to very strongly preferred | 6 | The preference is strong but not overwhelming. |
| Strongly preferred | 5 | There is a clear preference for one factor over the other. |
| Moderately to strongly | 4 | The preference is moderate, leaning towards strong. |
| Moderately preferred | 3 | There is a moderate preference for one factor. |
| Equally moderately preferred | 2 | The factors are slightly more than equally preferred. |
| Equally preferred | 1 | Both factors are of equal importance. |

To maintain a clear differentiation between measurement points, odd numbers are consistently used. Even numbers are reserved for instances where there is a necessity for consensus among evaluators. The weights assigned to the TMS metrics are displayed in Table 2.

**Table 2.** TMS metrics weights.

| TMS | Weight | AHP Scale | References |
|---|---|---|---|
| Heat dissipation efficiency | It is critical for maintaining battery efficiency and longevity by preventing overheating. Given its direct impact on performance and safety, it is highly important. | 9 | [16] |
| Cost-effectiveness | Important for the overall feasibility and economic viability of the BESS project. This includes both upfront and operational costs. | 3 | [17,18] |
| Response to dynamic loads | Paramount for systems that experience significant fluctuations in demand or operational conditions, impacting the ability to maintain optimal performance. | 7 | [17,19] |
| Safety and environment | Essential, considering the potential risks associated with battery operation and the increasing emphasis on sustainable energy solutions. | 5 | [20] |

Initially, the criteria were established as depicted in Figure 8. They were then assessed in pairs to ascertain their relative significance and the corresponding weight in relation to the objective. The process began by establishing the relative importance of the TMS metrics, which led to the creation of a priority vector (Eigenvector) matrix, as presented in Table 3.

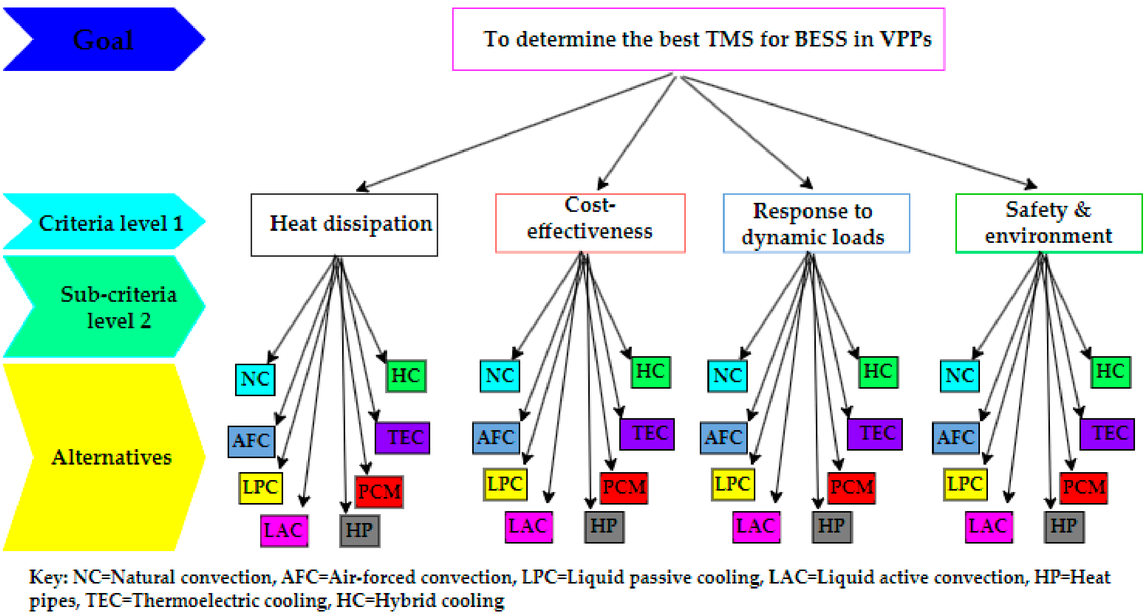



**Figure 8.** AHP criteria flow diagram.

**Table 3.** Priority (Eigenvector) matrix.

| | HD | CE | RDL | SE |
|---|---|---|---|---|
| **HD** | 1 | 3 | 1 | 2 |
| **CE** | 3/9 | 1 | 1/2 | 1/2 |
| **RDL** | 1 | 2 | 1 | 1 |
| **SE** | 1/2 | 2 | 1 | 1 |

**Key: HD** = Heat dissipation, **CE** = Cost-effectiveness, **RDL** = Response to dynamic loads, and **SE** = Safety and environment.

Then normalization was performed to give relative weight to each criterion [43] by dividing each value by the total column value, as shown in Table 4.

**Table 4.** Normalized priority matrix.

| | HD | CE | RDL | SE |
|---|---|---|---|---|
| **HD** | 1/2.833 = 0.353 | 3/8 = 0.375 | 1/3.5 = 0.286 | 2/4.5 = 0.444 |
| **CE** | 0.333/2.833 = 0.118 | 1/8 = 0.125 | 0.5/3.5 = 0.143 | 0.5/4.5 = 0.111 |
| **RDL** | 1/2.833 = 0.353 | 2/8 = 0.250 | 1/3.5 = 0.286 | 1/4.5 = 0.222 |
| **SE** | 0.5/2.833 = 0.176 | 2/8 = 0.250 | 1/3.5 = 0.286 | 1/4.5 = 0.222 |

Subsequently, the impact of each criterion was quantified through computations based on the priority vector. This vector illustrated the relative weights of each criterion, which were derived by averaging all the criteria, as detailed in Table 5. Since the sum of the values in each column equals 1, this approximation was utilized to streamline the calculation process. The discrepancy between the precise and approximate values is intentionally kept below 10% [40].

**Table 5.** Priority contribution.

| | Eigenvector (Calculation) | Eigenvector |
|---|---|---|
| **HD** | (0.353 + 0.375 + 0.286 + 0.444)/4 = 0.3645 | 36.45% |
| **CE** | (0.118 + 0.125 + 0.143 + 0.111)/4 = 0.1243 | 12.43% |
| **RDL** | (0.353 + 0.250 + 0.286 + 0.222)/4 = 0.2778 | 27.78% |
| **SE** | (0.176 + 0.250 + 0.286 + 0.222)/4 = 0.2335 | 23.35% |

For comparison, Python (version 3.10.12) mathematical software with NumPy (version 1.25.2) and SciPy (version 1.11.4) was used to determine the exact Eigenvector values through the potential matrices. (Figure A1 shows the Python code used).

The approximate and exact Eigenvector values are nearly identical, as shown in Table 6. Consequently, the effort to calculate the exact vector can be omitted. The next step involved assessing inconsistencies to gather sufficient data to evaluate the consistency of the decisions and the choices made. The consistency index is employed for this purpose, and it is derived from the maximum Eigenvector value, which is obtained by multiplying each element in the Eigenvectors by the corresponding column of the original comparison matrix and summing the results [41] as shown in Table 7.

**Table 6.** Approximate vs. exact Eigenvectors.

| | Approx. Eigenvector | Exact Eigenvector | Difference |
|---|---|---|---|
| **HD** | 0.3645 | 0.3659 | 0.0014 (0.383%) |
| **CE** | 0.1243 | 0.1238 | 0.0005 (0.404%) |
| **RDL** | 0.2778 | 0.2778 | 0.0000 (0.000%) |
| **SE** | 0.2335 | 0.2326 | 0.00387 (0.387%) |

**Table 7.** Maximum Eigenvector (λmax).

| **Eigenvector** | 0.3659 | 0.1238 | 0.2778 | 0.2326 |
|---|---|---|---|---|
| **Total (Sum)** | 2.833 | 8.000 | 3.500 | 4.500 |
| **Max Eigenvalue (λmax)** | (0.3659 × 2.833) + (0.1238 × 8.000) + (0.2778 × 3.500) + (0.2326 × 4.500) = 4.046 | | | |

The calculation of the consistency index is given by Equation (6).

$$CI = \frac{\lambda max - n}{n - 1} \quad (6)$$

where:

CI is the consistency index, λmax is the maximum Eigenvalue, and n is the number of the evaluated criteria.

Now, CI = $\frac{4.091-4}{4-1}$ = 0.015

To verify whether the consistency index (CI) is adequate, the consistency rate (CR) was determined.

CR is the ratio between the consistency index and the random consistency index (RI), and the matrix would be consistent if the resulting ratio was less than 10%, as shown by Equation (7).

$$CR = \frac{CI}{RI} <\approx 10\% \quad (7)$$

where

CR represents the consistency ratio, CI stands for the consistency index, and RI denotes the random consistency index.

The RI value is fixed by the number of criteria, as shown in Table 8 of the AHP criteria table, which provides determined values.

**Table 8.** Criteria table.

| **N** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

Now, CR = $\frac{0.015}{0.9}$ = 0.017 which is 1.7%

Since the value is less than 10%, the matrix was considered consistent, and the priority criteria results for the first level are shown in Figure 9.

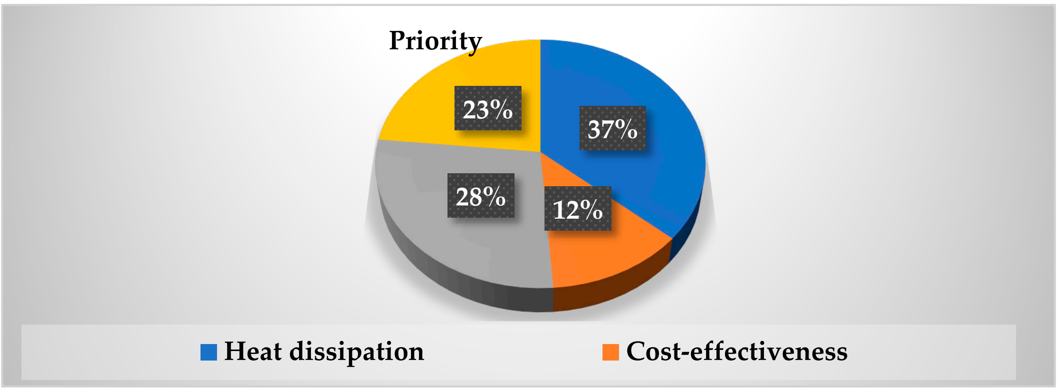



**Figure 9.** TMS metrics graph.

This formed the criteria for level 1 computations as shown in Figure 8, which the AHP-OS can do at a good CR. Therefore, from criteria level 2 to the end, data analyzed by the AHP software (Rev 192) will be presented. (Figure A2 shows the results as given by AHP-OS for TMS metrics).

*3.2. Comparison Data concerning TMS Metrics*

Using the prioritized TMS metrics, another hierarchy for criteria level 2 was established where various TMS options were evaluated based on their performance in each metric by comparing data from different previous studies to establish the Saaty scale. Pairwise comparisons were again conducted to establish the relative importance of different TMS options within each metric. The software was able to perform sensitivity analysis to assess the weight uncertainties, overlap, and robustness of the decision-making process [42]. This involved varying the weights assigned to each criterion and observing the impact on the overall rankings of TMS options. It helped identify the relative importance of different criteria and their influence on the final decisions.

i. Heat dissipation-plays a crucial role in assessing thermal management solutions for BESS in VPPs. The restricted heat dissipation capacity of natural convection, which depends on passive airflow, makes it less efficient for larger BESS fittings [44]. To enhance heat dissipation, air-forced convection can be employed, facilitated by fans or blowers [45]. Yet, air proves to be less effective compared to other mediums due to its lower specific heat and heat transfer coefficient [46]. Liquids, with their higher heat transfer coefficients compared to air, offer a more effective means of active cooling. This involves actively circulating cooling fluids to promote efficient heat dissipation [37]. Heat pipes are notable for their excellent thermal conductivity, enabling rapid heat transfer [37]. Meanwhile, PCM offers variable yet consistent temperature control and moderate heat dissipation [37]. On the other hand, thermoelectric modules utilize the Peltier effect to convert power into thermal differences, allowing thermoelectric cooling to be used independently or in conjunction with other cooling methods to manage heat [47]. Hybrid cooling systems optimize heat dissipation by combining active and passive strategies [47], thereby reducing the vulnerabilities inherent in cooling systems. The efficacy of hybrid cooling varies depending on specific configurations. Based on the information provided, weights were assigned to each TMS as shown in Table 9. Subsequently, the criteria were re-evaluated in pairs using the AHS-OS, resulting in 28 pairwise comparisons.

**Table 9.** TMS weights outcomes in heat dissipation.

| TMS | Weight | AHS Scale | References |
|---|---|---|---|
| **Natural convection** | Less effective in high-power applications due to its passive nature. | 2 | [48] |
| **Air-forced convection** | More effective than natural convection due to the forced air movement, but might still struggle with very high heat loads. | 4 | [48] |
| **Liquid-passive cooling** | More effective than air cooling due to the higher heat transfer coefficients of liquids over air. | 6 | [48,49] |
| **Liquid-active cooling** | By actively pumping coolant, this method can achieve even higher heat dissipation rates than passive systems. | 7 | [48–50] |
| **Heat pipes** | Effectively transfers heat away from the source with minimal temperature difference. | 7 | [48] |
| **PCM** | Absorb a large amount of heat with minimal temperature change. | 5 | [48] |
| **Thermoelectric cooling** | Generally, it is not the most efficient for large-scale heat dissipation due to its power consumption. | 3 | [48] |
| **Hybrid cooling** | Can be designed to maximize heat dissipation effectiveness, adapting to various operational scenarios. | 8 | [48] |

Table 10 presents the criterion-consolidated priorities and normalized pairwise comparison matrix for heat dissipation as produced from the run in the AHP-OS with twenty-eight (28) comparisons and a CR of 0.7%.

**Table 10.** Priority matrix for heat dissipation.

| | NC | AFC | LPC | LAC | HP | PCM | TEC | HC |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.50 | 0.33 | 0.25 | 0.25 | 0.33 | 0.50 | 0.25 |
| **AFC** | 2.00 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 |
| **LPC** | 3.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **LAC** | 4.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **HP** | 4.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **PCM** | 3.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **TEC** | 2.00 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 1.00 | 0.33 |
| **HC** | 4.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 | 3.00 | 1.00 |

**Key:** **NC** = Natural convection at 4.3% rank 8, **AFC** = Air-forced convection at 8.9% rank 6, **LPC** = Liquid passive cooling at 15.5% rank 4, **LAC** = Liquid active cooling at 16.1% rank 2, **HP** = Heat pipes at 16.1% rank 2. **PCM** = PCM cooling at 14.4% rank 5, **TEC** = Thermoelectric cooling at 7.7% rank 7, and **HC** = Hybrid cooling at 17.0% rank 1. (Figure A3 results obtained by AHP-OS are shown).

ii. Cost-effectiveness-stands out as a cost-effective solution for smaller BESS installations owing to its inherent design, minimal energy consumption, and low maintenance demands [51]. For medium- to large-scale BESS, air-forced convection is moderately cost-effective [52], although it necessitates additional equipment such as blowers or fans [51]. On the other hand, liquid passive cooling proves ideal for medium- to large-scale BESS setups, providing a blend of efficiency and cost-effectiveness. However, liquid active cooling, though effective for larger-scale BESS requiring substantial heat dissipation, entails a higher initial cost [50]. Following that, heat pipes emerge as a cheap choice for medium- to large-scale BESS installations, distinguished by their low passive operation, costs, and marginal maintenance requirements.

PCM demonstrates cost-effectiveness across all scales of BESS, offering advantages such as straightforward installation, low energy intake, and negligible maintenance. Conversely, thermoelectric cooling is less economically viable due to the requirement for additional components, increased energy intake, and more intricate fitting processes [53]. The cost-effectiveness of hybrid cooling systems varies based on the specific blend of techniques employed [54]. Optimization of these systems involves customizing the combination to align with the requirements of the BESS. Table 11 illustrates the performance outcomes of TMS in terms of cost-effectiveness, which were utilized in the AHP-OS.

**Table 11.** TMS weights outcomes in cost-effectiveness.

| TMS | Weight | AHS Scale | References |
|---|---|---|---|
| **Natural convection** | Highly cost-effective due to minimal components and maintenance needs. | 9 | [51] |
| **Air-forced convection** | Moderate cost due to the need for fans and blowers and the potential for higher operational energy costs. | 5 | [51] |
| **Liquid-passive cooling** | High initial setup costs due to plumbing and coolant, but low operational costs. | 7 | [55,56] |
| **Liquid-active cooling** | High initial and operational costs due to the use of pumps and maintenance. | 3 | [50] |
| **Heat pipes** | Moderate to high cost-effectiveness. Initial costs can be offset by low maintenance and high efficiency. | 5 | [57] |
| **PCM** | High initial costs for PCM materials can be balanced by low operational costs, given their passive nature. | 7 | [58] |
| **Thermoelectric cooling** | It is the least cost-effective due to its high energy consumption and the cost of thermoelectric materials. | 1 | [53] |
| **Hybrid cooling** | It depends on the specific combination of TMSs used. They are designed to optimize performance while being mindful of costs. | 7 | [54] |

Table 12 shows the criterion consolidated priorities as well as the normalized pairwise comparison matrix for cost-effectiveness from AHP-OS with twenty-eight (28) comparisons and a CR of 1.1%.

**Table 12.** Priority matrix for cost-effectiveness.

| | NC | AFC | LPC | LAC | HP | PCM | TEC | HC |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 2.00 | 1.00 | 3.00 | 2.00 | 1.00 | 9.00 | 1.00 |
| **AFC** | 0.50 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 5.00 | 1.00 |
| **LPC** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 7.00 | 1.00 |
| **LAC** | 0.33 | 0.50 | 0.50 | 1.00 | 0.50 | 0.50 | 3.00 | 0.50 |
| **HP** | 0.50 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 5.00 | 1.00 |
| **PCM** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 7.00 | 1.00 |
| **TEC** | 0.11 | 0.20 | 0.14 | 0.33 | 0.20 | 0.14 | 1.00 | 0.14 |
| **HC** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 7.00 | 1.00 |

**Key: NC** = Natural convection at 19.6% rank 1, **AFC** = Air-forced convection at 13.2% rank 5, **LPC** = Liquid passive cooling at 14.9% rank 5, **LAC** = Liquid active cooling at 6.9% rank 7, **HP** = Heat pipes at 13.2% rank 5, **PCM** = PCM cooling at 14.9% rank 2, **TEC** = Thermoelectric cooling at 2.3% rank 8, **HC** = Hybrid cooling at 14.9% rank 2. (Figure A3 results obtained by AHP-OS are shown).

iii. Response to dynamic loads:Natural convection is cost-effective and suitable for smaller BESSs, but it may struggle to respond to sudden load changes due to its reliance on natural airflow [59]. While air-forced convection employing fans or blowers offers enhanced reactivity for medium- to large-scale BESSs that undergo frequent load variations [59].

Liquid active cooling is well-suited for handling significant load fluctuations because of its pump-driven cooling loop [60,61], whereas liquid passive cooling is less responsive but adequate for minor load changes. Equally, heat pipes are effective for both small and large-scale BESSs due to their excellent responsiveness. However, pure PCM may be less effective at higher discharge rates due to its slower response [59]. Thermoelectric cooling stands out for its superior responsiveness, making it ideal for dedicated BESS uses requiring precise heat control [62]. The reactivity of hybrid cooling systems depends on the combination of approaches used; however, their flexibility allows them to be adapted to various load conditions [63]. Table 13 showcases the TMS performance outcomes for response to dynamic loads, which were evaluated using AHP-OS.

**Table 13.** TMS weights outcomes in response to dynamic loads.

| TMS | Weight | AHS Scale | References |
|---|---|---|---|
| **Natural convection** | Slower to respond to sudden changes in thermal loads due to its passive nature. | 2 | [59,62] |
| **Air-forced convection** | Better than natural convection due to forced air movement but limited by the air's thermal properties. | 4 | [59] |
| **Liquid-passive cooling** | More responsive than air due to the higher thermal conductivity and heat capacity of liquids. | 5 | [60,61] |
| **Liquid-active cooling** | Very responsive due to active circulation, allowing quick adjustment to changing thermal loads. | 7 | [60,61] |
| **Heat pipes** | Highly responsive due to their efficient heat transfer capabilities, quickly moving heat away from hot spots. | 7 | [59] |
| **PCM** | Can absorb a lot of heat quickly during phase change but might struggle once the material is fully melted or solidified. | 5 | [60] |
| **Thermoelectric cooling** | Can be very responsive as it allows for rapid adjustments in cooling power. Its effectiveness is dependent on the power supply and is energy intensive. | 6 | [62] |
| **Hybrid cooling** | It can be highly effective if it is configured to leverage the strengths of each component system. | 8 | [64] |

Likewise, the AHS-OS was able to produce 28 pairwise comparisons for the response to dynamic loads metric using the consolidated priorities and normalized pairwise comparison matrix as shown in Table 14, with a CR of 0.8%.

**Table 14.** Priority matrix for response to dynamic loads.

| | NC | AFC | LPC | LAC | HP | PCM | TEC | HC |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 0.50 | 0.33 | 0.25 | 0.25 | 0.33 | 0.33 | 0.25 |
| **AFC** | 2.00 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 0.50 | 0.50 |
| **LPC** | 3.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **LAC** | 4.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **HP** | 4.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **PCM** | 3.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **TEC** | 3.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **HC** | 4.00 | 2.00 | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 |

**Key: NC** = Natural convection at 4.2% rank 8, **AFC** = Air-forced convection at 9.2% rank 7, **LPC** = Liquid passive cooling at 13.4% rank 5, **LAC** = Liquid active cooling at 15.1% rank 2, **HP** = Heat pipes at 15.1% rank 2, **PCM** = PCM at 13.4% rank 5, **TEC** = Thermoelectric cooling at 14.6% rank 4, and **HC** = Hybrid cooling at 15.1% rank 1. (Figure A3 results obtained by AHP-OS are shown).

iv. Safety and environment:Air-forced convection, while effective, carries risks such as overheating, thermal runaway, and fire if fans or blowers fail, and it contributes to noise pollution [65]. In contrast, natural convection is environmentally friendly and safe [66]. The choice of coolant in liquid passive cooling can impact both system safety and environmental health [67]. Liquid-active cooling requires stringent safety measures due to the potential for fluid leaks and pump failures. Heat pipes are generally secure and eco-friendly, although they can degrade over time and become pollutants [68]. Similarly, PCM is environmentally benign and non-toxic, but it can break down and pose environmental risks [56]. Whereas thermoelectric cooling systems have higher energy demands and a risk of overheating, necessitating careful handling and design. The safety and environmental ramifications of hybrid cooling systems hinge on the particular blend of techniques employed [48]. By merging the benefits of liquid and air cooling, hybrid cooling enhances thermal control and consistency in battery packs. This integration leads to enhanced battery performance and safety while mitigating the environmental impact associated with toxic coolants or extreme energy consumption. Table 15 illustrates the TMS performance outcomes for safety and environmental considerations, as evaluated using AHP-OS.

**Table 15.** TMS weights outcomes in safety and environment.

| TMS | Weight | AHS Scale | References |
|---|---|---|---|
| **Natural convection** | High safety due to its simplicity and no moving parts; environmentally friendly due to passive operation. | 8 | [66] |
| **Air-forced convection** | Safe, but fans and electrical components add complexity; energy use for fans impacts its environmental score. | 6 | [65] |
| **Liquid-passive cooling** | It is safe if leak-proof systems are used; coolant choice impacts environmental friendliness. | 5 | [67] |
| **Liquid-active cooling** | It requires careful design to prevent leaks; the environmental impact depends on the coolant and energy use of pumps. | 4 | [69] |
| **Heat pipes** | Very safe due to sealed operation; environmentally friendly with the correct material choice. | 7 | [68] |
| **PCM** | Safe and environmentally friendly due to passive operation; choice of PCM material determines environmental impact. | 7 | [56,63] |
| **Thermoelectric cooling** | Safety is generally high; however, the environmental impact of power consumption for cooling can be significant. | 4 | [70] |
| **Hybrid cooling** | Environmental impact and safety depend on the blend of systems used that are designed for high safety and lower environmental impact. | 7 | [71] |

Table 16 presents the consolidated priorities and normalized pairwise matrix for safety and environment as generated from the AHP-OS analysis involving twenty-eight (28) comparisons the consistency ratio (CR) stands at 0.8%.

**Table 16.** Priority matrix for safety and environment.

| | NC | AFC | LPC | LAC | HP | PCM | TEC | HC |
|---|---|---|---|---|---|---|---|---|
| **NC** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **AFC** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **LPC** | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **LAC** | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 0.50 |
| **HP** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **PCM** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 | 1.00 |
| **TEC** | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 | 0.50 | 1.00 | 0.50 |
| **HC** | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 | 1.00 |

**Key: NC** = Natural convection at 14.3% rank 1, **AFC** = Air-forced convection at 14.3% rank 1, **LPC** = Liquid passive cooling at 12.4% rank 6, **LAC** = Liquid active cooling at 7.9% rank 7, **HP** = Heat pipes at 14.3% rank 1, **PCM** = PCM cooling 14.3% rank 1, **TEC** = Thermoelectric cooling at 7.9% rank 7, and **HC** = Hybrid cooling at 14.3% rank 1. (Figure A3 results obtained by AHP-OS are shown).

## 4. Results and Discussion

The comparative review of TMS for BESS highlights the critical importance of effectively managing heat dissipation, especially in the dynamic operating conditions typical of VPPs.

Table 17 presents the overall score for each TMS across the four metrics as processed by AHP-OS. To visualize the relationship between the different TMS and the four metrics, a bar chart was generated by AHP-OS, as shown in Figure 10. Heat dissipation efficiency emerged as the top priority TMS metric at 36.6%, followed by response to dynamic loads at 27.8%, safety and environment at 23.3%, and cost-effectiveness at 12.4%.

**Table 17.** TMS decision hierarchy across levels 1 and 2.

| Level 0 | Level 1 | Priority | NC | AFC | LPC | LAC | HP | PCM | TEC | HC |
|---|---|---|---|---|---|---|---|---|---|---|
| **Determining the best TMS for BESS in VPPs** | Heat dissipation | 0.366 | 0.043 | 0.089 | 0.155 | 0.161 | 0.161 | 0.144 | 0.077 | 0.170 |
| | Cost-effectiveness | 0.124 | 0.132 | 0.149 | 0.069 | 0.132 | 0.149 | 0.023 | 0.049 | 0.149 |
| | Response to dynamic loads | 0.278 | 0.042 | 0.092 | 0.134 | 0.151 | 0.151 | 0.134 | 0.146 | 0.151 |
| | Safety and environment | 0.233 | 0.143 | 0.143 | 0.124 | 0.079 | 0.143 | 0.143 | 0.079 | 0.143 |
| **Consolidated weights of alternatives (%)** | | | **8.5** | **10.8** | **14.1** | **12.8** | **15.0** | **14.2** | **9.0** | **15.6** |

**Key: NC** = Natural convection, **AFC** = Air-forced convection, **LPC** = Liquid passive cooling, **LAC** = Liquid active cooling, **HP** = Heat pipes, **TEC** = Thermoelectric cooling, and **HC** = Hybrid cooling. (Figure A4 shows results obtained by AHP-OS).

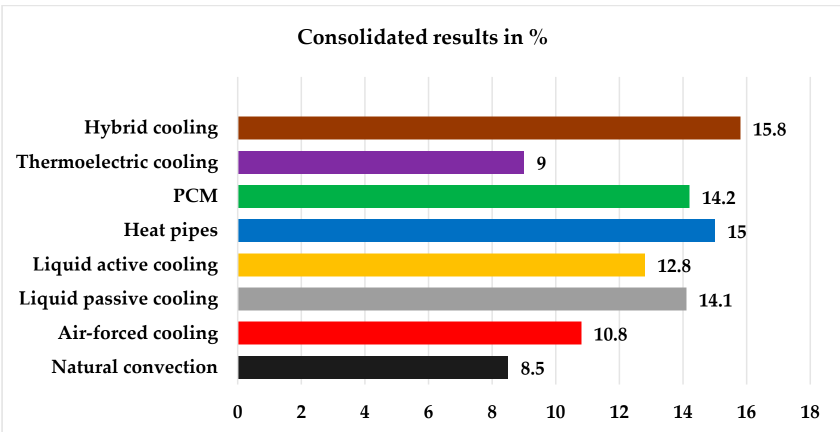



**Figure 10.** TMS score across the metrics graph.

Hybrid cooling has the highest overall score and the lowest standard deviation, which means it is the most similar to the ideal TMS and has the most balanced performance across all metrics. Thermoelectric cooling has the lowest overall score and the highest standard deviation, which means it is the least similar to the ideal TMS and has the most variable performance across the metrics.

Heat pipes and liquid active cooling are leading with scores of 16.1%, showcasing their superior capability in heat dissipation. On the contrary, natural convection and thermoelectric cooling are at the lower end, scoring 4.3% and 7.7%, respectively, indicating lesser effectiveness in heat management. Natural convection emerges as the most economical option at 19.6%, followed by liquid passive and PCM at 14.9%, while thermoelectric cooling trails with the least cost-effectiveness at 2.3%. Liquid active cooling, heat pipes, and hybrid cooling stand out with a 15.1% score, reflecting their adaptability to dynamic operational demands.

Meanwhile, natural convection and air-forced convection are less responsive, with scores of 4.2% and 9.2%, respectively. Heat pipes, natural convection, and PCM all score highly at 14.3%, underscoring their safety and minimal environmental impact. Similarly, liquid-active cooling and thermoelectric cooling have the lowest scores 7.9%, suggesting concerns in these areas. Thermoelectric has low scores for all metrics except for response to dynamic loads, which means it is poor at removing heat, costly, and unsafe, but it is fast to react to changing conditions.

Effective combinations within the hybrid cooling system include the following:

i. Heat pipes + PCM: This combination yields an average effectiveness score of 14.60%. Heat pipes are well-known for their capacity to efficiently conduct heat away from heat sources with minimal temperature differentials, rendering them superb for rapid heat transfer. This hybrid system can offer continuous thermal regulation when combined with PCM, which absorbs and releases thermal energy during phase changes. This is especially advantageous during peak load conditions, where the BESS experiences significant thermal stress. The PCM component provides a buffer that absorbs excess heat, thereby preventing overheating and enhancing the system's response to thermal fluctuations.
ii. Heat pipes + liquid passive cooling: With an average effectiveness score of 14.55%, this arrangement leverages heat pipes' efficient heat transfer abilities alongside the consistent cooling provided by liquid passive systems. Liquid passive cooling utilizes a coolant to transfer heat away from the battery cells, operating on the principle of natural convection without the need for mechanical pumps. This method is inherently reliable and requires minimal maintenance. Coupled with heat pipes, it ensures that heat is quickly removed from hot spots and evenly dissipated across the BESS, maintaining an optimal operational temperature range.

Balancing performance and cost are crucial, requiring tailored solutions for different applications and load profiles. Sensitivity analysis confirms the robustness of the decision-making process [72], aiding in the identification of key factors driving TMS selection. The findings have significant implications for BESS design and operation in VPPs, guiding stakeholders in maximizing reliability, efficiency, and sustainability. By considering multiple criteria and conducting sensitivity analysis, stakeholders can optimize TMS selection to enhance overall BESS performance while minimizing costs and environmental impacts. The study provides a structured approach to TMS decision-making, offering valuable insights for stakeholders seeking to deploy BESS effectively within VPPs.

## 5. Conclusions

This study has demonstrated the critical importance of effective TMS for BESS in VPPs. Through a comparative review, hybrid cooling systems have emerged as the most effective solution for managing the thermal environment of BESS. The research highlights the superior performance of combinations such as heat pipes with PCMs and liquid passive cooling.

Heat pipes paired with PCMs provide robust performance in environments with fluctuating thermal loads, ensuring stable thermal regulation and preventing overheating. Similarly, the integration of heat pipes with liquid passive cooling offers consistent and efficient cooling under varied operational conditions. These hybrid systems not only optimize thermal management but also enhance the safety, longevity, and performance of BESS, thereby supporting the stability and efficiency of VPPs.

The study's contributions are significant for stakeholders aiming to implement more reliable and efficient energy storage systems within VPPs. By addressing the challenges of thermal management, this research supports advancements in grid stability and renewable energy integration.

Future research should focus on conducting experiments to measure the extent of key parameters such as temperature distribution, cooling efficiencies, and power stability and the use of additional statistical techniques like the Technique for Order of Preference by Similarity to Ideal Solution (TOPSI) to further enhance the decision-making process.

**Author Contributions:** Conceptualization, N.K.M. and C.C.-k.; methodology, N.K.M.; software, N.K.M.; validation, N.K.M. and C.C.-k.; formal analysis, N.K.M.; investigation, N.K.M.; resources, N.K.M.; data curation, N.K.M.; writing—original draft preparation, N.K.M.; writing—review and editing, C.C.-k.; visualization, C.C.-k.; supervision, C.C.-k.; project administration, N.K.M.; funding acquisition, C.C.-k. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Kepco International Nuclear Graduate School.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funder had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

## Appendix A

```python
import numpy as np
from scipy.linalg import eig

# Define the decision matrix
decision_matrix = np.array([
    [1, 3, 1, 2],
    [3/9, 1, 1/2, 1/2],
    [1, 2, 1, 1],
    [1/2, 2, 1, 1]
])

# Compute eigenvalues and eigenvectors
eigenvalues, eigenvectors = eig(decision_matrix)

# Find the index of the dominant eigenvalue (maximum eigenvalue)
max_eigenvalue_index = np.argmax(eigenvalues)
dominant_eigenvalue = eigenvalues[max_eigenvalue_index]
dominant_eigenvector = eigenvectors[:, max_eigenvalue_index]

# Normalize the dominant eigenvector to get the priority vector
priority_vector = dominant_eigenvector / np.sum(dominant_eigenvector)

# Print the results
print("Eigenvalues:", eigenvalues)
print("Eigenvectors:")
print(eigenvectors)
print("Dominant Eigenvalue:", dominant_eigenvalue)
print("Dominant Eigenvector (unnormalized):", dominant_eigenvector)
print("Priority Vector (normalized to sum to 1):", priority_vector)
```

```
Eigenvalues: [ 4.04581928e+00+0.j         -2.29096423e-02+0.42994383j
 -2.29096423e-02-0.42994383j -7.20398333e-19+0.j        ]
Eigenvectors:
[[ 6.90883624e-01+0.j          7.40938940e-01+0.j
   7.40938940e-01-0.j          1.58960209e-18+0.j        ]
 [ 2.33811852e-01+0.j         -8.42126207e-02+0.03539579j
  -8.42126207e-02-0.03539579j -5.77350269e-01+0.j        ]
 [ 5.24545312e-01+0.j         -1.98948064e-01-0.50202832j
  -1.98948064e-01+0.50202832j  5.77350269e-01+0.j        ]
 [ 4.39162899e-01+0.j         -1.53163830e-01+0.35720153j
  -1.53163830e-01-0.35720153j  5.77350269e-01+0.j        ]]
Dominant Eigenvalue: (4.04581928450146+0j)
Dominant Eigenvector (unnormalized): [0.69088362+0.j 0.23381185+0.j 0.52454531+0.j 0.4391629 +0.j]
Priority Vector (normalized to sum to 1): [0.3658559 +0.j 0.12381455+0.j 0.27777181+0.j 0.23255774+0.j]
```

**Figure A1.** Python mathematical software code for exact Eigenvector determination.

**AHP Group Results**

**Project Result Data**
Selected scale: **0 - Standard AHP linear scale**

**Project Data**

| Field | Content |
|---|---|
| Session Code | nyHazU |
| Project Name | Determining the best TMS for BESS in VPPS |
| Description | TMS determination |
| Author | Nkerwa |
| Date | 2024-05-03 11:46:59 |
| Status | open |
| Type | Hierarchy |

**Project Participants**

| No | Sel | Name | Date |
|---|---|---|---|
| 1 | ☐ | Nkerwa | 2024-05-03 |

Refresh Selection ☐ check all ☐ uncheck all

**Decision Hierarchy**

| Level 0 | Level 1 | Glb Prio. |
|---|---|---|
| Determining the best TMS for BESS in VPPS | Heat dissipation 0.366 | 36.6% |
| | Cost-effectiveness 0.124 | 12.4% |
| | Response to dynamic loads 0.278 | 27.8% |
| | Safety & environment 0.233 | 23.3% |
| | | 1.0 |

**Consolidated Decision Matrix**

Aggregation of individual judgments for 1 Participant(s)

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 1 | 3.00 | 1.00 | 2.00 |
| 2 | 0.33 | 1 | 0.50 | 0.50 |
| 3 | 1.00 | 2.00 | 1 | 1.00 |
| 4 | 0.50 | 2.00 | 1.00 | 1 |

Done AHP-OS author: Klaus D. Goepel, BPMSG. Contact Last update: Apr 03, 2022 Rev: 192

**Figure A2.** AHP–OS results for TMS metrics.

Details Criterion: Heat dissipation - CR: 0.7%

**Consolidated Priorities**
Consistency Ratio CR: 0.7%

| Cat | | Priority | Rank |
|---|---|---|---|
| 1 | Natural convection | 4.3% | 8 |
| 2 | Air-forced convection | 8.9% | 6 |
| 3 | Liquid passive cooling | 15.5% | 4 |
| 4 | Liquid active cooling | 16.1% | 2 |
| 5 | Heat pipes | 16.1% | 2 |
| 6 | PCM | 14.4% | 5 |
| 7 | Thermoelectric cooling | 7.7% | 7 |
| 8 | Hybrid cooling | 17.0% | 1 |

Details Criterion: Cost-effectiveness - CR: 0.7%

**Consolidated Priorities**
Consistency Ratio CR: 0.7%

| Cat | | Priority | Rank |
|---|---|---|---|
| 1 | Natural convection | 19.6% | 1 |
| 2 | Air-forced convection | 13.2% | 5 |
| 3 | Liquid passive cooling | 14.9% | 2 |
| 4 | Liquid active cooling | 6.9% | 7 |
| 5 | Heat pipes | 13.2% | 5 |
| 6 | PCM | 14.9% | 2 |
| 7 | Thermoelectric cooling | 2.3% | 8 |
| 8 | Hybrid cooling | 14.9% | 2 |

Details Criterion: Response to dynamic loads - CR: 0.8%

**Consolidated Priorities**
Consistency Ratio CR: 0.8%

| Cat | | Priority | Rank |
|---|---|---|---|
| 1 | Natural convection | 4.2% | 8 |
| 2 | Air-forced convection | 9.2% | 7 |
| 3 | Liquid passive cooling | 13.4% | 5 |
| 4 | Liquid active cooling | 15.1% | 1 |
| 5 | Heat pipes | 15.1% | 1 |
| 6 | PCM | 13.4% | 5 |
| 7 | Thermoelectric cooling | 14.6% | 4 |
| 8 | Hybrid cooling | 15.1% | 1 |

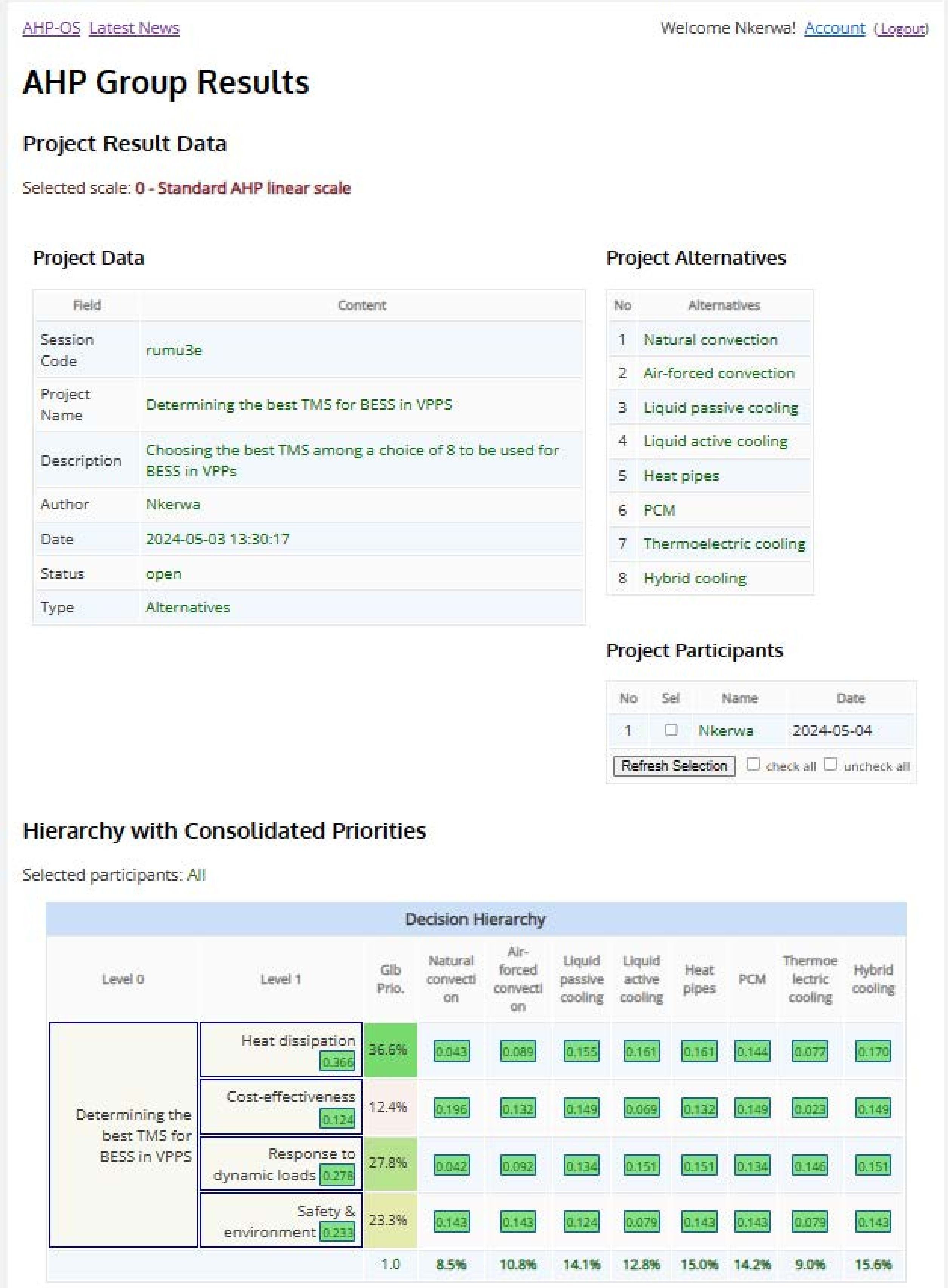
Details Criterion: Safety & environment - CR: 0.8%

**Consolidated Priorities**
Consistency Ratio CR: 0.8%

| Cat | | Priority | Rank |
|---|---|---|---|
| 1 | Natural convection | 14.3% | 1 |
| 2 | Air-forced convection | 14.3% | 1 |
| 3 | Liquid passive cooling | 12.4% | 6 |
| 4 | Liquid active cooling | 7.9% | 7 |
| 5 | Heat pipes | 14.3% | 1 |
| 6 | PCM | 14.3% | 1 |
| 7 | Thermoelectric cooling | 7.9% | 7 |
| 8 | Hybrid cooling | 14.3% | 1 |

AHP-OS author: Klaus D. Goepel, BPMSG. Contact Last update: Apr 03, 2022 Rev: 192

**Figure A3.** AHP–OS TMS results in every TMS metric.



AHP-OS Latest News Welcome Nkerwa! Account (Logout)

# AHP Group Results

## Project Result Data

Selected scale: 0 - Standard AHP linear scale

### Project Data

| Field | Content |
|---|---|
| Session Code | rumu3e |
| Project Name | Determining the best TMS for BESS in VPPS |
| Description | Choosing the best TMS among a choice of 8 to be used for BESS in VPPs |
| Author | Nkerwa |
| Date | 2024-05-03 13:30:17 |
| Status | open |
| Type | Alternatives |

### Project Alternatives

| No | Alternatives |
|---|---|
| 1 | Natural convection |
| 2 | Air-forced convection |
| 3 | Liquid passive cooling |
| 4 | Liquid active cooling |
| 5 | Heat pipes |
| 6 | PCM |
| 7 | Thermoelectric cooling |
| 8 | Hybrid cooling |

### Project Participants

| No | Sel | Name | Date |
|---|---|---|---|
| 1 | | Nkerwa | 2024-05-04 |

Refresh Selection check all uncheck all

### Hierarchy with Consolidated Priorities

Selected participants: All

Decision Hierarchy

| Level 0 | Level 1 | Glb Prio. | Natural convection | Air-forced convection | Liquid passive cooling | Liquid active cooling | Heat pipes | PCM | Thermoelectric cooling | Hybrid cooling |
|---|---|---|---|---|---|---|---|---|---|---|
| Determining the best TMS for BESS in VPPS | Heat dissipation 0.366 | 36.6% | 0.043 | 0.089 | 0.155 | 0.161 | 0.161 | 0.144 | 0.077 | 0.170 |
| | Cost-effectiveness 0.124 | 12.4% | 0.196 | 0.132 | 0.149 | 0.069 | 0.132 | 0.149 | 0.023 | 0.149 |
| | Response to dynamic loads 0.278 | 27.8% | 0.042 | 0.092 | 0.134 | 0.151 | 0.151 | 0.134 | 0.146 | 0.151 |
| | Safety & environment 0.233 | 23.3% | 0.143 | 0.143 | 0.124 | 0.079 | 0.143 | 0.143 | 0.079 | 0.143 |
| | | 1.0 | 8.5% | 10.8% | 14.1% | 12.8% | 15.0% | 14.2% | 9.0% | 15.6% |

**Figure A4.** AHP–OS consolidated results for TMS metrics and TMSs.

## References


1. Dehghani-Sanij, A.R.; Tharumalingam, E.; Dusseault, M.B.; Fraser, R. Study of energy storage systems and environmental challenges of batteries. *Renew. Sustain. Energy Rev.* **2019**, *104*, 192–208. [CrossRef]
2. Zichen, W.; Changqing, D. A comprehensive review on thermal management systems for power lithium-ion batteries. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110685. [CrossRef]
3. Mevawalla, A.; Panchal, S.; Tran, M.K.; Fowler, M.; Fraser, R. Mathematical heat transfer modeling and experimental validation of lithium-ion battery considering: Tab and surface temperature, separator, electrolyte resistance, anode-cathode irreversible and reversible heat. *Batteries* **2020**, *6*, 61. [CrossRef]
4. Burheim, O.S.; Onsrud, M.A.; Pharoah, J.G.; Vullum-Bruer, F.; Vie, P.J.S. Thermal Conductivity, Heat Sources and Temperature Profiles of Li-Ion Secondary Batteries. *ECS Meet. Abstr.* **2013**, *MA2013-02*, 1190. [CrossRef]
5. Li, G. Promotion of practical technology of the thermal management system for cylindrical power battery. *Energy Inform.* **2024**, *7*, 33. [CrossRef]
6. Hannan, M.A.; Al-Shetwi, A.; Begum, R.A.; Young, S.E.; Hoque, M.M.; Ker, P.; Mansur, M.; Alzaareer, K. The value of thermal management control strategies for battery energy storage in grid decarbonization: Issues and recommendations. *J. Clean. Prod.* **2020**, *276*, 124223. [CrossRef]
7. Boulaire, F.; Love, J.; Mackinnon, I. An adaptive renewable energy plant (AREP)—To power local premises and vehicles with 100% renewables. *Energy Strateg. Rev.* **2021**, *38*, 100703. [CrossRef]
8. Sakr, W.S.; EL-Sehiemy, R.A.; Azmy, A.M.; Abd el-Ghany, H.A. Identifying optimal border of virtual power plants considering uncertainties and demand response. *Alex. Eng. J.* **2022**, *61*, 9673–9713. [CrossRef]
9. Liu, H.; Wei, Z.; He, W.; Zhao, J. Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review. *Energy Convers. Manag.* **2017**, *150*, 304–330. [CrossRef]
10. Hamed, M.M.; El-Tayeb, A.; Moukhtar, I.; El Dein, A.Z.; Abdelhameed, E.H. A review on recent key technologies of lithium-ion battery thermal management: External cooling systems. *Results Eng.* **2022**, *16*, 100703. [CrossRef]
11. Zuo, W.; Zhang, Y.; E, J.; Li, J.; Li, Q.; Zhang, G. Performance comparison between single S-channel and double S-channel cold plate for thermal management of a prismatic LiFePO4 battery. *Renew. Energy* **2022**, *192*, 46–57. [CrossRef]
12. Chen, M.; Li, J. Nanofluid-based pulsating heat pipe for thermal management of lithium-ion batteries for electric vehicles. *J. Energy Storage* **2020**, *32*, 101715. [CrossRef]
13. Rashid, F.L.; Dulaimi, A.; Hatem, W.A.; Al-obaidi, M.A.; Ameen, A.; Eleiwi, M.A.; Jawad, S.A.; Bernardo, A. Recent Advances and Developments in Phase Change Materials in High-Temperature Building Envelopes: A Review of Solutions and Challenges. *Buildings* **2024**, *14*, 1582. [CrossRef]
14. Sanin-Villa, D. Recent Developments in Thermoelectric Generation: A Review. *Sustainability* **2022**, *14*, 16821. [CrossRef]
15. Zhou, R.; Chen, Y.; Zhang, J.; Guo, P. Research progress in liquid cooling technologies to enhance the thermal management of LIBs. *Mater. Adv.* **2023**, *4*, 4011–4040. [CrossRef]
16. Martín-Martín, L.; Gastelurrutia, J.; Nieto, N.; Ramos, J.C.; Rivas, A.; Gil, I. Modeling based on design of thermal management systems for vertical elevation applications powered by lithium-ion batteries. *Appl. Therm. Eng.* **2016**, *102*, 1081–1094. [CrossRef]
17. Odukomaiya, A.; Woods, J.; James, N.; Kaur, S.; Gluesenkamp, K.R.; Kumar, N.; Mumme, S.; Jackson, R.; Prasher, R. Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings. *Energy Environ. Sci.* **2021**, *14*, 5315–5329. [CrossRef]
18. Rao, Z.; Lyu, P.; Du, P.; He, D.; Huo, Y.; Liu, C. Thermal safety and thermal management of batteries. *Batter. Energy* **2022**, *1*, 20210019. [CrossRef]
19. Liu, H. Contribution of Battery Energy Storage System (BESS) to Power Systems Resilience. Ph.D. Thesis, University of Manchester, Manchester, UK, 2022.
20. Bravo Diaz, L.; He, X.; Hu, Z.; Restuccia, F.; Marinescu, M.; Barreras, J.V.; Patel, Y.; Offer, G.; Rein, G. Review—Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions. *J. Electrochem. Soc.* **2020**, *167*, 090559. [CrossRef]
21. Jeevarajan, J.A.; Joshi, T.; Parhizi, M.; Rauhala, T.; Juarez-Robles, D. Battery Hazards for Large Energy Storage Systems. *ACS Energy Lett.* **2022**, *7*, 2725–2733. [CrossRef]
22. Rangarajan, A.; Foley, S.; Trück, S. Assessing the impact of battery storage on Australian electricity markets. *Energy Econ.* **2023**, *120*, 106601. [CrossRef]
23. Borneo, D.R. Grid Energy Storage? Overview and Trends. 2019. Available online: https://www.osti.gov/servlets/purl/1678820 (accessed on 5 May 2024).
24. Laaroussi, A.; Laaroussi, O.; Bouayad, A. Environmental impact study of the NOOR 1 solar project on the Southern Region of Morocco. *Renew. Energy Environ. Sustain.* **2023**, *8*, 9. [CrossRef]
25. Fraser, T.; Chapman, A.J. Social equity impacts in Japan's mega-solar siting process. *Energy Sustain. Dev.* **2018**, *42*, 136–151. [CrossRef]
26. Marema, A.; Tlokolo, B.; Pandarum, A. Socio-Economic Benefits of Renewable and Storage Technologies in South Africa 2. 2022, pp. 1–11. Available online: https://www.ameu.co.za/Socio-economic%20benefits%20of%20renewable%20energy%20technologies%20-%20Abram%20Marema.pdf (accessed on 5 May 2024).

27. Pinel, P.; Cruickshank, C.A.; Beausoleil-Morrison, I.; Wills, A. A review of available methods for seasonal storage of solar thermal energy in residential applications. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3341–3359. [CrossRef]
28. Truong, C.N.; Naumann, M.; Karl, R.C.; Müller, M.; Jossen, A.; Hesse, H.C. Economics of residential photovoltaic battery systems in Germany: The case of tesla's powerwall. *Batteries* **2016**, *2*, 14. [CrossRef]
29. Georgakarakos, A.; Mayfield, M.; Buckman, A.H.; Jubb, S.A.; Wootton, C. What are Smart Grid Optimised Buildings? In Proceedings of the Living and Sustainability: An Environmental Critique of Design and Building Practices, Locally and Globally, London, UK, 8–9 February 2017; pp. 21–36.
30. Martin, S.; Mosier, N.; Nnorom, O.; Ou, Y.; Patel, L.; Triebe, O.; Cezar, G.; Levis, P.; Rajagopal, R. Software defined grid energy storage. In Proceedings of the 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Trans-portation, Boston, MA, USA, 9–10 November 2022; pp. 218–227. [CrossRef]
31. Peftitsis, D. *Systems: Practices, Difficulties and Prospects*; Kaunas University of Technology: Kaunas, Lithuania, 2021.
32. Lu, M.; Zhang, X.; Ji, J.; Xu, X.; Zhang, Y. Research progress on power battery cooling technology for electric vehicles. *J. Energy Storage* **2020**, *27*, 101155. [CrossRef]
33. Walvekar, H.; Beltran, H.; Sripad, S.; Pecht, M. Implications of the Electric Vehicle Manufacturers' Decision to Mass Adopt Lithium-Iron Phosphate Batteries. *IEEE Access* **2022**, *10*, 63834–63843. [CrossRef]
34. Akbarzadeh, M.; Kalogiannis, T.; Jaguemont, J.; Jin, L.; Behi, H.; Karimi, D.; Beheshti, H.; Van Mierlo, J.; Berecibar, M. A comparative study between air cooling and liquid cooling thermal management systems for a high-energy lithium-ion battery module. *Appl. Therm. Eng.* **2021**, *198*, 117503. [CrossRef]
35. Karlsson, S. Life Cycle Assessment of Borehole Thermal Energy Storage. no. 2019. 2022. Available online: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-310321 (accessed on 5 May 2024).
36. Colagrande, S.; D'Ovidio, G. Electric energy harvesting solutions review from roads pavements. In Proceedings of the Transport Means 2018 International Conference, Trakai, Lithuania, 3–5 October 2018; pp. 5–10.
37. Landini, S.; Leworthy, J.; O'Donovan, T.S. A Review of Phase Change Materials for the Thermal Management and Isothermalisation of Lithium-Ion Cells. *J. Energy Storage* **2019**, *25*, 100887. [CrossRef]
38. Wang, H.; Soong, W.L.; Pourmousavi, S.A.; Zhang, X.; Ertugrul, N.; Xiong, B. Thermal dynamics assessment of vanadium redox flow batteries and thermal management by active temperature control. *J. Power Sources* **2023**, *570*, 233027. [CrossRef]
39. Wang, H.; Li, H.; Ji, Z.; Yang, Z.; Jiang, C.; Lin, H. Cooling the electrode tabs with air to manage the heat transferred through the collectors in traction battery. *J. Energy Storage* **2022**, *48*, 103982. [CrossRef]
40. Goepel, K. Implementation of an Online software tool for the Analytic Hierarchy Process (AHP-OS). *Int. J. Anal. Hierarchy Process* **2018**, *10*, 469–487. [CrossRef]
41. Das, D.; Sharma, R.K.; Saikia, P.; Rakshit, D. An integrated entropy-based multi-attribute decision-making model for phase change material selection and passive thermal management. *Decis. Anal. J.* **2021**, *1*, 100011. [CrossRef]
42. Dwivedi, A.; Kumar, A.; Goel, V. A consolidated decision-making framework for nano-additives selection in battery thermal management applications. *J. Energy Storage* **2023**, *59*, 106565. [CrossRef]
43. Bulut, M.; Özcan, E. A novel approach towards evaluation of joint technology performances of battery energy storage system in a fuzzy environment. *J. Energy Storage* **2021**, *36*, 102361. [CrossRef]
44. Napa, N.; Agrawal, M.K.; Tamma, B. Design of novel thermal management system for Li-ion battery module using metal matrix based passive cooling method. *J. Energy Storage* **2023**, *73*, 109119. [CrossRef]
45. Martín-Martín, L.; Gastelurrutia, J.; Larraona, G.S.; Antón, R.; del Portillo-Valdés, L.; Gil, I. Optimization of thermal management systems for vertical elevation applications powered by lithium-ion batteries. *Appl. Therm. Eng.* **2019**, *147*, 155–166. [CrossRef]
46. Hassan, A.M.; Alwan, A.A.; Hamzah, H.K. Numerical Study of Fan Coil Heat Exchanger with Copper Foam. *Int. J. Fluid Mach. Syst.* **2023**, *16*, 73–88. [CrossRef]
47. Can, A.; Selimefendigil, F.; Öztop, H.F. A review on soft computing and nanofluid applications for battery thermal management. *J. Energy Storage* **2022**, *53*, 105214. [CrossRef]
48. Wüllner, J.; Reiners, N.; Millet, L.; Salibi, M.; Stortz, F.; Vetter, M. Review of Stationary Energy Storage Systems Applications, Their Placement, and Techno-Economic Potential. *Curr. Sustain. Energy Rep.* **2021**, *8*, 263–273. [CrossRef]
49. Kaczorowska, D.; Rezmer, J.; Jasinski, M.; Sikorski, T.; Suresh, V.; Leonowicz, Z.; Kostyla, P.; Szymanda, J.; Janik, P. A case study on battery energy storage system in a virtual power plant: Defining charging and discharging characteristics. *Energies* **2020**, *13*, 6670. [CrossRef]
50. Hailu, G.; Henke, M.; Petersen, T. Stationary Battery Thermal Management: Analysis of Active Cooling Designs. *Batteries* **2022**, *8*, 23. [CrossRef]
51. Tao, F.; Zhang, W.; Guo, D.; Cao, W.; Sun, L.; Jiang, F. Thermofluidic modeling and temperature monitoring of Li-ion battery energy storage system. *Appl. Therm. Eng.* **2020**, *181*, 116026. [CrossRef]
52. Qin, P.; Sun, J.; Yang, X.; Wang, Q. Battery thermal management system based on the forced-air convection: A review. *eTransportation* **2021**, *7*, 100097. [CrossRef]
53. Elmaaref, M.M.A.; Askalany, A.A.; Salem, M.; Harby, K. Solar thermoelectric cooling technology. In Proceedings of the 3rd International Conference on Energy Engineering, Aswan, Egypt, 28–30 December 2015; pp. 1–7.

54. Peng, Z.; Li, Z.; Zeng, J.; Yu, J.; Lv, S. Thermo-economic analysis of absorption-compression hybrid cooling systems with parallel subcooling and recooling for small scale low-grade heat source and low temperature application. *Int. J. Refrig.* **2022**, *138*, 220–232. [CrossRef]
55. Cai, S.; Li, Y. Incentive Policy for Battery Energy Storage Systems Based on Economic Evaluation Considering Flexibility and Reliability Benefits. *Front. Energy Res.* **2021**, *9*, 634912. [CrossRef]
56. Nižetić, S.; Papadopoulos, A.M.; Giama, E. Comprehensive analysis and general economic-environmental evaluation of cooling techniques for photovoltaic panels, Part I: Passive cooling techniques. *Energy Convers. Manag.* **2017**, *149*, 334–354. [CrossRef]
57. Chen, Z.; Yu, Z.; Fu, J.; Yang, J. Analysis and Design of Air-heat pipe Composite Cooling of High Power Density Motor. *Appl. Therm. Eng.* **2023**, *236*, 121495. [CrossRef]
58. Nadjahi, C.; Louahlia, H.; Lemasson, S. A review of thermal management and innovative cooling strategies for data center. *Sustain. Comput. Inform. Syst.* **2018**, *19*, 14–28. [CrossRef]
59. Behi, H.; Karimi, D.; Jaguemont, J.; Gandoman, F.H.; Kalogiannis, T.; Berecibar, M.; Van Mierlo, J. Novel thermal management methods to improve the performance of the Li-ion batteries in high discharge current applications. *Energy* **2021**, *224*, 120165. [CrossRef]
60. Xin, Q.; Xiao, J.; Yang, T.; Zhang, H.; Long, X. Thermal management of lithium-ion batteries under high ambient temperature and rapid discharging using composite PCM and liquid cooling. *Appl. Therm. Eng.* **2022**, *210*, 118230. [CrossRef]
61. Xu, K.; Zhang, H.; Zhu, J.; Qiu, G. Thermal Management for Battery Module with Liquid-Cooled Shell Structure under High Charge/Discharge Rates and Thermal Runaway Conditions. *Batteries* **2023**, *9*, 204. [CrossRef]
62. Li, X.; Zhong, Z.; Luo, J.; Wang, Z.; Yuan, W.; Zhang, G.; Yang, C.; Yang, C. Experimental Investigation on a Thermoelectric Cooler for Thermal Management of a Lithium-Ion Battery Module. *Int. J. Photoenergy* **2019**, *2019*, 3725364. [CrossRef]
63. Wazeer, A.; Das, A.; Abeykoon, C.; Sinha, A.; Karmakar, A. Phase change materials for battery thermal management of electric and hybrid vehicles: A review. *Energy Nexus* **2022**, *7*, 100131. [CrossRef]
64. Hekmat, S.; Molaeimanesh, G.R. Hybrid thermal management of a Li-ion battery module with phase change material and cooling water pipes: An experimental investigation. *Appl. Therm. Eng.* **2020**, *166*, 114759. [CrossRef]
65. Rahman, N.M.A.; Haw, L.C.; Kamaluddin, K.A.; Abdullah, M.S.I. Investigating photovoltaic module performance using aluminium heat sink and forced cold-air circulation method in tropical climate conditions. *Energy Rep.* **2023**, *9*, 2797–2809. [CrossRef]
66. Youssef, R.; Hosen, M.S.; He, J.; Jaguemont, J.; De Sutter, L.; Van Mierlo, J.; Berecibar, M. Effect analysis on performance enhancement of a novel and environmental evaporative cooling system for lithium-ion battery applications. *J. Energy Storage* **2021**, *37*, 102475. [CrossRef]
67. Chen, Y.; Kang, Y.; Zhao, Y.; Wang, L.; Liu, J.; Li, Y.; Liang, Z.; He, X.; Li, X.; Tavajohi, N.; et al. A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards. *J. Energy Chem.* **2021**, *59*, 83–99. [CrossRef]
68. Ning, Y.; Tao, R.; Luo, J.; Hu, Q. Application and Research Progress of Heat Pipe in Thermal Management of Lithium-Ion Battery. *Trends Renew. Energy* **2022**, *8*, 130–144. [CrossRef]
69. Nishida, R.; Zhong, J.; Shinshi, T. Forced liquid cooling of piezoelectric stack actuator utilizing silicone oil. *Precis. Eng.* **2022**, *75*, 120–128. [CrossRef]
70. Atta, R.M. Thermoelectric Cooling (Chpater 12). In *Bringing Thermoelectricity into Reality*; IntechOpen: London, UK, 2018; pp. 247–267.
71. Abdelkareem, M.A.; Maghrabie, H.M.; Abo-Khalil, A.G.; Adhari, O.H.K.; Sayed, E.T.; Radwan, A.; Elsaid, K.; Wilberforce, T.; Olabi, A.G. Battery thermal management systems based on nanofluids for electric vehicles. *J. Energy Storage* **2022**, *50*, 104385. [CrossRef]
72. Dweiri, F.; Kumar, S.; Khan, S.A.; Jain, V. Designing an integrated AHP based decision support system for supplier selection in automotive industry. *Expert Syst. Appl.* **2016**, *62*, 273–283. [CrossRef]