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*A Review*

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Review

# Towards an Ultimate Battery Thermal Management System: A Review

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**Abstract:** The prevailing standards and scientific literature offer a wide range of options for the construction of a battery thermal management system (BTMS). The design of an innovative yet well-functioning BTMS requires strict supervision, quality audit and continuous improvement of the whole process. It must address all the current quality and safety (Q&S) standards. In this review article, an effective battery thermal management is sought considering the existing battery Q&S standards and scientific literature. The article contains a broad overview of the current existing standards and literature on a generic compliant BTMS. The aim is to assist in the design of a novel compatible BTMS. Additionally, the article delivers a set of recommendations to make an effective BTMS.

**Keywords:** battery thermal management system (BTMS); battery management systems (BMSs); thermal imaging; calorimetry; isothermal calorimeter; batteries; quality and safety (Q&S) standards; Li-ion batteries

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## 1. Introduction

The main barriers to the deployment of large fleets of vehicles on public roads equipped with lithium-ion batteries continue to be safety, costs related to cycle and calendar life, and performance. These challenges are coupled with thermal effects in the battery, including capacity/power fade, thermal runaway, electrical imbalance among multiple cells in a battery pack, and low-temperature performance [1,2]. Ideally, most batteries are expected to operate at an optimum average temperature with a very narrow differential range [3,4]. While designing a battery cell, pack, or system, the rate of heat dissipation must be fast enough so that the battery never reaches the thermal runaway temperature. The event of reaching the thermal runaway temperature triggers the commencement of the irreversible decomposition of battery composition, i.e., electrolyte and electrodes are damaged. Generally, those decomposition reactions are exothermic (heat producing). It implies that the temperature increases more and more once the thermal runaway temperature is reached. It irreversibly triggers a chain reaction of self-heating and ultimately the destruction of the cell [5].

Temperature excursions and non-uniformity of the temperature of the battery cell are the main concerns and drawbacks for different applications. The thermodynamics of lithium-ion cells are complicated by the presence of liquid electrolyte mixtures as well as single-phase and multiphase solids. Heat generation may result from mixing and phase change, as well as the main electrochemical reactions [6–11]. Reliable prediction of temperature profiles of individual cells, and of a battery system, requires first of all accurate measurement level of the total heat-generation rate. Thus, measurements of temperature rise and the heat dissipation or absorption of battery cells are essential.

In general, temperature affects several aspects of a battery including the operation of the electrochemical system, round-trip efficiency, charge acceptance, power and energy capability,

reliability, life and lifecycle cost. Although the capacity increases as the operating temperature is raised, the degree of capacity fade also increases. On the other hand, poor performance is observed at low operating temperature [12,13]. In addition, excessive or uneven temperature rise in a system or pack reduces its lifecycle significantly [14]. The high temperature during charge and discharge will lead to the possibility that temperatures will exceed permissible levels, consequently decreasing the battery performance. Furthermore, the uneven temperature distribution in the battery pack will lead to a localized deterioration. Therefore, temperature uniformity, within a cell and from cell to cell, is important for achieving maximum lifecycle of cells, packs, and battery systems.

The employed heating and cooling method could create an uneven temperature distribution inside the battery pack, depending on the location of each stack or system, and external ambient conditions [15–19]. This uneven temperature in the cells could trigger an uneven temperature distribution in the pack. Thus, the pack could lead to an unbalanced system. It restricts the optimum performance. Additionally, the lifetime of the battery pack is reduced. Accordingly, it reduces the operational lifetime of the application of the pack that it is designed for, e.g., electrical vehicles (EV). Depending on the electrochemistry and working temperature, each kind of cell works better or worse depending on its specific circumstances and working temperature. Therefore, in order to keep the temperature within the pack's narrow range level, a battery thermal management system (BTMS) plays a vital role [20,21].

Heat is generated and released from the cell during both charge and discharge. If the heat generated in the cell/pack is not removed efficiently, then it is stored, raising the temperature of the cell/pack and the total battery system [22]. The magnitude of the overall heat-generation rate from a battery pack under load dictates the size and design of the cooling system [23]. Different kinds of Li-ion batteries have different characteristic values; for instance, battery heat flux measurement represents the heat generated inside the cell. A thermal management strategy requires that these data be measured accurately [24,25] to design a proper BTMS.

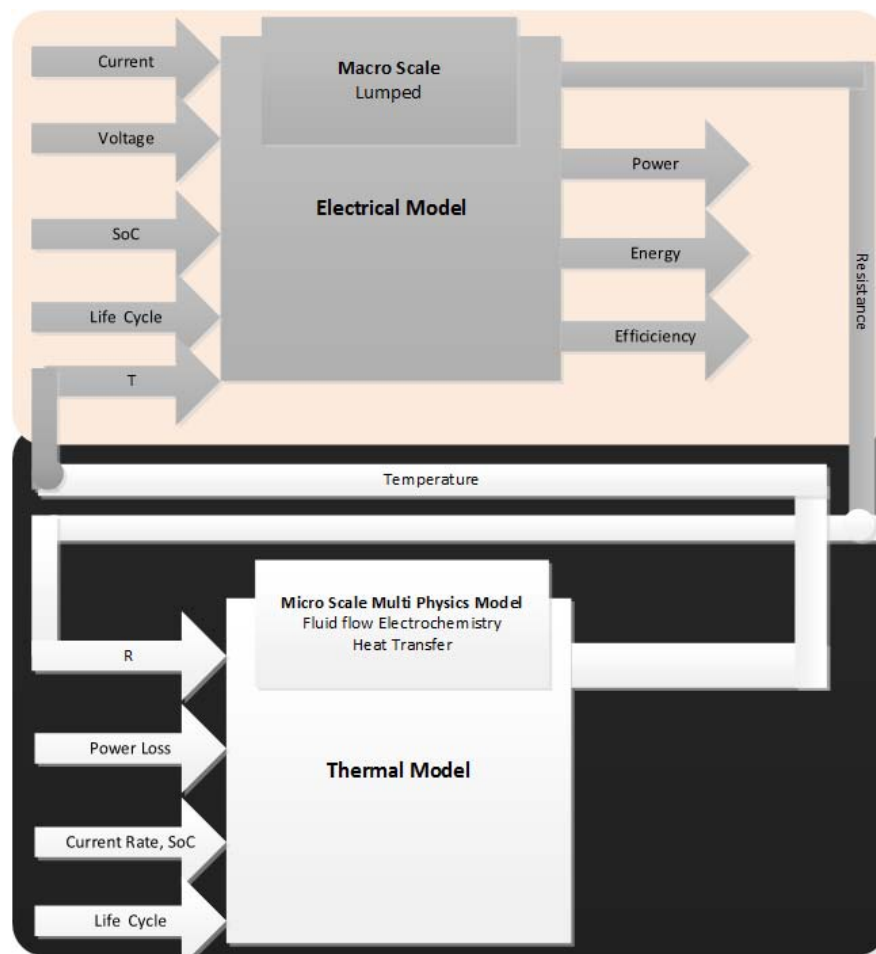
Figure 1 presents a generic battery thermal management system (BTMS).



Figure 1. Battery thermal management system (BTMS).

This article aims to define the physical design, construction and material requirements of BTMS for anticipated application. Those are required to qualify properly a BTMS inside a battery system irrespective of chemistries for the particular applications [26]. The usages of standardized procedures from reputable organizations allow this article to present a fair and impartial comparison of thermal management for battery pack design. It is intended to improve safety and performance. This article is written to provide a common framework of BTMS manufacture and design to evaluate the options of different BTMSs applicable for various operating conditions. Nevertheless, those that operate near the ambient temperatures can also benefit from the existence of BTMS [27,28]. It must be noted that there

exists several available studies reviewing these models [29–34]. Since modelling is out of the scope of the article, the details are deliberately avoided. Figure 2 in the following represents the generic schematics of BTMS modelling.



**Figure 2.** Electrical and thermal model coupling [35].

The structure of the article is arranged as follows. Section 2 gives a general overview concerning the expected characteristics and requirements of a generic BTMS originating from current standards as well as the generic thermal requirements of a battery system. Section 3 analyses specifically quality and safety standards. Section 4 provides the accessory level composition and required interfaces. Section 5 provides some recommendations and suggestions stemming from different standards and research studies. Section 6 provides the conclusion of the article.

## 2. Expected Characteristics and Requirements of a Battery Thermal Management System (BTMS)

The BTMS is an important and integral part of a battery management system (BMS) [36–38]. BTMS is comprised of a combination of hardware and software. It is used fundamentally to preserve the temperature of battery cells in a pack at an optimal range [39–43]. It helps to enhance the lifetime while ensuring safe and secure operation of the battery pack [44–47]. It is therefore inevitable that BTMS is typically associated with the process of retaining the operational temperature at an optimal level through keeping the temperature gradient within a relatively narrow range [48]. The BTMS must be designed to suit automotive criteria, which include [49,50]: being lightweight, easily packaged in the desired application—for example, EVs—and they must be compact, reliable, cost-effective, easy to assembly and placed in an appropriate position [51–53].

Depending on the operating and ambient conditions, the employed method inside BTMS can either be employed for cooling, heating or insulating. A traditional BTMS includes air as the medium, and an electric blower or fan to mobilize it. On the other hand, liquid BTMSs include water, glycol, oil, acetone, refrigerants, and Phase Change Material (PCM) thermal management systems. In order to ensure uniform and adequate cooling, the BTMS is composed of controller and associated controller algorithm adjusting for different cells' temperatures and operation statuses.

Depending on electrochemical-physical characteristics and corresponding reactions, the optimum operating range of different batteries will differ. The optimum range for most general batteries requires operating near room temperature (15–35 °C) [54,55]. By keeping the temperature within a narrow optimum level, it helps to lengthen the battery pack lifetime. Since the performance of a battery pack depends on the performance of individual cells, the cooling scheme should be activated when the battery is exposed to the high rate of charge and discharge [56]. Moreover, depending on altitude and geographical condition, the operation of BTMS varies.

Thermal insulation is needed in case of reducing the heat loss from high temperature either during the desired application's operation and stand-by. Battery pack thermal management and control could be achieved by air or liquid systems [57–59], active or passive approaches. Increasing the insulation thickness was suggested for slowing the rate of temperature increase while parking in the summertime, although this also appears to be similarly beneficial for winter operations [60,61]. Figure 3 illustrates a generic BTMS structure [62,63].

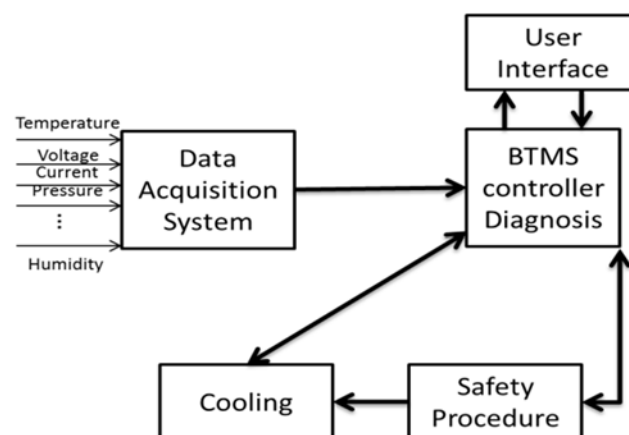
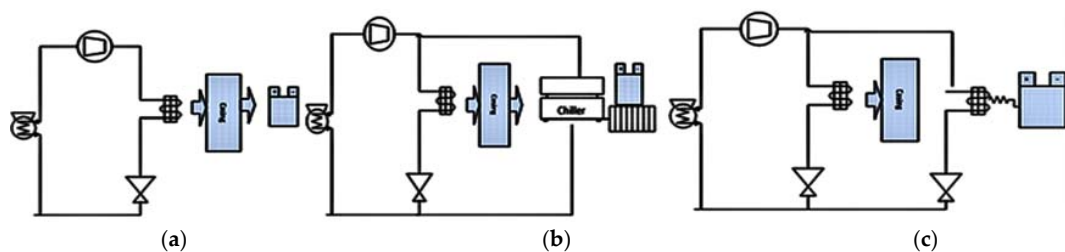


Figure 3. A generic view of the composition of BTMSs [37].

A generic BTMS is made up of cooling, heating and insulation components. The intensity, direction of cooling and heating will depend on the application requirement to maintain the temperature at a uniform range. A provision must be made for ventilation if the battery generates potentially hazardous gasses [64]. In order to extend low-temperature operability where it may be of concern, a heating system may be equipped as a part of a BTMS. The battery must be heated rapidly after a cold start-up. Another way to deliver the heat may be through heating the battery coolant by means of heat exchangers with the engine coolant. There would be a delay in the initiation of heating as the engine gradually warms up. Therefore, electric heating is responsible for raising battery temperature from cool ambient temperature to the desired temperature before the system start-up. Upon start-up, the BTMS should be able to verify that all sensors and actuators, such as contactors, fans, and pumps, are responding correctly. Also, individual modules that determine the state of charge [65], state of health, wiring corrosion, sensor or contactor failures are performing appropriately [20]. In the periphery of thermal management systems, it is important to be aware that there should be no hazard caused by ignition sources, leakage currents, electrolyte flooding, etc. Figure 4 and Table 1 present a generic comparison among the air, liquid and refrigerant cooling systems.

**Table 1.** Comparison between different cooling schemes in traditional BTMSs [66]. HEV: Hybrid electric vehicle; and PHEV: Plug-in Hybrid Electric Vehicles.

Cooling Scheme	Description	Application	Nominal Temperature Difference Allowed Between the Cells
Air	-Both cooling and heating is feasible; -Good performance; -Normally large space needed; -Cheapest; -Lower development effort is needed.	Application is limited but in most cases sufficient for HEV/48V/12V applications	Temperature difference between air and cells can be > than 15 °C limitation
Liquid	-Lowest temperature gradients; -Cooling and heating is feasible; -Best performance.	Liquid cooling can be found in EV, PHEV, HEV, 48V batteries	Cooling plate 1–3 °C
Refrigerant	-“Aggressive” cooling due to very low cooler temperatures. Intelligent thermal management and specific pack design needed to avoid a too-aggressive cooling and condensation of humidity.	HEV, 48V batteries	Cooling plate 3–8 °C



**Figure 4.** (a) Air cooling; (b) liquid and (c) refrigerant cooling [65].

The following Table 2 corresponds different aspects of a generic BTMS.

**Table 2.** Different aspects of a battery thermal system.

Attribute	Sub-Attribute	Description
Safety	Required elements	Heater system components
	Requirement	All heater system components, except the connector terminals to the external heater power supply, shall be electrically insulated and installed in a manner which minimizes potential battery damage due to electrical shorting, sparking, or other electrical hazards and which minimizes potential damage to the insulation of the heater system components. They should meet the required size and space constraints.
	Protection Schemes	All heater control devices shall be sealed in a manner which prevents, during their operation, the ignition of explosive gas mixtures which may occur within the battery [26,67].
	Positioning	For safety, the positioning of heating elements shall be such as to minimize thermal gradients within the battery [68].
Physical or mechanical performance	Required elements	Draft system and other accessories used in the thermal management.
	Requirements	Any restrictive system used in the application should not obstruct the normal electrical operation or ventilation of the module through both physical and electrical obstacles.
	Special Arrangement	The retention system should not hinder the airflow around the battery system for well-functioning thermal management or ventilation of the entire battery system [20].
Durability	Required elements	Battery systems and components.
	Requirements	Those should endure the application shock effects like vibration of the desired application e.g., engine, shock induced by component installation, in use operation or crash.
	Cause	Battery packs may be exposed to the vulnerable position like the underside of the vehicle, which could result in ground contact or other impacts such as road debris [20,69–71].
	Action	In order to ensure the reliability, the maximum heat output of the system shall not damage battery components with which it is in contact.

Table 2. Cont.

Attribute	Sub-Attribute	Description
Ripple current	Required elements	Charging systems of a battery.
	Requirements	The charging current is not applied to alternative current of over 50 kHz ripple frequency since lithium-ion batteries do not respond to such effects [8].
	Cause	Since the ripple charging current frequency is one of the reasons for heating up of the battery system suitable range as stipulated by the standard is to be used.
Accuracy of measuring instruments	Required elements	Available sensors for voltage, current, temperature and time counting.
	Requirements	In the available sensors, the overall accuracy of controlled or measured values when conducting testing in accordance with this standard:
	Tolerances	0.1% for voltage; 1% for current; 2 °C (3.6 °F) for temperature; 0.1% for time; 1% for dimension. The accuracy of the measuring instruments shall follow the relevant requirements of the applicable standards listed [9].
Materials for fire resistance	Required elements	The materials those are used in a different battery and corresponding BTMS accessories, battery casings or enclosures.
	Requirements	Those should be non-flammable or flame-retardant in accordance with applicable standards. The quantity of combustible materials in the containment system should be documented and considered as part of the area fire loading [72]. The BTMS shall be made from an insulating material that remains resistant to the foreseeable abuse operating conditions.
	Special	The cell container utilized in lead acid batteries shall be made of non-porous, acid-resistant material, such as polypropylene, polystyrene and polycarbonate.

### 3. Quality and Safety Standards

To ensure that the battery thermal management's quality is consistent over its whole lifetime, some quality aspects need to be monitored [73]. Thus, broadly speaking, the target is not only to achieve the best performance but also to retain a certain quality standard spanning from the beginning of life (BoL) to end of life (EoL) of the battery application [37,68–70,74,75].

Table 3 contains important existing standards regarding BTMS.

Table 3. Existing standards regarding BTMS.

Short Name	Title	Battery	Working Group Year	Reference
IEC 62660-2	Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 2: Reliability and abuse testing.	Li-ion	IEC International Electrotechnical Committee IEC (2010)	[71]
IEC 60952-2	Aircraft batteries—Part 2: Design and construction requirements.	Li-ion PbAc	IEC (2013)	[26]
IEC 61427-1	Secondary cells and batteries for renewable energy storage—General requirements and methods of test—Part 1: Photovoltaic off-grid application.	Li-ion PbAc	IEC (2013)	[72]
IEC 61960 Edition 2.0	Secondary cells and batteries containing alkaline or other non-acid electrolytes—Secondary lithium cells and batteries for portable applications.	Li-ion	IEC (2011)	[76]
IEC 62133 Edition 2.0	Secondary cells and batteries containing alkaline or other non-acid electrolytes; Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications.	alkaline or other non-acid electrolytes	IEC (2012)	[77]
IEEE Standard 1187-1996	IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries for Stationary Applications.	Li-ion PbAc	Institute of Electrical and Electronics Engineers IEEE (1996)	[48]
IEEE Standard 1375-1998	IEEE Guide for the Protection of Stationary Battery Systems.	Li-ion PbAc	IEEE (1998)	[54]

Table 3. Cont.

Short Name	Title	Battery	Working Group Year	Reference
IEEE Standard 1578-2007	IEEE Recommended Practice for Stationary Battery Electrolyte Spill Containment and Management.	Li-ion PbAc	IEEE (2007)	[78]
IEC 60664-1 Edition 2.0	Insulation coordination for equipment within low-voltage systems—Part 1: Principles, requirements and tests.	Li-ion PbAc	IEC (2007)	[79]
IEC 62485-2 Edition 1.0	Safety requirements for secondary batteries and battery installations—Part 2: Stationary batteries	Li-ion PbAc	IEC (2010)	[80]
IEC 60896-11 Edition 1.0	Stationary lead-acid batteries—Part 11: Vented types; General requirements and methods of tests.	PbAc	IEC (2002)	[22]
IEC 60896-21 Edition 1.0	Stationary lead-acid batteries—Part 21: Valve-regulated types—Methods of test	PbAc	IEC (2004)	[81]
IEC 62485-3 Edition 1.0	Safety requirements for secondary batteries and battery installations—Part 3: Traction batteries.	Li-ion PbAc	IEC (2010)	[82]
SAE J2464	EV and HEV Rechargeable Energy Storage System (RESS) Safety and Abuse Testing Procedure.	Li-ion PbAc	International automotive standardization SAE (2010)	[83]
SAE J 2289	Electric Drive Battery Pack System Functional Guidelines (Revised 2008)	Li-ion	SAE (2008)	[20]
SAE J 2929	Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-Based Rechargeable Cells.	Li-ion	SAE (2008)	[15]

### 3.1. Quality

The interested stakeholders need to prepare and implement a quality plan that outlines the audit practices. They should ensure periodical inspection of the system that contains cell materials, components and covers the whole process of producing a battery system that includes BTMS. The stakeholder should identify and must have a knowledge of the process capabilities as well as include and adapt the necessary process controls regarding the corresponding battery pack safety and quality [77].

### 3.2. General Quality Test Features and Rules

BTMS manufacturer needs to supply the relevant technical documentation. The battery units shall function per the recommended practice. In the case of occurrence of the significant change in a definite design feature, material and/or process relevant quality inspection should be arranged [84] to ensure that the altered BTMS system complies with the existing safety, performance and/or durability requirements for the specified application. Moreover, each configuration and its performance shall be documented with photographs (if necessary) [85]. The shape, size and construction details and the maximum temperature reached of the inter-cell connectors during the corresponding test shall be reported [85]. In mission-critical installations (uninterruptible power supply (UPS) battery service) the knowledge of the temperature reached under actual discharge conditions is essential to determine whether potential hazards exist [81,86,87].

### 3.3. Safety

Safety is of prime importance for using BTMSs. Safety concerns include safeguarding against fire, explosion, and the corrosive nature of the electrolyte, as well as the venting of toxic or flammable gases [48,85,88–98]. All auxiliary equipment such as thermal sensors, thermostats, heaters and switching devices must be designed so that they cannot be the source of an explosion. The current-carrying components of the battery units should be dimensioned and constructed appropriately to provide safety against external short-circuit conditions. Cells and battery systems are



to be designed and constructed robustly by ensuring they are safe under conditions of both intended use and reasonably foreseeable misuse [26,99]. In unlikely and unfortunate conditions, an internal short-circuit occurs, and thermal runaway can thus occur more easily, e.g., when the battery is charged under incorrect conditions [24,86,100–111]. Consequently, the lithium-ion secondary battery should never be charged at a higher voltage than this recommended upper limit charging voltage [77]. In some secondary cells, a different recommended temperature range other than 10–45 °C is applied due to the difference in thermal stability of the electrolyte and other thermal and electrical factors [109,112–114].

### 3.4. Protection Schemes

A number of protection schemes are needed to be employed for smooth and safe operation of the battery systems with a BTMS.

Table 4 contains a protection list for BTMSs.

**Table 4.** BTMS protection schemes.

Schemes	Attributes	Description	Reference
Protective equipment	Usage	The use of CO <sub>2</sub> fire extinguishers need to be avoided since some battery manufacturers prohibit their usage due to the increased probability of potential thermal shock.	[82]
	Placement of Battery	Storage of the battery casing should be in a clean, dry, and ventilated location.	
	Illumination	Adequate space and illumination for inspection, maintenance, testing, and cell/battery replacement must be provided.	
Protective measures against electrolyte hazard	Applicable equipment	The materials used in different battery and corresponding BTMS accessories, battery casings or enclosures, inside the battery materials.	[15]
	Requirement	Must be resistant to or protected against the chemical effects of the electrolyte measurement tools, such as funnels, hydrometers, thermometers that normally encounter electrolytes (in PbAc).	
	Additional requirement	Shall not be used for other purposes.	
Protective measures during maintenance	Applicable equipment	Batteries with BTMS shall not be connected or disconnected before the load or charging current has been switched off.	[82]
Protection against the harmful effects of accidental electrolyte leakage and spillage	Applicable equipment	The battery casings, trays, crates and compartments.	[80,82]
	Requirement	It should be protected against the harmful effects of accidental electrolyte leakage and spillage.	
	Accommodation requirements	<ul style="list-style-type: none"> <li>• Protection from external hazard, e.g., fire, water, shock, vibration, vermin;</li> <li>• Protection from hazards generated by the battery, e.g., high voltage, explosion hazards, electrolyte hazards, corrosion and ground short effects;</li> <li>• Protection from access by unauthorized personnel;</li> <li>• Protection from extreme environmental influences e.g., temperature, humidity, possible contamination.</li> </ul>	
Protection against hazardous gas	Cause	Under particularly stark catastrophic situations, lithium-based secondary cells can release gases (e.g., carbon monoxide (CO) and hydrogen fluoride (HF), organic electrolyte vapours, methane, and ethane or hydrogen gas, etc.) that are detrimental to humans in adequate concentrations or may be flammable in the air if adequate concentrations are present.	[79,92]
	Requirements	Preventing build-up of these gases become a priority. Therefore, a safety distance of a minimum of 0.5 m extending through the air without flames, sparks, arcs or glowing devices (maximum surface temperature 300 °C) is required. The dispersion of explosive gas depends on the gas release rate and the ventilation close to the source of release.	
	Safety distance calculation	Calculation of the safety distance from the source of release applies assuming a hemispherical dispersal of gas can be calculated.	

Table 4. Cont.

Schemes	Attributes	Description	Reference
Protection against exposure to water and other chemical fluids	Applicable equipment	The components of battery pack systems.	
	Requirements	It should be specified for resistance to normal application fluids, e.g., automotive fluids. Among these are: gasoline, diesel fuel, antifreeze, transmission fluids, brake fluid, windshield fluid, battery electrolyte, salt water, and carwash soap.	[20]
	Special care	A battery system may be exposed to water which raises concern for electrical tracking, water intrusion, seal performance, and mud build-up which could result in obstruction to air-cooling orifices or hydrogen build-up during charging.	
Protection against overcharging under faulty conditions	Applicable equipment	For faulty conditions (e.g., connection of faulty charger) when the battery system produces more hazardous gases than the normal ventilation system has been designed to handle.	
	Requirements	In these cases, protective measures should be taken so that thermal runaway conditions are avoided in case of high current charging and increase of thermal gradient; an electrical isolating fuse can be employed to disconnect the battery. Alternatively, the ventilation should be calculated to correspond to the maximum current available from the charger.	[16,115]

#### 4. State-of-the-Art Tools for Battery Thermal Management

Thermal imaging and calorimetric techniques with the help of the state-of-the-art measuring equipment are required. Integrated implementation is required to provide valuable information about cell and component thermal-related properties, behavior, and characteristics [116].

##### 4.1. Thermal Imaging

Table 5 presents different possible tools that can be used by imaging for measuring battery performance.

Table 5. Tools used for imaging battery thermal performance.

Features	IR	Liquid Crystal (LC) Thermography
Introduction	It is used to obtain a thermal fingerprint of the surface of any object. The IR technique is excellent for obtaining real-time, thermal images from a non-enclosed battery pack or system.	Liquid crystals with appropriate color/temperature range are applied to an object's surface. Thermo-chromic liquid crystals (TLCs) are a class of materials that reflect definite colors at specific temperatures and viewing angles. By using TLCs together with solid-state cameras, image digitizers, and higher-speed computer processors, a liquid-crystal thermography system can be built that makes fast, accurate, high-resolution surface-temperature measurements for locating hot spots and defects on batteries [117].
Sensor types	It is used to obtain a thermal fingerprint of the surface of any object.	With either video or still photography, it is possible to capture thermal images of the liquid crystals [117].
Resolution	Around 0.2 °C (vivid and dramatic colors).	Around 1 °C. With special optical equipment, the resolution can be around 0.40 °C.
Mechanism	The IR equipment converts the energy back to temperature for finding hot spots or temperature distribution on the surface of an object without using any intrusive temperature sensors.	A liquid crystal changes color depending on its temperature; By applying a very thin layer, the object's thermal performance does not change, but as the object's temperature changes, so do the color of the liquid crystal layer; If the color-temperature relation is calibrated, the temperature variation from the color changes can be determined.

Table 5. Cont.

Features	IR	Liquid Crystal (LC) Thermography
Advantages	Wider temperature range, higher accuracy, and more vivid colors.	LC thermography does not need special equipment and is visible through optically transmittable materials.
Disadvantages	The pack enclosure is made of non-IR transmittable materials such as metals, glass, and almost all clear plastics [27].	LC thermography is not as accurate and flexible as the IR thermography.
Usage in Battery system	It is widely used for temperature measurement in the battery system.	This technique is particularly useful for capturing thermal images of a battery pack in a clear enclosure with ventilation air through the pack [62].

#### 4.2. Calorimetric Methods

Calorimetry is used for heat-generation measurements [39,41,118–122]. At constant temperature conditions, isothermal calorimetry measures thermal power, i.e., heat-production rate. Table 6 contains the comparison between adiabatic and isothermal calorimeters.

Table 6. Comparison between adiabatic and isothermal calorimeters [123].

Attribute	Isothermal Calorimeter	Adiabatic Calorimeter
The heat-production rate measurement	Direct measurement is made. It directly measures the heat-production rate that is proportional to the rate of the electrochemical reaction.	Indirect measurement is made. It measures temperature (change) that is recalculated to give heat produced.
Knowledge of heat capacity	Specific knowledge of heat capacity of the battery is not needed.	The specific heat capacity of the battery is needed.
Activation energy of hydration information	There is no need for information on the activation energy of hydration; if needed, this can be determined by isothermal calorimetric measurements at different temperatures.	Activation energy is required for the evaluation. This is usually obtained indirectly from strength development measurements at different temperatures that need not have the same activation energy as the heat production.
Calibration requirement	Modern isothermal calorimeters are very stable and do not be calibrated more than a few times a year.	Many of the adiabatic calorimeters are calibrated at each run.
Temperature limit	The temperature never increases to unrealistic temperatures in an isothermal calorimeter.	Final temperatures during measurements in adiabatic calorimeters are very high, e.g., 90 °C, far above what is desirable in real constructions.

### 5. Recommendations and Suggestions

The noteworthy factors that can be very important for building a battery system with a BTMS is as follows: electrolyte resistance [91,124–134], electrolyte level [135–138], leakage [139], dissimilar metals, corrosion prevention [26,140], battery containers and components, as well as battery containers and covers [26]. Under no circumstances should a cell or battery short-circuit. For instance, the storage or casing should be thoroughly inspected for cells lying haphazardly that may incite short-circuiting either by themselves or with the help of conductive materials [77]. The cells or batteries must not be exposed to heat or fire; even averting storage in direct sunlight should become a common practice [77].

Several recommendations and suggestions are outlines in Table 7.

**Table 7.** Suggestions and Recommendations for an Effective BTMS.

Focus	Requirement	Suggestions and Recommendations	Reference
Environmental	Consideration of different geographical location, hazardous physical emission, altitude, storage and ventilation (details in Table 1)	Thermal design approaches should consider the application of the temperature performance ranges within which the battery system is designed to operate; A suitable example: a good measure for temperature range in an EV should be $-40$ – $60$ °C with a relative humidity range of 10% to 80% at 38 °C; Thermal design approaches should consider EV system temperature performance ranges; The manufacturer must provide environmental guidelines, i.e., storage temperature ranges, recharge intervals, etc., for extended off-plug storage directions to service facilities.	[15,20,80]
Safety	Documentation, proper training of operators and users, show the warning signs of potential hazards	The manufacturers need to provide documentation for transport, installation, commissioning, operation, maintenance, decommissioning and disposal of such cells and batteries for specified applications; The manufacturer shall advise the potential user if there are special considerations to be observed for the initial charging of batteries when the battery is operated under atypical conditions.	[26,77]
Regulatory	Certification conformity	The Type Certificate (TC) must be used for the approved intended application type design including any battery equipment; The usage and purpose of the battery cells and packs at the time of manufacture must be stipulated; The responsible organization should determine what the level of harmful concentration is that may be based on accepted industry practice or standards; The primary consideration should be given to avert this build-up of flammable gasses and consequently avoid flammable gas contact with known vehicle ignition sources to avoid fire hazard.	[1,26,78]
Physical/mechanical	Robust and sturdy build quality of the system	Any accessory used in the application should not hinder the ventilation of the module through the creation of physical or electrical or thermal obstacles.	[20]
Protective measures and documentation	Equipment, protection against hazards and operational precautions	In all cases, protection from hazards should be a priority for any battery stakeholders; All the necessary protection issues need to be clearly indicated in the document and explicitly shown.	[80,82]
Materials	Material selection, impact of safety and quality	The materials used in different battery accessories, battery casings or enclosures inside the battery materials must be resistant to or must be protected against the chemical effects of the electrolyte measurement tools, such as funnels, hydrometers, thermometers that normally meet electrolytes.	[26,141,142]
Components	Conformance with the standards and synergy among the components	The intensity, direction of cooling and heating will depend on different application requirements to maintain the temperature within a uniform range.	[14,80,82,143,144]
Quality	Quality plan, strict supervision, appraisal and audit of performance Consistency of services, conformity to the standards	Usage of well-known PDCA (Plan-Do-Check-Act) cycles periodically. Quality audit is needed periodically to reach the best possible performance limit; The performance should be assessed, and the system should be tweaked.	[9,15,77,81,145–147]

## 6. Conclusions

In this article, a concise overview of the battery system is presented using both current literature studies and different well-established quality and safety standards. The basic focus is on enhancing the thermal-related performance of a battery system. Furthermore, some suggestions and recommendations are explicated in terms of the standards for improving the performance of state-of-the-art battery systems. The most important design parameters are design cost options and desired level of sophistication. The presented attributes can certainly enhance state-of-the-art battery thermal management systems (BTMS). The recommendations are made to extend BTMS lifetime, and to maintain reliability and efficiency. In order to ensure the quality of the compliant BTMS derived from the standards, a high level of inspection is also required.

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