


Review

# Thermal Management of Stationary Battery Systems: A Literature Review

Martin Henke and Getu Hailu \* 

College of Engineering, University of Alaska Anchorage, Anchorage, AK 99508, USA; mthenke@alaska.edu

\* Correspondence: ghailu@alaska.edu

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**Abstract:** Stationary battery systems are becoming increasingly common worldwide. Energy storage is a key technology in facilitating renewable energy market penetration and battery energy storage systems have seen considerable investment for this purpose. Large battery installations such as energy storage systems and uninterruptible power supplies can generate substantial heat in operation, and while this is well understood, the thermal management systems that currently exist have not kept pace with stationary battery installation development. Stationary batteries operating at elevated temperatures experience a range of deleterious effects and, in some cases, serious safety concerns can arise. Optimal thermal management prioritizes safety and balances costs between the cooling system and battery degradation due to thermal effects. Electric vehicle battery thermal management has undergone significant development in the past decade while stationary battery thermal management has remained mostly stagnant, relying on the use of active and passive air cooling. Despite being the default method for thermal management, there is an absence of justifying research or comparative reviews. This literature review seeks to define the role of stationary battery systems in modern power applications, the effects that heat generation and temperature have on the performance of these systems, thermal management methods, and future areas of study.

**Keywords:** battery; thermal management; lithium-ion; lead–acid; energy storage

## 1. Introduction to Stationary Batteries

In recent years, several fires have occurred at stationary battery installations throughout the United States and Korea. While the culprit was deemed to be mismanagement of the facilities, initially, the reputation of the enclosed Li-ion batteries drew attention [1,2]. Thermal management of large stationary battery installations is an emerging field, and due to lack of confidence in battery management systems, stationary battery systems are often implemented with 20–50% excess capacity to be cautious in operation [3]. While the safety factor is a necessary part of design, excessive overdesign can incur unneeded costs in implementation. Considering that the expensive initial cost of Li-ion batteries is often seen as the primary drawback of the technology, it is important that systems be sized correctly. Combined, unoptimized thermal management systems and excessively large installations hinder development of battery energy storage systems and underscore thermal management as a worthy topic of review.

As the name implies, a stationary battery is simply a battery used in energy storage placed in a static location. Upon further examination, these batteries can typically be divided by their function as either a standby battery (e.g., batteries in an uninterruptible power supply) or a cycling battery (e.g., batteries comprising an energy storage system) [4]. While there are significant differences between the operational characteristics of these systems, the underlying principles and science remain the same. An element of interest in efficient and safe operation of stationary batteries is thermal management. While battery heat generation and the deleterious effects of elevated temperature are well understood,

most of the research has focused on applications towards electric vehicles. To better understand and optimize stationary battery systems, investigation into the role of thermal management is necessary.

By nature, many sources of renewable energy are variable in their power generation. To overcome this issue, it is accepted that most forms of renewable energy require an energy storage system (ESS) in order to establish a reliable and cost-effective electrical system [5–10]. For this purpose, there are a wide variety of technologies available. Pumped hydropower, hydrogen energy storage, flywheels, compressed air energy storage, thermal storage, supercapacitors, and electrochemical systems have all seen some degree of investigation and implementation for the purpose of addressing the issue of renewable energy production intermittency. Falling within the electrochemical division, battery energy storage systems (BESSs) have seen significant investment and development due to favorable characteristics, such as rapid discharge, modularity, and flexible scaling [3,11,12]. While BESS systems cannot match the massive quantities of energy storage capacity achievable by technologies such as pumped hydropower, batteries do not have geographic limitations, and modern technologies boast higher round trip energy efficiency than many other storage methods. In addition to storage, the short response time of BESSs can yield other benefits related to grid stability and cost [13]. While batteries are the primary method of energy storage for small-scale and private renewable energy systems [14], BESSs currently account for approximately only 3% of the total national energy storage capacity in the United States; however, in recent years, successful implementation of large-scale utility systems has increased [12,15,16].

In modern electrical and data systems, stability and constant uptime are critical aspects of system performance. Another application of stationary batteries can be to ensure system stability using an uninterruptible power supply (UPS). Power interruptions are costly events, with the majority of the costs incurred within the commercial and industrial sectors in the form of lost revenue, materials, and interrupted labor [17]. For example, telecommunication is especially vulnerable to short power interruptions, as power outage for less than a second can cause long periods of interrupted service as data centers restart [18]. These periods of downtime can be costly and result in contract penalties for telecommunication service providers [17,19]. In addition to being costly, these events are also periods in which telecommunications are most desirable for emergency services and, thus, pose a public safety risk. In the interest of prioritizing system uptime for public safety and avoiding costly downtime, it is the industry standard that all data centers are equipped with a UPS. While the battery installation powering a single server may be small, the technology can be scaled up to hundreds of megawatts in capacity to support industrial processes while backup power is brought online [15,20,21].

## 2. Battery Types

Despite there being many types of batteries, all cells operate on the conversion of chemical energy to electrical energy. The primary types of cells used in stationary systems are lead–acid and lithium-ion (Li-ion). While there are alternative technologies, including but not limited to nickel–cadmium, sodium–sulfur, or flow batteries, their discussion and analysis will be omitted in favor of Li-ion and lead–acid batteries, which are most prominently used within BESSs and UPSs, respectively, and have many operational characteristics in common [3,7,12,22]. Sodium–sulfur batteries operate at temperature ranges from 300 to 350 °C, and flow batteries utilize separate electrolytes stored in reservoirs which are then pumped through the cell during charge/discharge [22]. Accounting for the unique characteristics of these battery technologies and the unique management methods is not within the scope of this review.

There are a range of performance characteristics to note when assessing the viability of a battery technology for a stationary system. Energy density is the quantity of energy stored per kilogram of battery mass; similarly, power density is the maximum discharge power capable for the battery per kilogram of mass (in some cases, volume is used instead).

As a general rule, a battery is considered to have reached the end of its functional life when it can only achieve 80% of its original rated capacity [23]. To assess expected battery longevity, there is

no clear time frame that can be given as life expectancy as this characteristic is dependent on cycling frequency, discharge/recharge characteristics, thermal conditions, and other factors. One method to assess battery life is through the cycle-life characteristic, which is the number of full discharges and recharges a battery can endure before degrading to the aforementioned 80% reduced capacity [24,25]. It is worth noting that cycle life accounts for full discharges, which are especially stressful for battery technologies such as lead–acid. In applications where partial discharges are more common (such as power smoothing or UPS applications), cycle life may not be an accurate reflection of the number of cycles a battery can endure [23]. In a process known as calendar aging, battery capacity is lost naturally over time even when the cell is not in use; this process is greatly accelerated if the battery experiences high temperatures [26]. The effects of calendar and cyclic aging depend on both the cell technology and the application characteristics the battery experiences.

A safety characteristic relevant to thermal management is a phenomenon known as thermal runaway. In this failure mode, the chemical reaction rate within the cell increases uncontrollably, and the temperature of the battery increases in kind. This failure mode can result in fire or an explosion and, deservedly, has been the focus of substantial research [27–29].

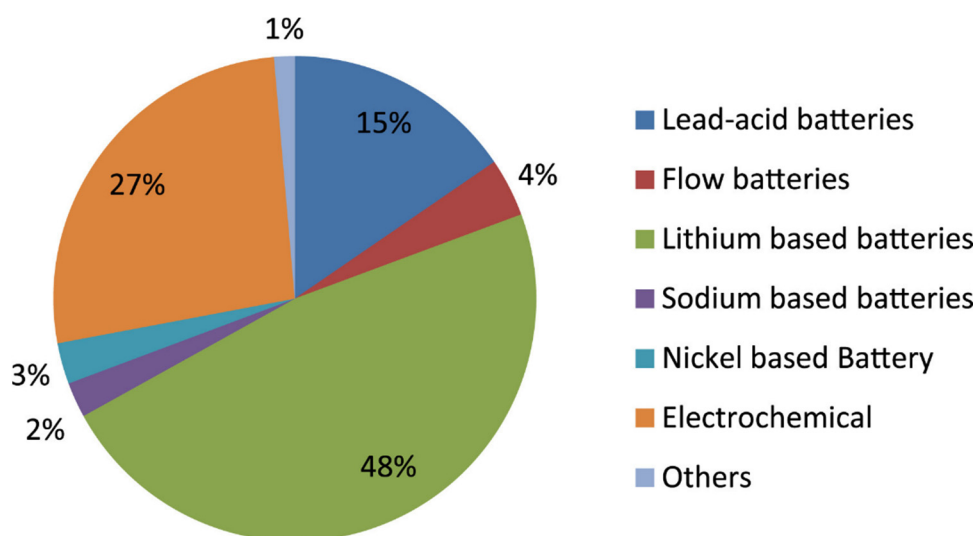
### 2.1. Lead–Acid

As a well-established technology, lead–acid batteries currently make up the majority of standby battery installations and have been used in stationary applications for many decades [30–32]. Lead–acid batteries are often inexpensive in comparison to alternative battery technologies and their operation and uses are well understood [33]. There are several drawbacks to the technology, including low round trip energy efficiency, poor cycle life, and low power and energy density [34–37].

The primary types of lead–acid batteries used in stationary systems are the sealed valve regulated lead–acid battery (VRLA) and the flooded/vented lead–acid battery. Hydrogen evolution is a constant byproduct of all lead–acid batteries and the management of this byproduct is the primary difference between the sealed and vented lead–acid batteries. The less expensive of the two types, vented batteries release this hydrogen into the surrounding environment and require routine maintenance to replenish electrolyte within the cell [38]. For vented batteries, a ventilation system is required so that a fire hazard does not arise due to high hydrogen gas concentration in the environment [39]. While more expensive, VRLA batteries do not require electrolyte to be refilled or a ventilation system for the purpose of hydrogen removal as the generated hydrogen is allowed to recombine with oxygen within the cell and is not expelled into the environment [3,40]. VRLA batteries may be further improved by increasing carbon concentrations within the cathode of the battery. These carbon-enhanced batteries have come to be known as advanced lead–acid batteries, and the chief performance improvement derived from this design is a drastically improved cycle life [12,41].

Regarding thermal performance, the lead–acid battery failure mode in response to elevated temperatures is typically degradation in the performance of the cell [12]. Nonetheless, lead–acid batteries can experience thermal runaway when nearing the end of service life or when subjected to an excessively large float current [29].

For UPS applications, lead–acid batteries are the most common choice as they require little maintenance, have low costs in implementation, and are trusted for safe and reliable operation. The low cycle life characteristic of lead–acid batteries is not as consequential as discharge/recharge cycles are infrequent and, thus, battery degradation due to cycling is not a primary concern [4,42,43]. For ESSs, lead–acid batteries have been disadvantaged due to poor cycle life. However, with the revelation of advanced lead–acid batteries, the technology is a competitive option for BESS implementation with significant market presence, as seen in Figure 1; this is primarily due to low investment cost and its role as a mature and well understood technology [44]. Lastly, it is worth noting that lead–acid batteries are the most readily and efficiently recycled battery technology, which plays a role in the overall sustainability of the energy systems utilizing a BESS [41].



**Figure 1.** Division of US battery energy storage system (BESS) projects by technology with respect to total MW capacity. Electrochemical refers to unspecified technologies [15].

## 2.2. Lithium-Ion

Li-ion batteries, developed in the 1970s, have seen significant development in the past decade with further implementation expected in the coming years. Li-ion batteries offer high round trip energy efficiencies, are durable to frequent cycling, and have high power and energy density [33,45,46]. While the technology is promising, it is currently limited by elevated investment costs and concerns about catastrophic failure modes in thermal runaway [47–49]. Despite these obstacles, Li-ion batteries have surged to become the dominant technology used in transportation and have been instrumental in unlocking the potential of electric vehicles [47].

While lead–acid remains the most prevalent technology in standby power systems, Li-ion batteries are expected to overtake lead–acid technologies in the future as prices decrease and stabilize. Economic analysis has shown that Li-ion technology could be preferable due to decreasing investment costs and increased cycle life; the technology is currently in the early stages of commercialization in application to UPSs, with self-contained UPSs being manufactured for use in data centers [50–53].

Thermal runaway in stationary lithium-ion batteries is a subject of high concern as large Li-ion batteries have high energy density and the surface area (area of convective heat dissipation) of larger cells does not grow in proportion to the increase in power density. In the case of thermal runaway, Li-ion batteries are reputed for catastrophic failure modes, which may include combustion and explosion [27]. Together, the tendency and consequences of thermal runaway in stationary Li-ion batteries have established the requirement for robust thermal management for thermal runaway prevention and the need for backup safety measures in the event of catastrophic failure [52].

In application to energy storage, Li-ion BESS systems have surged in recent years to become the dominant battery technology used in large BESS applications, as seen in Figure 1 [15,54,55]. The expected characteristics of both lead–acid and Li-ion battery technologies in application to a utility scale BESS are presented in Table 1. Note that while Li-ion surpasses lead–acid in all performance characteristics, the initial cost can be up to two- to three-times higher than lead–acid batteries in some cases [56–58]. This high initial cost remains as one of the primary obstacles to the selection/implementation of Li-ion batteries in stationary systems [33]. Nevertheless, in UPS applications dominated by VRLA batteries, Li-ion batteries are fast gaining market share, and as power demands of UPS systems increase, it is expected that Li-ion batteries will become more common [53,59,60].

**Table 1.** Typical battery characteristics in application to a large energy storage system (ESS) [56–58,61].

Battery Type	Energy Density (Wh/kg)	Efficiency -	Usage Life (Years)	Cycles Life (Cycles)	Cost (\$/kWh)
Lead–Acid	30–50	75–85%	2–3	500–1000	120–300
Lithium-Ion	100–250	95% to ~100%	5–6	>1000	200–325

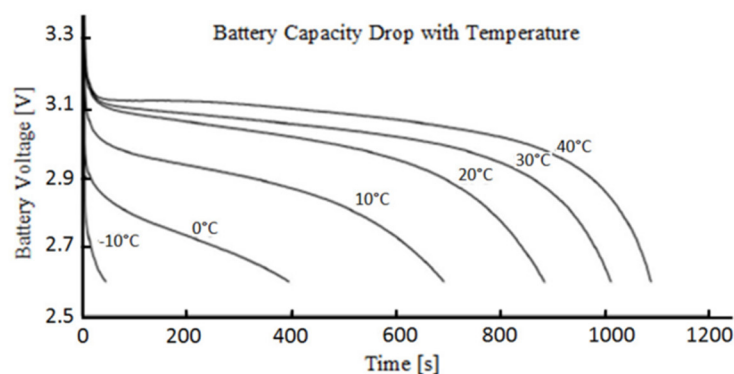
### 3. Battery Heat Generation and Effects

Regardless of the type of battery, heat generation is a common side effect of both charge and discharge cycles in batteries. Uncontrolled heat generation can cause safety concerns and operational failure; yet, even below maximum operating temperature, excessive heat can drastically decrease the service life expectancy of a battery or result in system malfunction [62–64]. Due to adverse effects arising from battery operation at high temperature, a thermal management system for batteries is desired to extend the operational lives of batteries, minimize system maintenance, prevent system failure, and prioritize safety.

The electrochemical reaction as the basis of battery operation is governed by the Arrhenius equation shown in Equation (1). In this equation,  $k$  represents the rate of the electrochemical reaction;  $\lambda$  and  $\Lambda$  are constants corresponding to the ratio of the Boltzmann constant to activation energy and the pre-exponential factor respectively; and  $T$  represents the temperature in Kelvin.

$$k = \Lambda * \exp(-\lambda/T) \quad (1)$$

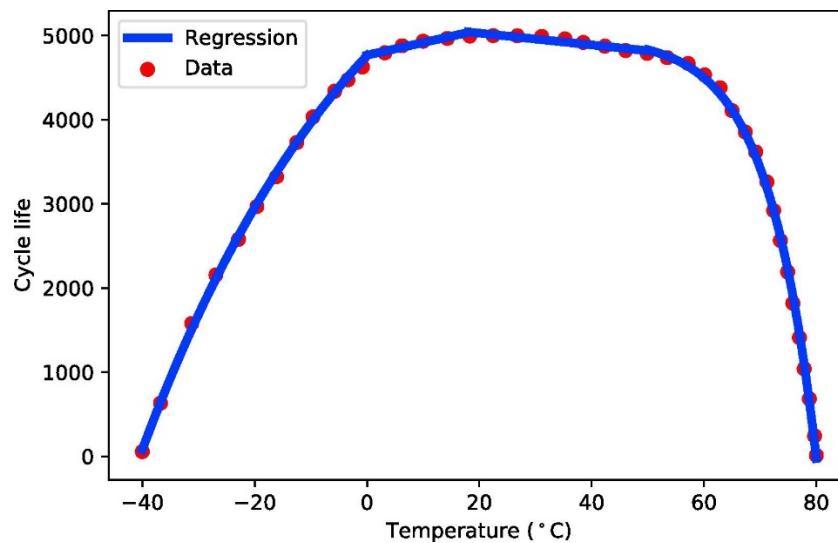
Examining the relationship between these variables, it is apparent that as temperature increases, the rate of the electrochemical reaction increases in response [65]. Effectively, this means that at higher temperatures, the battery will have increased power output, as can be seen in Figure 2. However, accompanying this increase in output are several adverse effects, including battery degradation and accelerated aging. These effects are visually represented in Figure 3, for which the optimal temperature range for a Li-ion ion battery can be seen.



**Figure 2.** Li-ion battery capacity discharge curves dependent on temperature at a steady 3C (Coulombs) discharge rate [66].

As energy is transferred through a battery, a normal side effect is the generation of heat. While at low levels of discharge this heat may be dissipated sufficiently by natural convection, in periods of high power, it becomes necessary to dissipate heat through forced convection to prevent battery degradation. In the event of rapid discharge, batteries generate significant amounts of heat due to the internal resistance of the cell [66]. Known as joule heating, this thermal generation is proportional to the square of the current output of the cell, and as power demands increase, the heat generation will grow rapidly. In addition to discharge heat, float point charge of standby batteries can also contribute to internal heat generation. When fully charged, standby batteries are maintained at a low voltage,

known as float voltage, to compensate for self-discharge over time. While necessary, float voltage has a downside that nearly all the float charge current is converted to heat [18].



**Figure 3.** Li-ion battery cycle life over a range of average operational temperatures [67].

To derive an equation for the overall heat balance of a battery with convective heat dissipation, the first step is to account for joule heating due to internal resistance of the battery during discharge. This can be calculated using Equation (2), in which  $R$  represents the internal resistance of the cell and  $I$  is the current discharge.

$$Q_{res} = I^2 R \quad (2)$$

In discharge, there is also heat generation due to the reversible heating component of entropy change, which can be approximated as seen below in Equation (3).  $Q_{rev}$  represents the reversible heating and is the product of current, battery temperature, and the change in entropy.

$$Q_{rev} = IT_b \frac{dV}{dT} \quad (3)$$

Neglecting conduction to external surfaces and radiation, the primary mode of heat dissipation for batteries is through convection, represented in Equation (4), where the convective heat generation is a product of the convective heat transfer coefficient  $h$ , the surface area of the battery, and the temperature difference between the battery surface and surrounding fluid.

$$Q_{conv} = -hA(T_b - T_a) \quad (4)$$

Summing the resistive heating, reversible heat generation, and the convective heat dissipation derived in Equations (2)–(4), the overall heat balance equation for batteries experiencing convective cooling can be derived as shown Equation (5) [68], in which  $m$ ,  $C_p$ , and  $\Delta T$  represent the mass, specific heat, and temperature change, respectively.

$$mC_p\Delta T = Q_{res} + Q_{rev} + Q_{cov} \quad (5)$$

Equation (5) represents a reduced thermal balance equation from the total thermal model as seen in Figure 4. The model has been reduced by assuming other terms of heat generation and dissipation to be negligible in comparison to the three included in Equation (5).



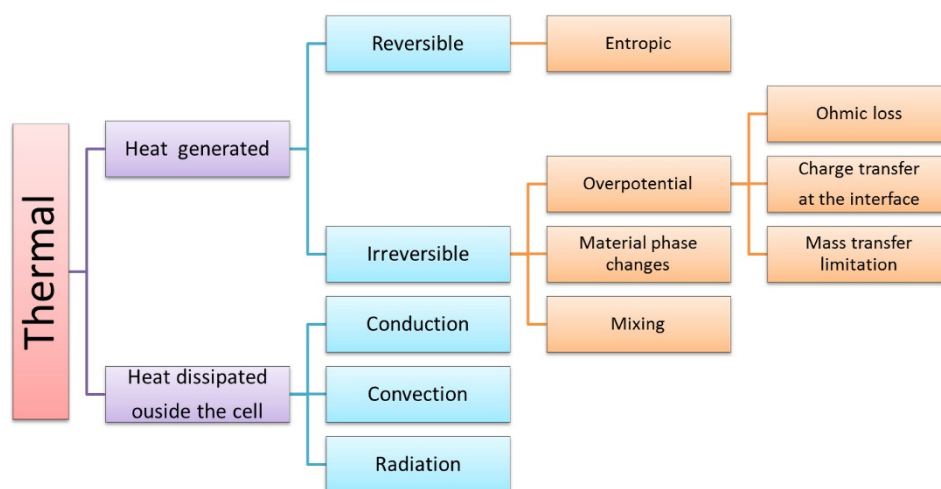


Figure 4. Comprehensive thermal model for a lithium-ion battery [69].

Examining battery life efficiency, a primary contributor to cell performance degradation is operation at high temperatures [35]. At temperatures above 50 °C, batteries experience a range of deleterious effects: self-discharge, voltage drop, reduction in energy capacity, and malfunction. In assessing battery aging, a primary factor is the average operational temperature of the battery [70]. Generally, lead–acid batteries see a 50% reduction in operation life for each 10 °C increase in average operating temperature above the recommended operating temp [18,51]. For Li-ion batteries, this 50% reduction in life occurs for a 15 °C increase above the rated operating temperature [71,72]. Thus, thermal management is essential to maintaining batteries as they generate heat or experience elevated temperatures due to environmental effects.

While lead–acid batteries remain the industry standard for standby batteries, they must be kept within a temperature range of 20–25 °C to prevent steep operational life reductions and prevent thermal runaway. In hot climates, keeping stationary batteries within operational temperatures of 20–25 °C can be especially burdensome as outside air must be cooled before being distributed to batteries. In response, there has been interest in the use of battery technologies better suited to increased operational temperatures. Nickel–cadmium and lithium-based batteries also show decreased operational life at temperatures near 35 °C; however, this effect is much less pronounced in comparison to lead–acid batteries [71]. The cost analysis depends on battery technology, outdoor environmental temperature, electricity cost, and a range of other factors. Research is ongoing, yet preliminary analysis shows that under suitable conditions (primarily hot climates), alternative battery technologies operating under increased temperatures are a viable option for reducing power consumption and extending battery life [53,73,74].

In the event that battery heat generation exceeds the rate of dissipation, the increase in temperature leads to a further increase in current and temperature, thus resulting in a positive feedback loop in which there is uncontrolled current and temperature increase. This phenomenon is known as thermal runaway and could result in failure, melting, or combustion of the battery [40,75]. While this phenomenon could be seen in any battery, large cells such as those used in stationary battery systems are especially susceptible to thermal runaway because the surface area of the battery does not increase at a comparable rate to the capacity of the battery in the design of large cells [68]. Furthermore, Li-ion cells contain flammable materials and are notable for susceptibility to thermal runaway, thus making the phenomenon of special importance to the thermal management of Li-ion systems.

An additional factor to account for in the thermal management of stationary battery systems is prevention of temperature differences between batteries. According to IEEE standards, stationary batteries connected in series should not exceed more than 3 °C in temperature differential. Temperature differences between batteries results in reduced battery life spans and increased risk of failure. For an

individual battery, it is also important to avoid spot cooling as a temperature gradient over a single cell could lead to the battery becoming electrically imbalanced and malfunctioning [40,75,76].

#### 4. Discussion of Thermal Management

While the necessity of thermal management for stationary batteries is clear, there is currently a clear lack of research on methods for stationary battery thermal management (BTM). According to the IEEE/ASHRAE guide for thermal management of stationary batteries, the objectives of the thermal management systems are to optimize battery performance within budgetary constraints and to provide maximum safety [40,54,75,77]. The research and development of new cooling methods is ongoing, with passive and free cooling, forced air, liquid cooling, phase change materials, and other methods being investigated [71,78–80]. However, the vast majority of efforts in developing novel battery thermal management are directed for application in electric vehicle battery packs [81–83]. Despite the wide array of options, passive air cooling systems remain the standard for all battery cooling in data centers, and the only option addressed in IEEE/ASHRAE standards recommend a bulk cooling approach tailored towards the thermal management of room/enclosure rather than the individual batteries [40,75].

##### 4.1. Air BTM Systems

Air cooling systems have several benefits that make them the preferred method of battery thermal management. As an established technology, ventilation systems are understood, inexpensive to install and maintain, and reliable. Air cooling also is notable for its uniform heat dissipation, preventing temperature differentials between batteries or spot cooling single locations [84]. An additional benefit of ventilation is that hazards from battery hydrogen gas evolution are avoided as air is mixed or expelled into the environment [39]. Given the benefits and low costs, air cooling has been the preferred method of BTM for stationary batteries [85]. Several basic configurations for air cooling systems are shown in Figure 5. Research has shown free and advanced passive cooling systems to be highly efficient by reducing the energy that must be provided by a refrigeration cycle or fan [78,79,86]. However, this practice is dependent on favorable outdoor environmental conditions and requires a controls system. Comparing cooling methods, generally, air cooling is preferable to liquid cooling for stationary batteries. While liquid cooling systems offer better cooling performance, they are often more expensive, complex, and susceptible to malfunction [84,87,88].

Currently, the general approach taken to battery thermal management is bulk room ventilation as shown in schematic (b) of Figure 5. Direct air cooling is discouraged in systems without proper design as it can result in temperature imbalances between batteries or spot cooling [89]. In 2001, a survey of utility and telecoms lead–acid battery installations reported that only half of the installations use some type thermal control method and only 30% monitor installation temperature. The use of stationary battery installations in southern climates was also limited, and thermal management concerns are speculated as a driving factor behind this trend [90]. Batteries are often stored in an enclosure and, while convenient for being centralized and safely contained, this demands especially robust thermal management to limit high temperatures [91,92].

Adaptive thermal management of stationary batteries, while common in application to portable batteries, shows promise in extending battery life while simultaneously decreasing energy by only providing cooling when required [93–95]. Systems of this type are reliant on accurate battery state measurements with frequent sampling rates in order to provide cooling in response to heat generation. In practice, the only battery states that are available to continuously measure for a sealed cell are voltage, current, and battery surface temperature [11,24,84,96]. This presents a problem in that the first two parameters do not directly correlate to heat production and predictive models may shift as batteries age. While surface temperature may seem to be the obvious characteristic to measure, the core of a battery can have a significantly higher temperature or spot cooling may occur in specific locations on the cell [96]. Nonetheless, when implemented correctly, adaptive cooling provides a



means to improve battery life and decrease energy usage for large thermal management systems. Despite these advantages, little information was found during this review pertaining to the prevalence of implementation of adaptive cooling to stationary batteries.

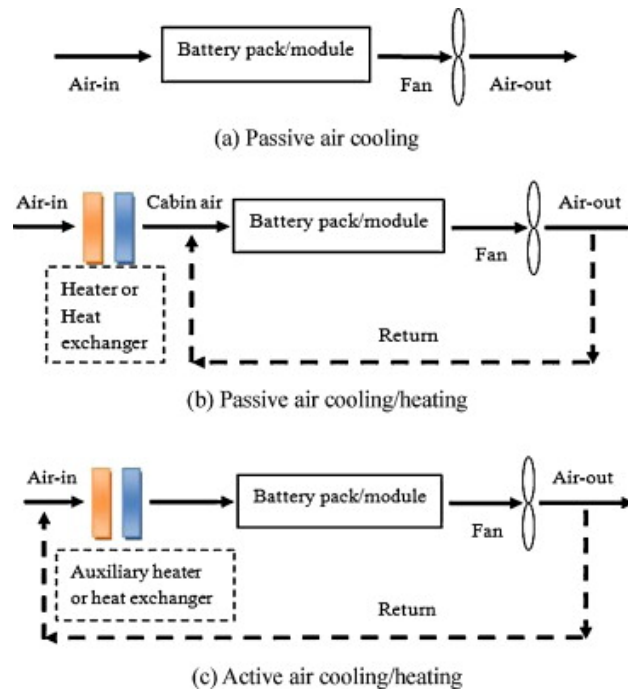


Figure 5. Basic battery pack air cooling schematics [35].

#### 4.2. Alternative Stationary BTM Systems

Despite being a common method of BTM for electric vehicles, liquid battery cooling systems have seen little development in application to stationary systems. Liquid systems have been demonstrated to be highly effective in heat dissipation by utilizing pumped coolant (as shown in Figure 6) to effectively increase the convective heat transfer coefficient and thus total convective heat dissipation. In electric vehicles where rapid discharge and high heat generation is a common operational characteristic, liquid convection BTM is the most popular method of thermal management and has been successfully implemented in many commercially available electric vehicles to provide effective cooling [81,82,85]. Despite the high performance of liquid BTM, there are drawbacks in the form of increased system complexity, maintenance, cost, and the potential for leaks [47,97,98].

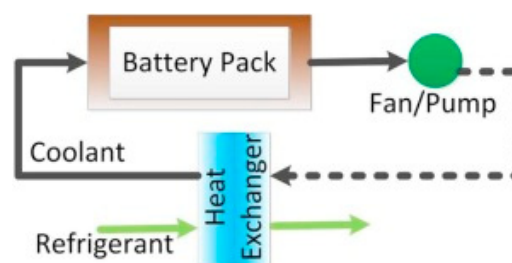


Figure 6. Basic schematic of a liquid battery cooling system [98].

An emerging competitor, phase change material (PCM) BTM systems use the heat absorbed in the phase change process of a substance to maintain batteries a constant temperature [85,99]. One of the most attractive characteristics of PCM systems is the ability to work passively so that input energy is not required in operation [100]. Drawbacks of PCM BTM include added weight and volume for the

material. PCM may also be limited in cases of extreme heat generation as low thermal diffusivity of the phase change material may limit the response time of heat transfer. In the case of continual cycling and heat generation, absorbed heat must ultimately be removed from the PCM, thus potentially requiring a supplementary cooling system [101]. There are also concerns involving the thermomechanical behaviors of many common PCMs, and research regarding material selection and system design must be done before commercialization [35,47]. Again, most research has been done with the intended application to mobile battery systems and further research needs to be done to assess the viability of PCM BTM strategies to high capacity stationary batteries.

#### 4.3. EV BTM Systems

Initially recognized as a major barrier to electric vehicle (EV) viability and a safety hazard, BTM for Li-ion batteries has been the subject of extensive research and development. With high discharge rates, heat generation, and limited space, EV BTM solutions have successfully employed novel methods and technologies in commercialized systems [62,102]. For example, direct air cooling as a means of heat dissipation is often avoided for stationary batteries, and yet this method has been applied to EV battery packs with great success. Liquid cooling systems have also been employed effectively in several commercially available EVs. It is worth noting that the operational characteristics of EV batteries differ from stationary batteries in that there are strict limitations of available space and very high heat generation rates which demand robust thermal management. However, this does not rule out the potential transfer of EV BTM research to stationary applications and could potentially serve as a basis of improvement for the sector. In fact, the juxtaposition of advancements in EV BTM with the stagnation of stationary BTM provides evidence that there is significant room for improvement within the stationary battery sector.

### 5. Conclusions

In modern stationary battery systems, the generation of heat resulting in deleterious effects and potential dangers due to mismanagement are understood phenomena. While air cooling is the standard method of stationary BTM, comprehensive research into the optimization and efficacy of this method was found to be absent from scientific literature. In particular, research contrasting active and passive air cooling efficiency and comparative lifetime cost analysis are missing from academic literature despite both methods currently being in use. Future research into active air cooling and the development of technical standards could potentially yield benefits in the form of more effective cooling systems without greatly increasing complexity or equipment costs.

In addition to reviewing the currently applied thermal management methods, examining novel thermal management technologies, such as liquid cooling or phase change materials, is worthwhile to assess their viability for stationary applications. For this purpose, the considerable progress made in EV BTM may serve as a basis for the development of stationary BTM systems. Liquid cooling has been shown to be highly effective in the high-power applications of electric vehicles, however, the development of stationary scale liquid cooling systems and assessment of economic viability has yet to be performed.

There has been a significant increase in the number and scale of stationary battery installations in the past decade. As stationary battery installations pivot towards high power density Li-ion batteries, the need for more robust cooling systems that keep pace with the increased heat generation to avoid battery degradation and prevent catastrophic failure becomes apparent. To this end, a comparative assessment of currently employed methods of stationary BTM is required, and the potential adaptation of EV BTM technologies should be investigated.

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