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*Review*

# Advances in Standardised Battery Testing for Enhanced Safety and Innovation in Electric Vehicles: A Comprehensive Review

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**Abstract:** Standardised battery tests are essential for evaluating the safety, reliability, and performance of modern battery technologies, especially with the rapid emergence of innovations such as solid-state and lithium–sulphur batteries. This review reveals critical shortcomings in current international standards (e.g., IEC, IEEE, SAE), which often do not keep pace with technological developments and are not harmonised across regions, limiting their effectiveness in real-world applications. The paper stresses the need for the continuous review of test protocols through collaboration between researchers, manufacturers, and regulators. A detailed case study of the BYD Dolphin battery demonstrates the practical importance of comprehensive testing in real-world conditions, spanning electrical, thermal, and mechanical ranges. The review concludes that up-to-date, harmonised, and scenario-specific test methods are needed to ensure accurate battery assessment, support global comparability, and enable the safe introduction of next-generation batteries for electric mobility and energy storage. Future work should prioritise operational monitoring, open access data sharing, and the development of sustainability-focused practices such as recycling and reclamation.

**Keywords:** standards; battery technology; battery testing

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## 1. Introduction

The aim of this article is to present current and future trends in electric vehicles (EVs) and battery production, as well as the relevant regulations. It also describes how battery testing is carried out and presents a method for conducting a standardised test and selecting the right equipment.

In the last century, lead–acid and nickel-based batteries were prevalent in electric vehicles, but today lithium-ion (Li-ion) batteries dominate. New technologies, such as rechargeable solid-state batteries, Li-$O_2$, Li-S, and all-solid-state batteries are being developed for the next generation of EVs. In addition, there is a growing focus on using more abundant materials such as sodium and zinc to replace expensive lithium. In the future, data-based modelling methods are expected to improve the efficiency and scalability of batteries in electric vehicles [1].

Table 1 compares the energy capacity and energy losses of different battery types, as well as the most important characteristics, and provides a useful tool for evaluating different technologies [2–7].

**Table 1.** Energy performance and efficiency of various battery types.

| Battery Type | Energy Capacity (Wh/kg) | Energy Loss (%) | Notes |
|---|---|---|---|
| Lead–Acid Battery | 30–40 | 15–25 | Older technology, low energy density, good regeneration potential. |
| Nickel–Cobalt–Manganese (NCM) Li-ion | 140–200 | 5–15 | Excellent energy density, expensive materials, widely used in electric vehicles. |
| Lithium Iron Phosphate (LiFePO4) | 90–160 | 10–20 | Good thermal stability, lower energy density, long lifespan. |
| Li-$O_2$ (Lithium–Oxygen) | 2000–3500 | 30–40 | Very high energy density, but still under development. |
| Li-S (Lithium–Sulphur) | 350–500 (theoretical: up to 2500) | 15–30 | High energy density, but limited lifespan and cycle stability. |
| ASSB (All-Solid-State Battery) | 500–800 (theoretical: up to 2500) | 10–20 | Excellent safety, high energy density, still in research phase. |

Li-S batteries have recently received considerable attention due to their high theoretical energy density and capacity, which could offer a promising alternative to conventional lithium-ion batteries. One of their main advantages is the extremely high theoretical capacity of the sulphur cathode, which is about 1675 mAh/g, significantly higher than the capacity of conventional lithium-ion batteries. In addition, the theoretical energy density of the total cell can be increased up to 2500 Wh/kg, which is particularly remarkable as such a high energy density can allow for the development of smaller and lighter batteries while providing a longer range. Lithium–sulphur batteries, therefore, have significant potential but also face a number of technological challenges that need to be further developed to achieve their performance and wide applicability [8].

All-solid-state batteries are a promising alternative to conventional lithium-ion batteries using solid electrolytes, offering a higher energy density and improved safety. The total cell energy density depends, to a large extent, on the materials used and the cell design. For example, for silicon-based ASSBs, the total cell energy density can reach 2500 Wh/kg [9].

Challenges include the reliance on rare materials such as lithium and cobalt, and the need to improve recycling and treatment as lithium-ion batteries power more and more electric vehicles. The research aims to improve performance through advanced modelling and to find sustainable alternatives in materials and charging processes [10].

At the same time, recent research emphasises the role of electrochemical battery technologies in mitigating the impacts of the high integration of variable renewable energy sources. Although these storage systems can be costly to deploy, they are key to increasing the share of renewable energy and maintaining grid stability. Technologies such as lithium-ion, vanadium-redox, and zinc–bromide batteries are particularly suitable for time-shifting, peak load management, and grid balancing due to their high capacity, long discharge times, and fast response times. In addition, each battery type is well suited for different applications such as voltage regulation, frequency regulation, and providing reserve capacity. The introduction of grid-forming power electronics solutions can further reduce technological barriers. All these results provide useful guidance for energy suppliers and investors to choose appropriate, more flexible, and sustainable energy storage technologies [11].

Linked to this approach, another recent study carried out a detailed analysis of electric and hydrogen (HES) energy storage technologies, taking into account full life-cycle costs and carbon emissions. The results showed that, for EES systems, in particular for lithium-ion, lead–acid, sodium–sulphur, and vanadium-redox batteries, the manufacturing costs and associated emissions are the biggest burden. However, lithium-ion technology shows lower costs and emissions in most scenarios. The economics of HES systems are mainly influenced by the cost of renewable energy, and piped hydrogen transport has proven to be the most efficient solution for longer distances. Although electric and hydrogen energy storage are not directly comparable, it is calculated that hydrogen can offer a competitive alternative, especially for transport purposes. In future developments, making renewable energy cheaper, improving electrolysis efficiency, and introducing smart design systems and cheaper manufacturing solutions will be essential to further reduce costs and emissions [12].

In relation to this issue, another recent study looked at the integration of EES and HES, with a particular focus on addressing the problems arising from the fluctuations in renewable energy sources. The study provides a detailed overview of how EES and HES systems can be combined, taking into account different technical, economic, and environmental aspects. The results show that complementing solar and wind energy with energy storage solutions significantly increases system stability and the share of renewables in the energy mix. In particular, the combination of solar, wind, and small- to medium-sized battery storage is an effective solution for remote areas. The potential of hydropower should also be exploited where available. The research underlines that combining different energy storage technologies (e.g., pumped, compressed air, or thermal storage) can be one of the most effective ways to develop flexible and reliable energy production systems. In the future, particular attention will need to be paid to the economical operation of such systems, to increasing the lifetime of storage, and to intelligent modelling and control solutions to make energy storage even more effective in supporting sustainable energy transition [13].

In this context, another recent review focused on the development of carbon-based additives to improve the performance of lead–acid batteries (LABs). These developments will help reduce the effects of sulphation and increase the overall cycle life and efficiency of batteries, especially during deep discharge or partial charge. Carbon-based materials such as graphite and carbon nanotubes improve electrochemical performance by increasing charge storage and minimising hydrogen evolution during cycling. Although the performance of LABs remains limited by temperature sensitivity and limited charge acceptance, innovations in electrode design and the use of carbon-based composites are key strategies to increase efficiency and longevity. Despite these challenges, LABs continue to offer significant advantages, particularly in terms of cost-effectiveness and recyclability, making them valuable components of the global energy storage market, especially for larger scale applications [14].

Lead–acid battery regeneration systems are well established and have achieved significant commercial success for many brands. However, regeneration methods for lithium-ion batteries are less developed, and further research and testing is needed to determine their effectiveness. Future efforts should focus on refining battery regeneration processes and increasing their commercial viability to better fit the principles of the circular economy [15]. In addition, new diagnostic methods based on CAN data have been proposed to monitor battery status and predict failures, which could provide a cost-effective solution for battery management in electric vehicles [16].

In addition to the growing use of batteries in electric vehicles, addressing their environmental impact requires examining whether batteries should be reused or recycled. This includes identifying the battery source and carrying out tests. Finding the right treatment and reuse can extend battery life and reduce environmental impacts, despite the challenges and costs involved [17]. There are also alternative solutions, such as the combination of Li-ion batteries and LNG, which offer an effective alternative to conventional fuels, as both reduce the environmental impact. LNG has lower carbon and emissions than diesel, making it a greener choice. Li-ion batteries store energy quickly, allowing for LNG consumption to be reduced. The combination of the two technologies increases fuel efficiency and reduces environmental impact [18].

The link between EVs and the electricity grid is a key element in creating a sustainable energy supply. EVs are capable of a two-way energy exchange, which provides the opportunity to optimise the grid. One such mechanism is Grid-to-Vehicle (G2V), where the electric grid provides the charging of the EV's batteries. The other important technology is Vehicle-to-Grid (V2G), which allows EVs to feed energy stored in their batteries back into the grid, helping to make it more stable and resilient [19]. Real-time grid–battery interactions play a crucial role in modern energy systems. The role of EVs in frequency regulation is significant, as they can quickly absorb or release energy, thus contributing to the stabilisation of the grid's frequency [20]. In addition, EVs help to manage peak load, as they can supply energy to the grid during peak periods and charge it during low-load periods, thus reducing the problems caused by uneven load on the grid [21].

Demand for lithium-ion batteries will grow significantly by 2030, driven by several key factors. Stricter global regulations, such as the EU's 2035 internal combustion engine ban, will drive the uptake of electric EVs. In addition, sustainability initiatives and a shift in consumer preferences towards greener technologies will further drive demand, as EVs are expected to account for 90% of passenger car sales in each country by 2030 [22].

By 2030, the transport sector will be the largest driver of global battery demand, with light vehicles and passenger cars being the main contributors:

Consumer electronics and others: 5.5%,

Energy storage systems: 32.7%,

Commercial vehicles: 30.3%,

Passenger transport: 29.9%.

COVID-19 has posed challenges for China's electric vehicle industry, initially leading to a decline in sales due to travel restrictions and loss of revenue. However, concerns about public transport safety have increased interest in larger EV models. Government support has fostered a boom and innovation, while consumer interest in EVs as a cleaner and safer alternative to public transport has also increased in the EU [23].

By 2025, the European market is expected to recover from COVID and stabilise at around 17 million vehicles by 2035, with EV sales estimated to account for around 60% of sales by 2030. Internal combustion engine (ICE) vehicles are expected to account for around 7% of the market in the same year. Many premium car brands are planning a full switch to electric drive ahead of the regulations. European regulations will have a significant impact on EV sales as manufacturers strive to meet annual $CO_2$ quotas. EV sales have increased from 0.38 million in 2019 to 2.2 million in 2023. Automakers are prioritising deliveries of pure electric vehicles (BEVs) in the fourth quarter of the year to secure government subsidies and comply with $CO_2$ regulations.

The market for lithium-ion batteries (LIBs) is growing rapidly, creating uncertainty around future demand and the supply of critical raw materials. Although LIB production capacity is increasing, forecasting long-term demand is challenging, raising concerns about oversupply. To support sustainable development, it is essential to establish manufacturing and recycling facilities and develop a skilled workforce to avoid supply chain disruptions that could hinder the uptake of electric vehicles [24].

EU battery legislation aims to stimulate the growth of domestic industries, promote environmental protection, and achieve a circular economy. However, uncoordinated policies in globally important regions make it difficult to predict the consequences of regulation. The unintended consequences may affect the EU first but will have an impact on producers and recyclers worldwide. Disruptions to the European battery supply chain could limit the ability of car manufacturers to produce electric vehicles at the pace required by 2030 [25].

European Union regulations (Euro 7, EU 2030, EU 2035) are introducing stringent environmental standards that have an impact on the market.

Euro 7 regulation: Aims to reduce air pollutants from vehicles through stricter emission standards (e.g., nitrogen oxides, fine particulates). This will accelerate the transition to electric and hybrid vehicles, increasing demand for battery cells.

2030 "Fit for 55" target: The EU 2030 Climate Action Plan aims to reduce greenhouse gas emissions by at least 55% compared to 1990's levels, promoting investment in renewable energy and expanding the market for electric vehicles with additional incentives for battery research and development.

Legislation 2035: Requires all new cars in the EU to be zero-emission from 2035, effectively banning vehicles with internal combustion engines. This shift to electric or hydrogen-powered vehicles will significantly increase demand for batteries and competition between manufacturers.

Significant investment in battery cell production in Europe poses a risk of overcapacity, as many new entrants do not have OEM customers, putting them at a disadvantage compared to established suppliers.

The growth in battery production since 2019 underlines the need for a battery testing centre. Continuous improvements in battery performance and variation in chemical composition will make continuous testing essential.

China and Europe, as the largest and fastest-growing electric vehicle markets, require compliance with safety standards such as GB 38031-2020 [26] and UN ECE R100 [27]. OEMs such as BYD and Tesla use LFP battery cells to reduce cost and safety [28].

In the automotive industry, the focus is on battery packs and modules, but market research shows that there is also demand for testing smaller cells.

Standardised set-ups and tests are essential to ensure that the batteries available on the market are of the right quality for their intended purpose. These tests are, therefore, as important to the future development of portable electronics and electric vehicles as lithium-ion batteries themselves.

For example, the IEC 62619 standard [29] specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications such as stationary and mobile applications, including stationary applications and mobile applications such as forklifts, golf carts, automated guided vehicles, rail, and marine applications, but excluding road vehicles [30].

There are also calendar ageing tests that relate to wear and tear during periods of inactivity, particularly relevant in applications such as electric vehicles where downtime exceeds time in use. There are several databases on this topic, such as the CALCE group's data on battery cell tests and the EVERLASTING project's study with NCA/graphite cells, which show the effects of storage temperature and state of charge on battery ageing. These data, available online, provide critical insights into the behaviour of batteries during storage and will help inform future battery design and use strategies (Table 2) [31,32].

**Table 2.** Examples of battery standards.

| Cell | Module | Pack |
|---|---|---|
| UN 38.3 | UN 38.3 | UN ECE R100 |
| IEC 62133-1 | IEC 62281 | UN 38.3 |
| IEC 62133-2 | IEC 62619 | IEC 62619 |
| IEC 62281 | IEC 62620 | IEC 62281 |

**Table 2.** *Cont.*

| Cell | Module | Pack |
|---|---|---|
| IEC 62660-2<br>IEC 62660-3<br>IEC 61960-3<br>IEC 62619<br>IEC 62620<br>IEC 62660-1<br>IEC 62660-2<br>IEC 62660-3<br>IEC 63056 | IEC 62660-1<br>IEC 62660-2<br>IEC 62660-3<br>IEC 63056 | OEM standards |

**UN 38.3** [33]

Requires several tests to ensure the relative safety of batteries and cells during transport that vary based on the battery and components.

Contains safety requirements for the transport of lithium-ion batteries, including temperature tests, vibration tests, impact tests, and short-circuit tests. The standards are designed to ensure the safe transport of batteries.

**UN ECE R100**

The standard for the safety of batteries in electric vehicles, ensuring proper testing, such as overheating, mechanical damage, and other safety aspects.

**IEC 61959—Mechanical tests for sealed portable secondary cells and batteries** [34]

This standard outlines test methods, objectives, and acceptance criteria for portable secondary cells and batteries of various electrochemical systems (Ni-Cd, Ni-MH, and Lithium) in different sizes and shapes (cylindrical, prismatic, and button).

**IEC 61960-3—Performance tests for secondary lithium cells for portable applications** [35]

Specifies performance tests, designations, markings, dimensions, and other requirements for prismatic and cylindrical lithium secondary cells and batteries used in portable applications.

**IEC 61960-4—Coin secondary lithium cells for portable applications** [36]

Defines performance tests, designations, markings, dimensions, and requirements for coin secondary lithium cells and batteries used in portable applications, including memory backup applications.

**IEC 63056—Safety requirements for secondary lithium cells for electrical energy storage systems** [37]

Specifies safety requirements and tests for secondary lithium cells and batteries used in energy storage systems with a maximum DC voltage of 1500 V.

**IEC 62620—Lithium cells for industrial applications** [38]

Specifies the marking, tests, and requirements for secondary lithium cells and batteries used in industrial applications, including stationary applications.

**IEC 62619—Safety requirements for lithium cells in industrial applications**

Defines safety requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications, including stationary applications.

**IEC 62133-1—Safety for nickel-based portable sealed secondary cells** [39]

Specifies safety requirements and tests for portable sealed secondary nickel cells and batteries containing alkaline electrolyte under intended and reasonably foreseeable misuse conditions.

**IEC 62133-2—Safety for lithium-based portable sealed secondary cells** [40]

Specifies safety requirements and tests for portable sealed secondary lithium cells and batteries containing non-acid electrolyte under intended use and misuse conditions.

**IEC 62660-1—Performance testing for secondary lithium-ion cells for electric vehicles [41]**

Specifies performance and life testing for secondary lithium-ion cells used in electric road vehicles, including BEVs and hybrid electric vehicles (HEVs).

**IEC 62660-2—Reliability and abuse testing for lithium-ion cells in electric vehicles** [42]

Details test procedures to observe the reliability and abuse behaviour of secondary lithium-ion cells used in electric vehicles, including BEVs and HEVs.

**IEC 62660-3—Safety requirements for lithium-ion cells in electric vehicles** [43]

Defines test procedures and acceptance criteria for the safety performance of secondary lithium-ion cells in EVs, including BEVs and HEVs.

**IEC 62281—Safety of lithium cells during transport [44]**

Specifies test methods and requirements to ensure the safety of primary and secondary lithium cells and batteries during transport.

**IEC 62933-1—Vocabulary for electrical energy storage (EES) systems [45]**

Defines terms applicable to electrical energy storage (EES) systems, including terms necessary for parameters, test methods, planning, installation, safety, and environmental issues.

**IEC 62933-2-1—Unit parameters and testing methods for EES systems [46]**

Deals with EES system performance, defining unit parameters and testing methods.

**IEC 62933-4-4—Environmental requirements for battery-based energy storage systems with reused batteries [47]**

Addresses environmental concerns in the use of reused batteries for energy storage systems (BESSs), specifying requirements for preventing environmental issues.

**IEC 62933-5-2—Safety requirements for grid-integrated EES systems [48]**

Describes safety aspects for people and their surroundings for grid-connected EES systems using electrochemical subsystems.

**IEC 62933-5-3—Safety requirements for modifying grid-integrated EES systems [49]**

Covers overall safety aspects related to performing unplanned modifications in electrochemical-based energy storage systems.

**IEC 62109-1—Safety of power converters for photovoltaic systems [50]**

Defines minimum requirements for the design and manufacture of power converters for protection against electrical shock, energy hazards, fire, and other mechanical hazards.

**IEC 62109-2—Particular requirements for inverters in photovoltaic systems [51]**

Specifies safety requirements for DC-to-AC inverters and products with inverter functions used in photovoltaic power systems.

**IEC 62109-3—Safety for electronic devices combined with photovoltaic elements [52]**

Specifies safety requirements for electronic elements incorporated with photovoltaic modules or systems.

**IEC 60086-1—Primary batteries—General [53]**

Aims to standardise primary batteries in terms of dimensions, nomenclature, terminal configurations, markings, test methods, performance, safety, and environmental considerations.

**IEC 60086-2—Primary batteries—Physical and electrical specifications [54]**

Specifies physical dimensions, discharge test conditions, and discharge performance requirements for primary batteries.

**IEC 60086-4—Safety of lithium primary batteries [55]**

Specifies tests and requirements to ensure the safe operation of primary lithium batteries under intended use and foreseeable misuse.

## 2. Methodology of Battery Testing

The application of data-driven methods to battery safety faces challenges, particularly in collecting high-quality experimental data and extracting physical explanations from predictions. Large manufacturers may benefit from data-driven approaches, while smaller laboratories may find it more difficult to reproduce rare failure scenarios. Combining data-driven predictions with physics-based models and developing operando monitoring techniques could improve battery safety, and making data openly available would facilitate research efforts globally [56].

The knowledge needed to select battery testing equipment was derived from online research, manufacturer demonstrations, and laboratory visits. These visits showed that large, heavy-duty machines are not cost-effective for testing smaller cells, so different bench sizes were explored. Smaller machines are suitable for testing cells or modules, while larger machines are for handling battery packs. Battery safety testing identifies faults in lithium-ion batteries (LiBs) by simulating abuse conditions, including electrical (overcharge, short circuit), thermal (heating), and mechanical (compression, puncture) tests tailored to the application of the cell [57].

## 3. Developments in Smart, Active, and Distributed Energy Systems

In the context of modern energy infrastructure, smart, active, and distributed energy systems play a crucial role in optimising energy efficiency, improving grid stability, and increasing customer participation. In order to provide a structured comparison of these systems, Table 3 outlines their key features, benefits, challenges, and applications.

**Table 3.** Comparison of Intelligent, Active, and Distributed Energy Systems.

| Characteristics | Intelligent Power Systems | Active Power Systems | Distributed Power Systems |
|---|---|---|---|
| Definition | Advanced digital and automated systems that optimise energy production and consumption. | Systems that enable consumers to actively manage energy through storage or feed-in options. | Decentralised energy networks incorporating renewable sources and microgrids. |
| Main Objective | Enhance efficiency, optimise consumption, and improve grid stability. | Increase consumer engagement and cost-effectiveness. | Ensure local energy independence and improve flexibility. |
| Technological Basis | IoT, AI, advanced metering systems. | Smart meters, energy storage, dynamic pricing. | Solar energy, wind energy, battery storage, microgrids. |
| Key Benefits | More efficient energy management, reduced losses. | Flexible consumption, cost savings for users. | Independence from the central grid, improved energy security. |
| Challenges | High initial investment, data security concerns. | Encouraging consumer participation, technological integration. | Infrastructural requirements, regulatory barriers. |
| Application Examples | Smart grids, dynamic pricing models. | Residential solar systems with storage. | Community energy networks, islanded microgrids. |

Table 3 provides a structured overview of the three energy systems, facilitating a clearer understanding of their roles and differences. These systems are an integral part of the transition to a more efficient and resilient energy infrastructure. Future research should explore the integration of these approaches to maximise their benefits and address existing constraints [58].

Table 4 presents two technological areas that are crucial for the future of the energy sector: different types of batteries and modern energy systems. Although they have different functions, their combined use is key to achieving sustainable and efficient energy use.

Battery technologies are mainly used to store electrical energy. The different types—such as lead–acid, lithium-ion (NCM, LiFePO4), lithium–sulphur (Li-S), and solid-state batteries (ASSBs)—differ significantly in terms of energy density, energy efficiency (loss), safety, lifetime, and development status. Traditional technologies (e.g., lead–acid) offer a lower energy density, while newer developments (e.g., Li-$O_2$, ASSB) are theoretically capable of extremely high performance but are still in the research phase. The main challenges include the balance between material cost, cycle life, and energy density and safety.

**Table 4.** Batteries vs. smart grids: a side-by-side comparison.

| Aspect/Type | Battery Technologies | Energy Systems |
|---|---|---|
| **Technology Type** | Energy storage solutions (chemical-based) | Systems for energy generation, storage, and distribution |
| **Examples** | Li-ion (NCM, LiFePO4), Li-$O_2$, Li-S, ASSB, lead–acid | Intelligent power systems, active power systems, distributed power systems |
| **Main Objective** | Store energy, achieve high energy density, enhance safety and lifespan | Increase efficiency, decentralise energy, boost consumer engagement |
| **Energy Efficiency/Loss** | 5–40% energy loss depending on the type | System-level efficiency improvements, reduction of energy losses |
| **Energy Capacity/Density** | 30–3500 Wh/kg (theoretical max up to 2500–3500 for some types) | Not directly relevant; focus is on system-level energy management |
| **Maturity/ Development Stage** | Some are commercially available (Li-ion), others are still under development (ASSB, Li-$O_2$) | Increasingly adopted, but facing technological and regulatory challenges |
| **Key Challenges** | Lifespan, stability, cost, raw material prices, ongoing research phase | High initial investment, data security, infrastructure, and regulatory barriers |
| **Application Examples** | Electric vehicles, energy storage systems, solar energy setups | Smart grids, community energy networks, islanded microgrids |
| **Technological Basis** | Chemical reactions, material science | IoT, artificial intelligence, smart meters, renewable energy sources |
| **Key Benefits** | High energy density, long lifespan (for some types), improved safety | Flexibility, decentralisation, consumer control, energy independence |

On the other hand, there are three main types of energy supply systems: intelligent systems, active systems, and distributed systems. These are designed to improve energy efficiency, increase grid stability, and actively involve consumers in energy management. The technological basis for such systems is provided by IoT (Internet of Things), artificial intelligence, smart meters, and renewable energy sources. Intelligent systems optimise consumption and reduce waste; active systems allow users to store and recycle energy; while distributed systems, such as community microgrids, can be decoupled from the central grid, increasing energy independence.

Both areas are essential for the energy systems of the future: while batteries bridge the time gap between energy production and consumption, smart systems ensure efficient distribution, use, and control. A harmonised combination of the two is needed to create a reliable, sustainable, and resilient energy grid [59–61].

Artificial intelligence (AI) and machine learning (ML) are revolutionising the development of battery technologies and energy systems, playing a key role in increasing energy efficiency, reliability, and sustainability. An article published in the MDPI journal *Applied Sciences*, based on an analysis of more than 240 scientific papers, showed that the application of AI and ML in energy systems—including energy forecasting, fault detection, EV technology development, and smart building optimisation—is fundamentally improving system performance and scalability. Through effective data management and AI-based improvements, these technologies can bring significant advances in the design of green energy systems. However, challenges in the process, such as complex data management and the need for more advanced algorithms, suggest that future research and development will be key to overcoming these barriers. AI and ML will, therefore, not only increase energy efficiency but will also fundamentally determine the sustainability of the energy infrastructure of the future [62].

Another study aimed to apply machine learning (ML) to predict energy demand. Using five years of historical data, different models were tested, including hourly and daily forecasts, with and without external factors. The best results were obtained with the LSTM model for hourly forecasts, while the Gradient Boosting models based on decision trees proved successful for daily forecasts. The results show that external temperature increases accuracy, especially for hourly forecasts. In future research, it will be important to select the best ML model based on the forecast time horizon, data volume, and building type, and to generate forecasts using real-time data [63].

Other research aimed to apply AI-based fault detection and diagnostics methods to building energy systems. Two main approaches were investigated: data-driven and knowledge-based methods. Data-driven methods rely on training data and can detect faults with a high accuracy but only work within the range of the data. In contrast, knowledge-based methods have the advantage that they require less training data and can extrapolate from information beyond the training data. The research concludes that it would be important to combine the two approaches in the future to develop even more effective fault diagnosis methods, especially for real-world applications [64].

Another project proposed an ELM-PSO approach to optimise the management of renewable energy in smart grids. The new approach improves the accuracy of renewable energy forecasting and reduces the energy cost by optimising the parameters of the ELM algorithm. The results show that the ELM-PSO approach outperforms other optimisation techniques in terms of accuracy and cost reduction. This method can be applied to various renewable energy systems such as wind turbines, solar panels, and hydropower plants, contributing to improving the efficiency and reliability of renewable energy. The research is an important step in the development of renewable energy management in smart grids and offers a promising solution to address the challenges of renewable energy [65].

A study on AI explores different AI techniques in the field of energy efficiency, with a special focus on IoT-generated big data and anomaly detection. Energy efficiency reduces $CO_2$ emissions, thus mitigating climate change and improving human health. However, the application of AI systems raises privacy issues, as the models collect a lot of information about users and buildings, which can be misused in case of an attack. Solutions to protect user data could be anonymous data usage or federated learning, which allows for algorithm training on decentralised servers. Systems are not immune to attacks; especially those based on IoT devices are vulnerable to DoS and FDI attacks [66].

Another research provided an overview of the integration of AI techniques in the optimisation of energy use in different application areas. Through an in-depth analysis of 17 research methods, including studies of solar energy systems, thermal energy management, smart grids, industrial automation, fuzzy logic control, reinforcement learning, genetic algorithms, drawing intelligence, machine learning, neural networks, and predictive analytics, valuable insights into the strengths and limitations of these approaches were provided. The analysis highlighted the importance of AI-based algorithms and predictive analytics in monitoring energy use in real time and making dynamic adjustments, thereby increasing efficiency and sustainability in different sectors. The paper also presents future research directions that will facilitate the integration of AI in energy consumption optimisation [67].

The use of artificial intelligence (AI) and machine learning (ML) is becoming increasingly important in addressing climate change and optimising energy systems. AI and ML technologies are significantly improving the efficiency, predictability, and sustainability of energy systems, especially in predictive analytics and the optimisation of renewable energy operations. AI models are used not only to improve energy consumption and distribution, but also to predict maintenance needs, which reduces downtime and increases system reliability. In addition, AI and ML technologies are reforming energy management through real-time data processing and dynamic adaptation, enabling energy systems to respond more flexibly to global climate change and new energy demands. However, the application of AI and ML also faces challenges such as data quality and availability issues, high computational demands, and the risk of over-learning models. Despite these challenges, a large body of research points to the development and application of AI technologies as essential to the realisation of sustainable energy systems [68].

Another article provided an overview of the role of artificial intelligence (AI) in modern energy systems, focusing on four main areas: clean energy supply, demand-side management, transmission and distribution systems, and technological innovation. The results show that AI plays a key role in optimising renewable energy production, forecasting demand, and increasing the efficiency of energy systems. Applications of AI include optimising photovoltaic systems, demand-side management through smart meters, and the detection of grid faults. In addition, AI contributes to the development of energy materials such as photovoltaic systems and energy storage. The article also highlights three main trends: the role of AI is becoming more central, the commercial application of AI technologies is growing, and there are fundamental developments in the field of energy materials. However, the research also highlighted challenges such as privacy, security, and the environmental impact of AI applications [69].

Research and analyses show that AI (artificial intelligence) and ML (machine learning) have a key role to play in increasing energy efficiency and promoting sustainable energy supply. In particular, the application of AI will bring significant improvements in the optimisation of renewable energy systems, energy consumption forecasting, fault finding, and smart building management. Various research studies have also shown that AI-based systems can increase energy efficiency, reduce costs, and improve system reliability. Machine learning can be used to make more accurate predictions about energy consumption and detect faults in building energy systems more quickly. Optimisation methods for managing energy storage and renewable energy sources such as wind and solar power can further improve energy efficiency. However, research also highlights challenges such as data quality, the need to improve algorithms, and privacy concerns. Future research and development will be key to overcoming these barriers, and the role of AI-based systems in building sustainable energy infrastructures is expected to grow.

## 4. Battery Safety and Performance Tests: Practical Implementation

### *4.1. Detailed Description of Testing Procedure*

The different testing procedures have been grouped according to the knowledge acquired. This is shown in Table 5 [70].

- Performance and electrical tests
  These tests do not necessarily end in fire or explosion, so they can be carried out in the test hall.
  - **Charge and Discharge Test:** This test involves repeatedly charging and discharging the battery to assess its capacity, efficiency, and stability over several cycles [71].
  - **External Short Circuit Test**: This test simulates a direct connection between the positive and negative terminals of the battery to gauge the battery's response to short circuits and ensure that it does not ignite or explode. This type of short circuit is a form of electrical abuse that can destabilise the battery, especially during collisions or deformations [72].
  - **Overcharge**: The battery is charged beyond its maximum capacity to assess its ability to withstand overcharging conditions without failure or dangerous events [73].

    - **Forced Discharge**: This means that the battery is fully discharged, often to a voltage lower than its operating voltage range, to test its response and safety in extreme discharge conditions [74].
- Environmental tests
    - **Altitude Test**: The battery is tested in a low-pressure environment, such as at a high altitude, to ensure that it works safely and efficiently [75].
    - **Thermal Test**: The battery is exposed to extreme temperatures to evaluate its thermal stability and performance over a wide temperature range [76].
    - **Dust Test**: The battery is tested in dusty environments to ensure that its casing and seals are effective in keeping out dust [77].
    - **Salt Spray Test**: This test simulates a corrosive environment where the battery is exposed to salt spray to test its resistance to corrosion [78].
    - **IP Water Test**: The battery is subjected to different levels of water exposure to test its water resistance according to its ingress protection (IP) classification [79].
    - **Temperature Shock Test**: The battery is moved rapidly between temperature extremes to test its ability to withstand sudden temperature fluctuations without damage [80].
- Abuse tests

**Table 5.** Grouped breakdown of different testing procedures.

| Electrical | Climate | Abuse |
|---|---|---|
| Charge, discharge<br>Short circuit<br>Overcharge<br>Forced discharge | Low pressure<br>Thermal<br>Dust test<br>Salt spray test<br>IP water test<br>Temperature shock<br>High and low temperatures | Crush<br>Impact<br>Drop<br>Shock<br>Vibration<br>Fire resistance<br>Sled Test |

These tests examine how energy storage devices perform and fail in expected abuse situations, systematically documenting failure modes and responses. The objectives include testing to failure, performing quantitative analysis, documenting improvements, and developing new procedures to evaluate cell performance under likely abuse conditions.

These tests are the most dangerous, as there will almost certainly be an explosion or fire during the test.

- **Crush and Nail Penetration Test**: The battery is subjected to crushing forces to test its structural integrity and safety under extreme mechanical loads [81].
- **Drop Test**: The battery is dropped from a specific height to test its durability and performance after impacts.
- **Fire Resistance Test**: The battery is exposed to flames to assess its resistance to fire and ensure that it does not catch fire or explode [82,83].
- **Sled Test**: This test simulates accident conditions by moving a sled-mounted battery at a high speed on a track. The test evaluates the structural integrity and safety performance of the battery under impact forces [84].
- **Mechanical Shock Test**: The battery is subjected to sudden mechanical shocks to assess its resistance and safety.
- **Vibration Test**: The battery is subjected to vibration testing to evaluate its performance and durability under conditions that simulate transportation or use in a vibrating environment.

### 4.2. Equipment Needed to Perform the Tests

Table 6 shows the test equipment required for all tests. As mentioned above, the larger machines used to test EV battery packs have a much higher resource consumption. Therefore, it makes sense to use a smaller machine for the smaller types of tests (cell, module) [26].

**Table 6.** Different machine needs for tests.

| Test | Machine Name | Comment |
| --- | --- | --- |
| All electrical tests | Battery cycler | All types of electrical tests can be covered by 1 type of battery cycler equipment. |
| Thermal test | Climate chamber | These can be combined with vibration chambers |
| Vibration test | Vibration tester | The testing procedure is loud so you may want to place it separately |
| Shock test | Shock tester | The equipment should be explosion-proof |
| Altitude test | Vacuum chamber | |
| Drop test | Drop test machine | |
| Sled test | Sled test machine | This machine is large; it needs about a 4x10 m testing space |
| Fire resistance test | Fire resistance equipment | This machine should be isolated from everything |
| Crush and nail penetration test | Crush tester | The two tests can be performed together in one machine |
| Temperature shock test | Temperature shock chamber | Like the thermal test, but here the battery is moved rapidly between temperature extremes |
| Salt spray test | Salt spray chamber | OEM specific test |
| IP water test | IP testing equipment | OEM specific test |
| Dust test | Dust test chamber | OEM specific test |

### 4.3. Testing the BYD Dolphin Battery According to UN ECE R100

In this study, the battery pack of the BYD Dolphin was evaluated according to the UN ECE R100 standard, which provides guidelines for evaluating the safety, durability, and performance of electric vehicle batteries under various operating and accident conditions. With a total energy capacity of 44.9 kWh, a nominal voltage of 332.8 V, and a weight of 308.6 kg, the BYD Dolphin battery pack was subjected to rigorous tests to simulate electrical, mechanical, and thermal loads. These tests were essential to validating safety compliance and ensuring the reliability of the battery's performance. The detailed procedures and findings of each test stage are presented below.

**Electrical safety test:** To determine the Dolphin's battery pack's resilience to electrical faults, short circuit, overcharge, and over-discharge tests were conducted as required by the UN ECE R100 standard.

**Short-circuit test:** The battery pack was subjected to a controlled short-circuit to simulate an abnormal current surge by establishing a low-resistance connection between the poles, which generated peak currents to evaluate the safety characteristics of the package. The results showed that the BYD Dolphin battery's protective circuit immediately interrupted the current flow, effectively preventing the risk of thermal runaway.

**Overcharge and discharge test:** In the overcharge tests, the battery was charged above the rated voltage to simulate an electrical failure, while in the overload tests, the battery was discharged below the recommended minimum voltage. Dolphin's battery management

system (BMS) responded by stopping overcharging and overloading, preserving battery health and protecting against capacity loss. This indicates the strong ability of the BMS to control charge levels, which increases the overall safety of the battery.
**Mechanical load testing:** The UN ECE R100 standard requires mechanical tests to simulate the shocks and vibrations experienced during typical vehicle operations. In the case of the BYD Dolphin battery, these tests included vibration, mechanical shock, and compression.
**Vibration test:** The Dolphin battery was subjected to a multiaxial vibration test with vibrations between 7 and 50 Hz. The aim was to simulate the stresses, which were caused by continuous movement during the real driving conditions.

The results showed that the structural integrity of the battery was outstanding, as no cracks or structural separations were observed, and no leakage was observed. This robustness shows that the Dolphin battery is well able to withstand the vibration resistance requirements expected in automotive applications and can, therefore, be used with high reliability in real driving situations.

**Mechanical shock test:** The battery was subjected to abrupt accelerations along three orthogonal axes to simulate collision impacts. Each shock was applied at a peak acceleration, which was set by the UN ECE R100 standards. The battery maintained both structural and electrical stability, showing no internal displacements or external deformations, thereby proving its resilience to the sudden forces.
**Thermal stability and fire resistance testing**: It verified the Dolphin's battery performance across temperature fluctuations and its fire resistance.
**Thermal cycling test:** Exposing the battery to a temperature range of −40 °C to 60 °C in repeated cycles simulated extreme environmental conditions. It remained stable over the different cycles, and no capacity loss or safety risk was observed. This fact underlines the adaptability of the battery to different climatic conditions. This is key for different geographical applications. The results suggest that the Dolphin battery offers outstanding performance not only in terms of durability but also reliability, making it ideal for use in a wide range of environmental conditions.
**Fire resistance test:** During the test, the battery was exposed to direct flames. The casing and insulating materials of the battery pack performed exceptionally well. The test confirmed that Dolphin battery packs are designed with fire safety in mind and are highly effective in protecting the internal batteries from the risk of fire. The results show that this battery is a reliable choice for safe operation.

In summary, the testing of the BYD Dolphin battery under UN ECE R100 conditions showed strong resistance in the electrical, mechanical, and thermal categories. Battery features, including a sophisticated BMS and durable structural design, effectively protected the battery against electrical stress, shocks, and extreme temperatures. This test confirms that the BYD Dolphin battery meets the UN ECE R100 safety standards, making it reliable and suitable for market introduction in electric vehicles. The results also confirm that the Dolphin battery can be used in real-world environments and meets international standards.

## 5. Discussion

The results of this research are relevant for future trends in electric vehicles and battery production, especially regarding the dominance of new technologies such as Li-ion batteries and next-generation solutions. Researchers and manufacturers are working to improve regeneration techniques and performance, particularly in the areas of rare material substitution and sustainability.

The growth in demand for electric vehicles is expected to further increase the need for lithium-ion batteries, which will pose challenges in terms of material supply and manufacturing capacity. Several regulations, particularly the EU's 2035 targets, will further boost the uptake of electric vehicles but will also generate strong competition between manufacturers.

Testing batteries is critical to ensuring that they operate safely and efficiently. Various testing procedures, such as charging, short-circuit, and mechanical tests, help to optimise battery performance and minimise potential hazards. Compliance with industry standards is essential, especially in sectors such as transport and consumer electronics.

Research has also shown that data-driven methods can help improve safety and performance, but there are still many challenges ahead, especially for smaller laboratories. The widespread use and standardisation of battery safety testing will be key to future developments.

## 6. Conclusions

This review highlights the crucial importance of standardised battery testing in ensuring battery safety, reliability, and optimal performance, especially given the rapid evolution of battery technologies such as solid-state and lithium–sulphur batteries. Current international testing standards, while valuable, often struggle to keep pace with emerging technologies and diverse real-world conditions, leading to potential inconsistencies in evaluating battery behaviour.

Our analysis underscores the necessity of continuous updates to testing protocols, driven by close cooperation between industry experts, regulatory bodies, and the scientific community. Such collaborations can effectively bridge gaps and harmonise testing methods globally, improving comparability and enabling a safer integration of advanced batteries in applications such as electric mobility and energy storage.

The practical implementation of standardised testing protocols, illustrated through the detailed case study of the BYD Dolphin battery, confirmed that comprehensive testing across electrical, mechanical, and thermal domains is essential to validate battery safety and performance under realistic operating conditions.

Future work should focus on refining data-driven and operando-monitoring techniques, promoting open-access databases to facilitate a wider adoption of advanced testing methodologies, and further enhancing battery sustainability through improved recycling and regeneration practices. Such initiatives will significantly contribute to safer, more reliable, and environmentally conscious battery technologies.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| EV | Electric vehicles |
| Li-ion | Lithium-ion |
| EES | Electrical energy storage |

| | |
|---|---|
| HES | Hydrogen energy storage |
| ASSB | All-solid-state battery |
| CAN | Controller Area Network |
| LNG | Liquefied natural gas |
| ICE | Internal combustion engine vehicles |
| BEV | Pure electric vehicle |
| LIB | Lithium-ion battery |
| HEV | Hybrid electric vehicle |
| ESS | Energy storage systems |
| AI | Artificial intelligence |
| ML | Machine learning |
| OEM | Original equipment manufacturer |

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