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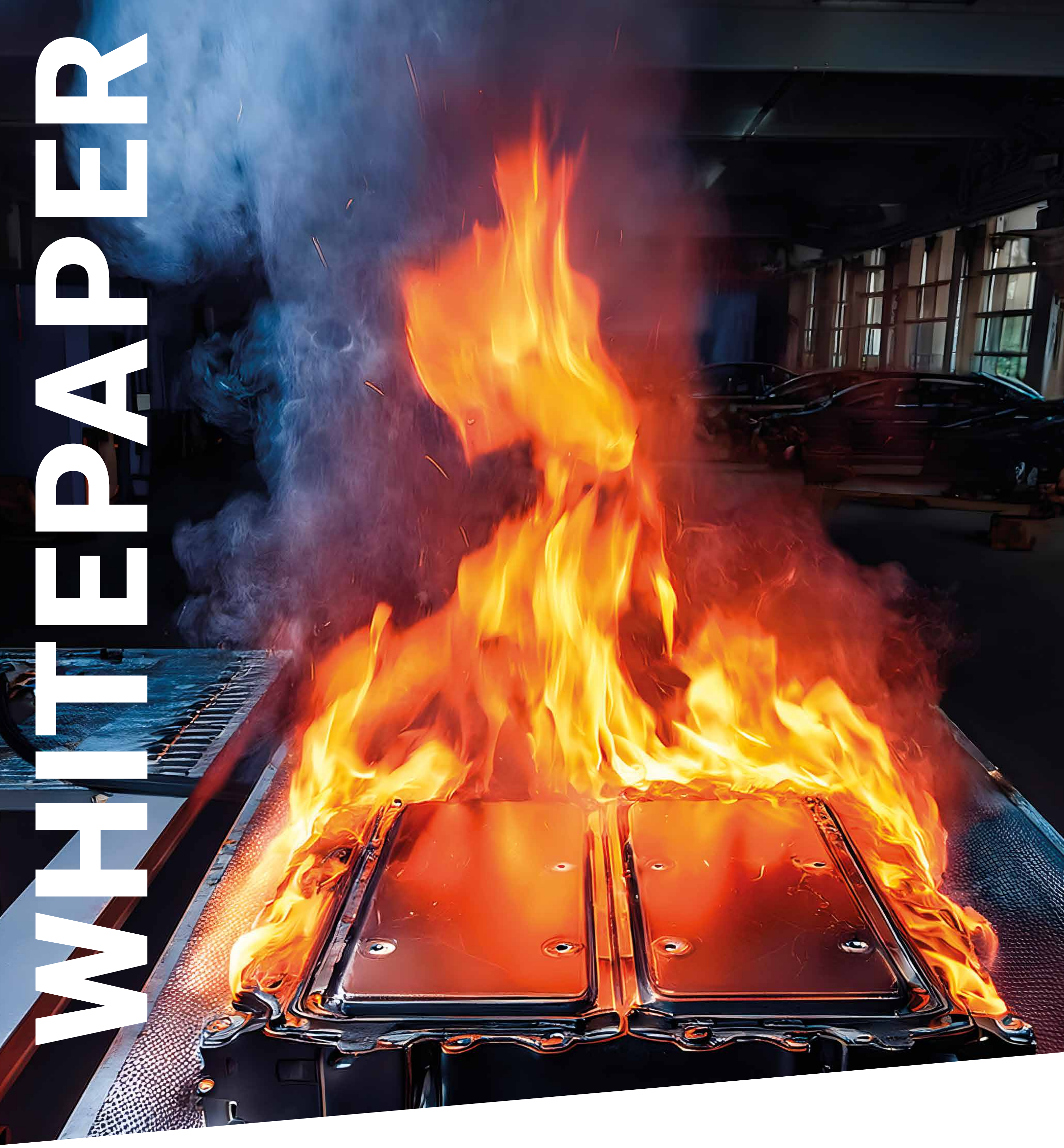

BATTERIES UNDER FIRE

WHY PRECISE MONITORING CAN SAVE LIVES

The key to avoiding fires and thermal disasters

WHITEPAPER

BatteryMonitor
Revolutionary monitoring for maximum safety
Innovative solutions for monitoring and cooling critical energy storage systems

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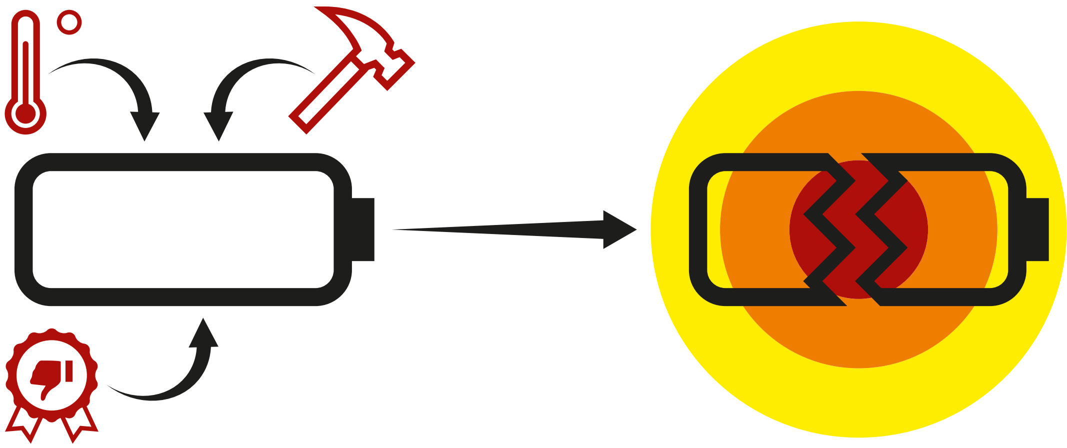
SECTION

1 INTRODUCTION

Lithium-ion batteries are essential components in modern energy systems and they are playing a key role in the trend towards electrification in important fields such as electromobility, stationary energy storage devices and industrial applications. With their high energy density, long service lives and outstanding performance, they are a key element in the transition to alternative energy. Their technical complexity and the safety challenges this brings call for in-depth understanding of how they operate, however [1, 2]. Reliable monitoring is essential in order to ensure that these systems can run smoothly [19]. The fire risk posed by lithium-ion batteries is now well known, as there have been a number of spectacular incidents resulting in major damage.

Importance of battery monitoring for safety

As lithium-ion batteries become more widespread, with larger sizes and greater energy density, the requirements for safety standards and monitoring systems are increasing significantly. In electromobility and stationary energy storage systems in particular, the large volumes of energy pose potential risks, with accidents that can be triggered by minor defects, such as short circuits or mechanical damage. Scenarios such as thermal runaway represent one of the most critical dangers, resulting from overheating, mechanical action or internal cell failure [19, 20].



Early detection and preventive measures are crucial in order to extend battery service life and reduce the fire risk and resulting dangers.

Efficient monitoring systems help to increase sustainability in two ways: they minimise the release of toxic substances and environmentally harmful emissions by preventing battery fires, but they also maximise the use of each battery system and significantly reduce material usage and waste [5, 6].

Challenges caused by inappropriate cooling and monitoring

Monitoring the battery temperature is one of the key challenges. Conventional methods often do not go beyond measuring the surface temperature. Because batteries have low thermal conductivity, this means that it takes some time for internal thermal problems to be detected [3, 4].

Modern systems like BatteryMonitor use innovative solutions that enable precise monitoring, almost in real time. Thanks to the use of a closed water circuit in combination with highly sensitive sensors, hot spots and thermal instabilities can be prevented effectively. At the same time, safety is increased and battery performance is optimised [6, 18].

Conclusion

Monitoring lithium-ion batteries across their entire life cycle is much more than just a technical challenge. Innovative solutions like the BatteryMonitor system are able to not only minimise safety risks but also make lasting improvements to the service life and efficiency of batteries. This represents a significant benefit for business, the environment and society [19, 20].

2 PROBLEM DEFINITION

The increasing use of lithium-ion batteries in critical applications like electromobility and stationary energy storage systems poses considerable challenges. The thermal stability of these energy storage devices is a key safety factor, as even minor defects in a battery call can have potentially catastrophic consequences. Without effective thermal management, the risk of overheating and thermal runaway significantly increases, which underlines the need for precise monitoring systems [18, 19].

Thermal management – a key problem

Lithium-ion batteries react extremely sensitively to changes in temperature. Mechanical damage, overcharging, internal short circuits or ageing processes can result in local overheating. Without a system for effective temperature control, these problems remain undiscovered until it is too late. The internal structure of the battery amplifies this risk: because of the batteries' high mass and low thermal conductivity, hazardous temperatures reach the cell core before they can be detected at surface level [4, 6].

This lag makes it difficult to detect critical conditions early on and can result in a local problem spreading throughout the entire battery system. Uncontrolled temperature development – also known as thermal runaway – is often the starting point for chain reactions that endanger not only the battery itself but also adjacent systems [1, 22].

The consequences of battery fires

- **High costs caused by infrastructure and vehicle damage:** battery fires can often cause significant financial loss. Vehicles affected by thermal instability are typically considered irreparable. The surrounding infrastructure – warehouses, workshops or transport vehicles – is often significantly impacted. Cases such as the fire at an electric bus depot in Stuttgart, which destroyed the entire depot, highlight the scale that these incidents can have. Because of the increased fire risk, special regulations have already been put in place for handling lithium-ion batteries [19, 25].
- **Environmental risks caused by toxic gases and polluted extinguishing water:** the chemical components of lithium-ion batteries release hazardous substances in the event of a fire. Toxic gases pollute the ambient air, while contaminated extinguishing water can cause long-term damage to soil and water. This causes not only environment pollution but also more costly disposal and stricter regulatory requirements. Furthermore, burnt batteries cannot be recycled, which entirely undermines their contribution to waste reduction. The area is also considered contaminated, and the Technical Rule for Hazardous Substances TRGS 524 'Protective measures for activities in contaminated areas' must be observed [7, 18,25].
- **Risk to human life:** the unpredictable development of battery fires makes them especially dangerous for people. A thermal runaway can occur suddenly and with high intensity, which makes firefighting difficult. Conventional fire extinguishing systems, such as sprinklers, are often not able to control battery fires effectively, as they have their own source of energy. This considerably endangers both rescue workers and employees in workshops, warehouses or transport companies [9, 12].

Conclusion

The risks of lithium-ion batteries without effective thermal management and precise monitoring are too great to be ignored. Battery fires not only threaten financial assets and the environment but also put human lives at risk. This emphasises the need for innovative monitoring solutions like BatteryMonitor, which can help to prevent these scenarios thanks to precise temperature control and early warnings [1, 20].

3 OPTIMISED TEMPERATURE CONTROL

Basic principles of cell defects

Optimization study of a Z-type airflow cooling system of a lithium-ion battery pack [24]
This study investigates in detail how energy is released in the event of a fault and what parameters are relevant for the thermal load of a battery system.

The calculations show that in a typical scenario with ten defective cells, roughly 65% of the stored electric and chemical energy is converted into heat. This assumption forms the basis of the **calculation of 428.8 kJ**, which is used in the water cooling analysis. This energy is made up of the electric and chemical energy of an individual battery cell.

Chemical reactions at high temperatures
Lithium-ion batteries are complex electro-chemical systems, and their stability becomes critical at temperatures **above 60 °C**.

At this point, the electrolytes begin to break down, triggering a chain reaction of exothermic processes. These reactions cause the temperature to rise, which can trigger a thermal runaway. The energy sources are as follows:
- **Chemical bond energy:** This energy is released from the materials of the cell, in particular cathode materials like lithium cobalt oxide and the electrolyte.
- **Electric energy:** The energy stored in the cell also forms part of the overall energy release when it is converted into heat [18, 19].

Energy during thermal runaway
During a thermal runaway, all of the cell's stored energy is released, including:
- **Electric energy:** The energy that is stored in the battery is fully converted into heat.
- **Chemical energy:** In addition, highly exothermic chemical reactions occur, in particular in the case of materials like lithium cobalt oxide (LiCoO), which becomes unstable at high temperatures and reacts.

Energy examples for a 18650 cell
- **Electric energy:** A typical 18650 cell (3,000 mAh, 3.6 V) contains roughly 38.88 kJ of stored electric energy:
- **Chemical energy:** Additional exothermic reactions can release 2–4 kJ, depending on the cell chemistry and at temperatures above 60 °C.

Overall energy:
An individual cell can release up to 42–44 kJ in the event of thermal runaway. In a battery pack containing multiple cells, this energy is multiplied, which can bring about a chain reaction and a massive release of energy [4, 18].

3.1 BASIC PRINCIPLES OF LITHIUM-ION BATTERIES

Why use water as a medium for monitoring?
Monitoring lithium-ion batteries effectively is a fundamental requirement if they are to be operated safely. At present, batteries that are not installed are often monitored without water cooling, which is a serious error. For installed batteries, the battery management systems (BMS) integrated into modern vehicles or thermal management systems ensure adequate monitoring and cooling. As soon as batteries are uninstalled or operated in an environment without active systems, major risks occur. Air, which was previously used as a cooling medium, was shown to be unsuitable years ago, particularly because of its low thermal conductivity and heat capacity [4, 5, 19].

The technical and physical foundations, quantitative calculations and specific advantages of using water-glycol as a cooling medium are described in detail below.

Why is cooling needed?
Lithium-ion batteries are temperature-sensitive. A temperature increase above specific limits can result in a condition known as thermal runaway. Without the support of a BMS or thermal management system, which batteries have when they are installed, the risk increases significantly. When batteries are no longer installed, for example during transport, storage or repair, they often do not have any effective temperature control.

Monitoring and control of the temperature is crucial in order to:
- retain the batteries' thermal stability.
- prevent damage to individual cells, which could spread to the entire battery system.
- avoid safety risks such as fire and explosion [1, 19].

Thermal runaway – a dangerous process
Thermal runaway often occurs at temperatures of roughly 60 °C, and becomes especially critical at 100 °C. In this state, chemical reactions inside the battery release large amounts of heat, further increasing the temperature.

Without an effective cooling medium like water, this process can escalate in a matter of seconds and cause uncontrollable damage [18].

3.2 PHYSICAL FOUNDATIONS OF WATER COOLING

Water is a perfect medium for controlling temperature, thanks to its exceptional thermal properties. Compared with air, water has a higher heat capacity and greater thermal conductivity, which enables more efficient heat dissipation.

This is especially important for batteries that are operated outside of a vehicle or system, without an active BMS [4, 5].

Heat capacity and thermal conductivity
- **Heat capacity:** Water has a specific heat capacity of 4.18 kJ/(kg·K), while the value for air is roughly 1.0 kJ/(kg·K). This means that water can absorb roughly four times more energy before its temperature increases [6].
- **Thermal conductivity:** The thermal conductivity of water is 0.6 W/(m·K), compared with air with just 0.025 W/(m·K). This enables heat to be distributed quickly and uniformly [4].

Uniform temperature distribution
A closed water circuit ensures that temperature is distributed uniformly within a battery system. This minimises the risk of hot spots, which can serve as the starting point of thermal runaway. Air, on the other hand, is an inefficient cooling medium because of its physical properties and was found to be unsuitable for this purpose years ago [4, 5].

3.3 CALCULATIONS FOR THE EFFICIENCY OF WATER COOLING

Temperature change with water cooling

$$\Delta T_{\text{Wasser}} = \frac{\text{Q}}{\text{m}\cdot\text{c}} = \frac{428{,}8}{10\cdot4{,}18} \approx 10{,}26\ \text{K}$$

The temperature of water increases by roughly 10.26 °C [6].

Temperature change with air cooling

$$\Delta T_{\text{Luft}} = \frac{\text{Q}}{\text{m}\cdot\text{c}} = \frac{428{,}8}{10\cdot1{,}0} = 42{,}88\ \text{K}$$

The temperature of air increases by roughly 42.88 °C [6].

The value **Q of 428.8 kJ** represents the overall energy that is released by ten faulty battery cells in the event of a fault. See the next item.

3.4 COMPARISON: TEMPERATURE MEASUREMENT WITH WATER CIRCUIT VS EXTERNAL MEASUREMENT

Given data for the water circuit

- Mass of the water: 10 kg
- Specific heat capacity of water: 4.18 kJ/(kg·K)

Given data for the battery

- Mass of the battery: 500 kg
- Specific heat capacity of the battery: 1.0 kJ/(kg·K)
- Released energy of a cell: 42.88 kJ

Additional assumptions

- Constant mass and heat capacity: It is assumed that the mass and the specific heat capacity of the media (water and battery) remain constant across the observed temperature range.
- Homogeneous temperature distribution: It is assumed that the heat is distributed evenly within the medium (no local differences in temperature).
- Insulated environment: It is assumed that no heat is dissipated to the environment.

3.4.1 TEMPERATURE MEASUREMENT WITH WATER CIRCUIT (E.G. BATTERYMONITOR)

Energy needed for temperature increase

For 10 litres of water, only 41.8 kJ is needed to raise the temperature of the water by 1 °C.

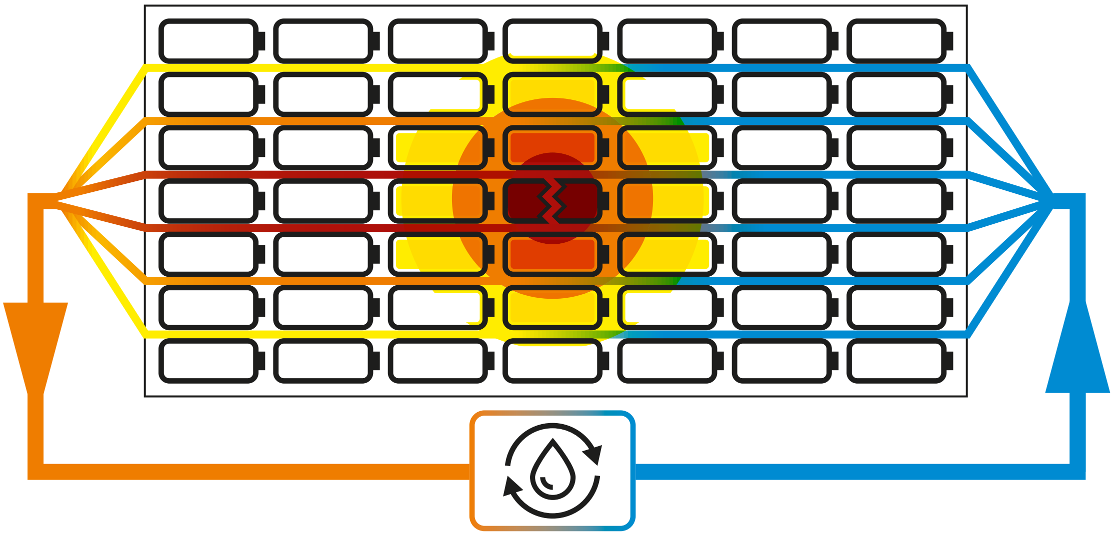
Calculation: Temperature change in the water circuit

The change in temperature is calculated by the following formula:

$$\Delta T = \frac{Q}{m \cdot c}$$

$$\Delta T_{\text{Wasser}} = \frac{42{,}88}{10 \cdot 4{,}18} \approx 1{,}03\ \text{K}$$

Result: The temperature of the water increases by 1.03 °C when a cell releases its maximum energy.



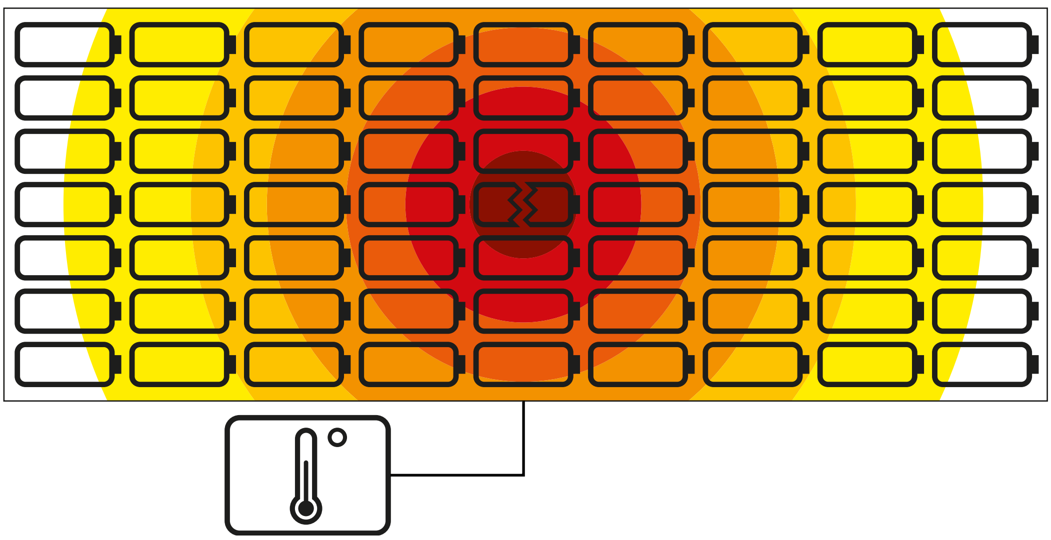
3.4.2 TEMPERATURE MEASUREMENT FROM THE OUTSIDE OF THE BATTERY

Energy needed for temperature increase:
The overall battery (mass: 500 kg, heat capacity: 1.0 kJ/(kg·K)) requires 500 kJ to increase by 1 °C.

Calculation: Temperature change without water circuit
The foundation remains the same:

$$\Delta T_{\text{Batterie}} = \frac{42{,}88}{500 \cdot 1{,}0} \approx 0{,}086\ \text{K}$$

Result: The temperature of the overall battery increases by 0.086 °C when a cell releases its maximum energy.



3.4.3 COMPARISON OF RESULTS

With water circuit:

- The temperature change is 1.03 °C, which enables a rapid and precise reaction to local heat sources.
- Hot spots and critical states can be identified almost in real time.
- This enables effective monitoring and prompt countermeasures that can avoid damage.

Without water circuit:

- The change in temperature is only 0.086 °C.
- The large mass of the battery distributes the released energy, resulting in a temperature increase that is minimal and slow.
- Critical states, such as local overheating, can easily remain undetected because of the thermal inertia.
- Without a water circuit, significantly greater damage needs to occur before a significant increase in temperature can be detected.

3.5 EXAMPLE SCENARIO: COMPARISON OF TEMPERATURE MONITORING WITH AND WITHOUT WATER CIRCUIT

Starting situation:

A battery pack containing 10 defective cells releases the maximum energy of 42.88 kJ per cell. The monitoring is performed once by means of a water circuit (e.g. BatteryMonitor) and once without a water circuit by means of external measurement of the overall battery.

Scenario 1: With water circuit (BatteryMonitor)

- Mass of the water: 10 kg
- Specific heat capacity of water: 4.18 kJ/(kg\cdotpK)
- Temperature difference: ΔT = 35 °C (environment 25 °C -> alarm 60 °C)
- Energy needed to increase the water temperature from 25 °C to 60 °C:

$$Q_{\text{Wasser}} = m_{\text{Wasser}} \cdot c_{\text{Wasser}} \cdot \Delta\text{T} = 10 \cdot 4{,}18 \cdot 35 = 1.463 \text{ kj}$$

Time until temperature increase to 60 °C

$$t = \frac{Q_{\text{Wasser}}}{Q_{\text{Zellen}}} = \frac{1.463}{428{,}8} \approx 3{,}41 \text{ Zeiteinheiten}$$

Scenario 2: Without water circuit (external measurement)

- Mass of the battery: 500 kg
- Specific heat capacity of the battery: 1.0 kJ/(kg\cdotpK)
- Temperature difference: ΔT = 35 °C (environment 25 °C -> alarm 60 °C)
- Energy needed to heat the battery from 25 °C to 60 °C:

$$Q_{\text{Batterie}} = m_{\text{Batterie}} \cdot c_{\text{Batterie}} \cdot \Delta\text{T} = 500 \cdot 1{,}0 \cdot 35 = 17.500 \text{ kj}$$

Time until temperature increase to 60 °C

$$t = \frac{Q_{\text{Batterie}}}{Q_{\text{Zellen}}} = \frac{17.500}{428{,}8} \approx 40{,}81 \text{ Zeiteinheiten}$$

Time units and typical duration

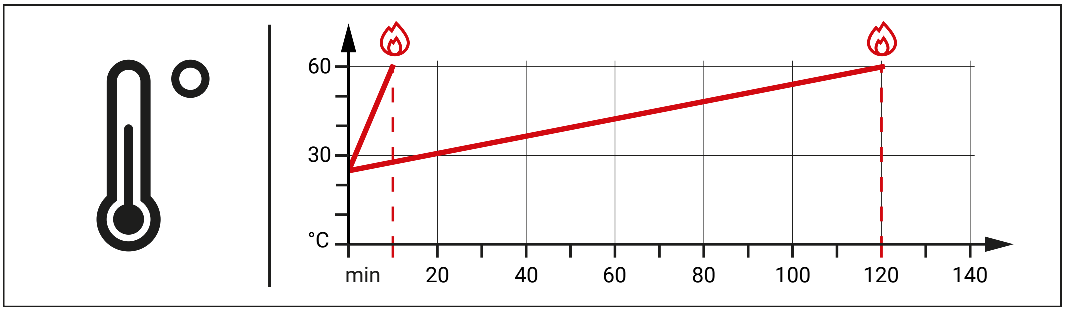
The time units used in the calculations relate to the time that a defective cell needs to release its maximum energy of **42.88 kJ**. This duration varies depending on the cell's chemical make-up and the ambient conditions (e.g. temperature, pressure). For the calculations, it is assumed that **1 time unit** is roughly **3 minutes**.

Comparison with time units taken into account

With a water circuit the time until the critical temperature increase from **25 °C to 60 °C is only 10 minutes** (3.41 time units × 3 minutes per time unit).

Without a water circuit, it takes **over 2 hours** (40.81 time units × 3 minutes per time unit) for the same temperature to be reached.

During this time, roughly **17,500 kJ of energy** must be released – this corresponds to the maximum energy of **408 defective cells**. The average power dissipation in this scenario is roughly **2.4 kW**, which shows that **without a water circuit, enormous damage needs to occur** before critical conditions can be detected.



Conclusion

- **Reaction time:** With a water circuit, the critical temperature in our scenario is **detected after roughly 10 minutes**, while **without a water circuit this takes over two hours** (see Figure 1). The **water-based measuring system thus reacts up to 12 times faster** and enables significantly earlier detection of the critical state.
- **Efficiency:** Systems like BatteryMonitor offer considerably faster and more precise monitoring, as the water cooling system absorbs the heat immediately and reflects the temperature development directly.
- **Safety:** In particular in batteries that are not installed or that do not have an active thermal management system, using a water circuit is essential when it comes to detecting local hot spots early on and preventing chain reactions. Our scenario clearly shows how different the scale of thermal damage can be.

Comment

The calculations are based on linear fault development in the cells, and exponential development would considerably reduce both time periods. Nevertheless, the advantage of using the water circuit method is clear: it reacts more quickly, can recognise critical states with fewer defective cells and the water itself acts as a buffer preventing escalation.

In addition to this, there are other effects that influence the measurement results need to be taken into account: the thermal inertia of the battery housing in the measurement without a water circuit can delay changes in temperature and conceal critical states. Equally, the temperature loss of the water flowing past the housing causes minor cooling, which can dampen the ingress of heat. Although these effects were not incorporated into the calculation in detail for the sake of simplicity, they should absolutely not be overlooked in practice.

4 BATTERYMONITOR

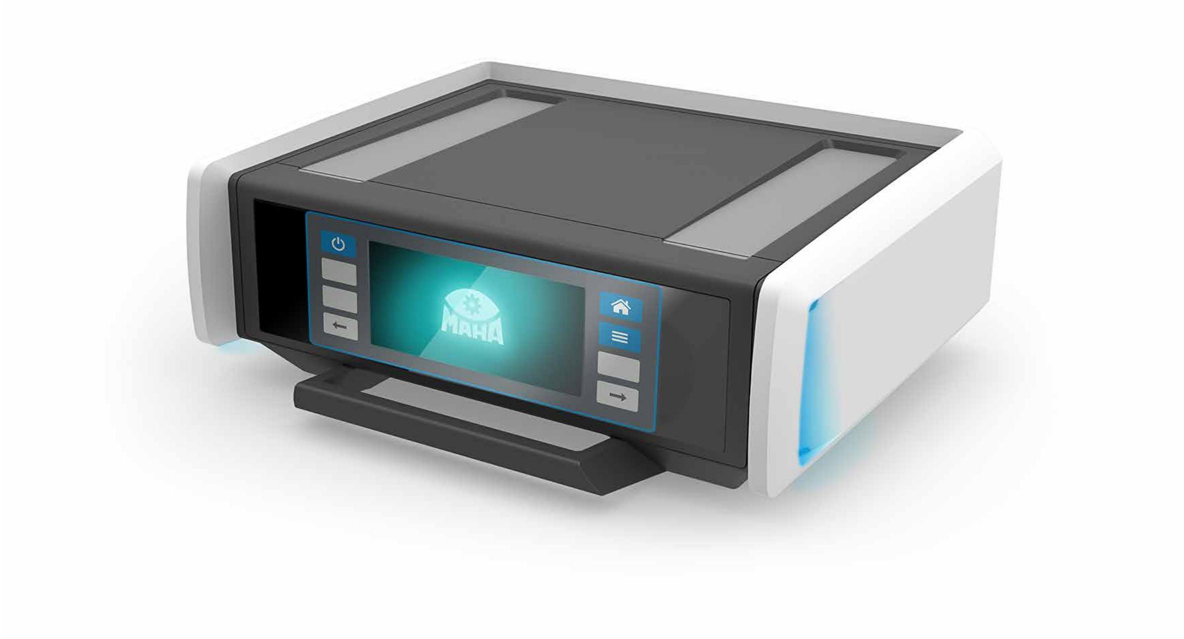


Figure 3: BatteryMonitor design study

Description of the device

BatteryMonitor is a highly modern monitoring device that was specially developed for precise temperature control and safety monitoring of lithium-ion batteries. It is based on an integrated water circuit that uses a water glycol mixture as a cooling and measuring medium [5, 18].

- **Installed water circuit:** The device has inlet and outlet ports that enable straightforward integration into closed circuits so that batteries or other components can be monitored safely.
- **Precise temperature measurement:** The continuous monitoring of the cooling medium enables early detection of thermal changes in the battery [4, 6].
- **Pump control:** An integrated pump, controlled by a PWM signal, ensures optimal circulation of the cooling medium.

- **Integrated sensors:** Advanced sensors measure both the temperature and the flow rate of the medium to ensure reliable system function [5].

Unique functions

BatteryMonitor provides a range of innovative functions that make it stand out from conventional monitoring systems:

- **Early detection of hot spots:** An integrated alarm system detects critical temperature peaks early on, before hazardous states such as thermal runaway can occur [6].
- **Control of external devices:** The system can be connected to cooling units or extinguishing systems, which can be activated automatically as needed.
- **Patented technology:** BatteryMonitor combines temperature monitoring, flow rate control and alarm management in a patented system specially developed for closed battery circuits [7].

Technology overview

BatteryMonitor combines cutting-edge hardware with user-friendly technology to provide ease of use and extensive functionality:

- **Touch TFT display:** An intuitive touchscreen interface enables rapid configuration of the system and display of all relevant data in real time [5].
- **Networking options:** The device supports Ethernet, Bluetooth and I/O interfaces for seamless integration into other devices and systems, via ConnectCube.
- **Embedded system:** The device is controlled by means of an installed embedded system that provides high precision and reliability [6].

BatteryMonitor is an innovative solution that combines temperature monitoring, cooling and safety in one device, making it ideal for use in workshops, in warehouses and for the transport of lithium-ion batteries.

5 APPLICATIONS

BatteryMonitor is a versatile solution for precise monitoring and cooling of lithium-ion batteries and is used in a variety of application fields. Thanks to its extensive adaptability, it provides maximum safety and efficiency, especially in the following scenarios [5, 6].

Workshops: Safety for batteries without integrated thermal management

BatteryMonitor monitors uninstalled batteries that do not have an integrated BMW or thermal management.

- **Storage of damaged batteries:** Mechanically damaged batteries or batteries with defective thermal management are monitored continuously so that critical states can be detected early on [6].
- **Fire protection:** If abnormal temperatures occur, the device issues an alarm and automatically actuates cooling units or extinguishing devices.
- **Documentation:** Logged measured data can be used to track storage conditions and provide verification in connection with guarantee claims [7].

Transport and storage: Minimised risks when temperatures change

When lithium-ion batteries are transported or stored, BatteryMonitor is a key safety measure.

- **Transportation of damaged batteries:** BatteryMonitor minimises overheating risks when damaged or used batteries are transported [18].
- **Storage monitoring:** Batteries in warehouses are monitored for external and internal temperature changes to prevent fire and damage.
- **Environmental protection:** Early detection of thermal anomalies helps to prevent battery fires that can release toxic gases and cause environmental pollution [19].

Stationary energy storage systems: Protection of battery units in buildings

BatteryMonitor provides perfect monitoring for stationary battery storage systems.

- **Hot spot prevention:** The water circuit ensures uniform temperature distribution and prevents individual cells from overheating.
- **Protection from continuous load overheating:** Automatic control of cooling systems extends the service lives and efficiency of stationary accumulators [5].
- **Cost savings:** Precise monitoring reduces the need for premature replacement [7].

Research and development: Optimised battery and cooling systems

In laboratories, BatteryMonitor supports engineers and scientists in developing innovative battery systems.

- **Validating prototypes:** Precise measurements identify thermal vulnerabilities in battery prototypes [6].
- **Cooling technology tests:** Engineers can use precise data to optimise new cooling systems [18].
- **Long-term monitoring:** Continuous temperature logging provides valuable insight into the thermal stability and ageing of battery cells [5].

Conclusion

BatteryMonitor is a universal solution for monitoring lithium-ion batteries. In workshops, during transport, in stationary energy storage devices or in research, the device ensures maximum safety, minimises risks and provides the foundation for innovation in battery technology [6, 7].

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About the author

During my work at Wölfle I have been able to garner valuable experience in battery management and cooling systems. Back in 2014, I successfully launched a system of this type in collaboration with VDL. Today, as the Managing Director of MAHA, I believe in the strictest safety standards, innovation and reliability – and this includes the monitoring of lithium-ion batteries.'

'Find out more about the importance of precise temperature monitoring and the essential safety aspects in this whitepaper.'

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