National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Knowledge brief

The ideal home battery: criteria for safety and sustainability

RIVM

A. van Leeuwenhoeklaan 9
3721 MA Bilthoven
P.O. Box1, 3720 BA Bilthoven
The Netherlands
www.rivm.nl/en

T 088 689 89 89

Authors:
S. Ouhajji
J.W.E. Coenen
L.H. Soeteman-Hernandez
F.F.H. Teunissen
N.W. van Veen
J.P.A. Lijzen
Centre:
VSP, DMG, VLH
Contact:
johannes.lijzen@rivm.nl
Reference:
KN-2026-0039
DOI:
10.21945/RIVM-KN-2026-0039
Date:
23 September 2026

1 Introduction

Context

The energy transition is advancing quickly, increasing the need for effective ways to store and manage renewable energy at the household level. Batteries are key to achieving this transition. In 2025, the development and use of home batteries in the Netherlands are accelerating, driven by government policies and rising prices of non-renewable energy (de Haan et al., 2026). Despite strong promotion and technological advances, home batteries currently face uncertainties related to their composition, risks related to substances, safety, environmental impact, and cost-effectiveness. Rather than evaluating each battery individually, it might be more efficient to define the characteristics of an *ideal* home battery. However, a clear description of criteria that constitutes an ideal home battery is lacking, hampering policy makers, innovators and the public to systematically compare technologies for safety and sustainability, and give direction to innovations. When implementing new energy technologies, it is important to make sustainable choices during product development, and evaluate the different options using clear criteria related to safety, sustainability, and long-term performance. Policy and regulatory measures can address these challenges and guide innovation. This exploratory study on SSbD-criteria for home batteries was carried out in the context of knowledge base for energy transition, financed by the Ministry of economic affairs and climate.

Policy context on batteries and safe-and-sustainable-by-design

The European Commission (EC) has identified sustainable prosperity, competitiveness and strategic autonomy as core priorities, emphasizing the need for innovation that strengthens Europe's economic resilience and global leadership (EU, 2025). Within this context, the regulatory framework for batteries, particularly those used in home energy storage systems, constitutes a key element of the EU's efforts to advance innovation that is Safe and Sustainable by Design (SSbD) (EU, 2023). To support this, policies such as the *Ecodesign for Sustainable Products Regulation* (ESPR; EU, 2024b), the Battery Regulation and the digital battery passports are introduced (EU, 2023).
The *ESPR* functions as the EU's overarching framework for improving the sustainability of products placed on the European market. It identifies batteries as a priority product group and introduces horizontal requirements for durability, reparability, energy efficiency, and circularity. The SSbD approach and criteria for home batteries can help to embed criteria into product design from the outset and help ESPR operationalisation.
Building on this foundation, the *EU Battery Regulation* establishes comprehensive lifecycle requirements for all batteries (including home batteries). It introduces requirements for safety, sustainability, and circularity, expands extended producer responsibility and mandates conformity assessments for design, material content, performance, and end-of-life management. The Battery Regulation also introduces the Digital Battery Passport, which will become mandatory in 2027 for certain types of batteries.

The passport provides traceability across the entire lifecycle by disclosing information on, among others, material composition, carbon footprint, performance, and recycling. The Critical Raw Materials Act (CRMA) (EU, 2024a) complements the Battery Regulation's due diligence requirements by strengthening supply chain resilience. Specifically, the CRMA aims to secure and diversify Europe's access to essential battery materials such as lithium, cobalt, and nickel, which are subject to significant geopolitical pressures. To achieve this, the Act promotes domestic extraction, processing, and recycling, while encouraging strategic partnerships to reduce dependency on single suppliers.

Dutch policy on batteries[1] aims to harness batteries as a key enabling technology for the energy and mobility transition, while addressing strategic dependence and sustainability. The strategy's overall goal is that the growing use of batteries in society proceeds safely, responsibly and sustainably. To achieve this, the government works along five pillars: securing and responsibly sourcing critical raw materials; increasing circularity (including implementing the EU Battery Regulation and producer responsibility, leading to recycling and design for longer lifetimes); improving safety (e.g. via knowledge development, SSbD principles, and cybersecurity measures); strengthening economic perspectives (e.g. via industrial policy and innovation funding); and integrating batteries into the future electricity system. Batteries are explicitly seen as one of the flexibility options to help solve grid congestion and safeguard security of supply, provided they are connected in a congestion-neutral way and embedded in robust regulatory frameworks.

Aim of the study

The main goal of this exploratory study was to develop a description of SSbD-criteria that constitute an ideal home battery and to translate these into a practical approach that guides towards more safe and sustainable innovation and enables comparison of existing and novel home batteries with this ideal. Life-cycle thinking is used to identify potential safety and sustainability problems early in the development process. The main research question was: *What parameters and accompanying criteria of the SSbD approach can be used in an approach for defining an ideal home battery, and to what extend do current and near-future batteries match these criteria?* The approach of setting ideal characteristics of a home battery may also serve as a basis for application to other energy transition technologies, support SSbD for batteries, and contribute to knowledge development for current safety and sustainability regulatory frameworks.

Methodology

First, the home battery landscape in the Netherlands was explored using questionnaires for suppliers and producers, interviews with knowledge organisations, and an exploration of relevant literature. Based on this inventory the types of home batteries currently in use or expected to become available in the next five years were identified and the characteristics were described (Section 2). Second, the properties of an ideal home battery were defined in terms of functionality, safety, sustainability, circularity, criticality of materials and cybersecurity (Section 3). These criteria were specified using literature and characteristics of 'ideal home batteries' were formulated. The refined criteria were applied to the selected types of home batteries (Section 4). Finally, in Section 5 conclusions were drawn regarding a practical approach with criteria for defining an ideal home battery.

[1] Kamerbrief over voortgang strategische aanpak batterijen december 2025 | Rijksoverheid.nl

2. Inventory of battery types and characteristics

Inventory of the market on home batteries

To gain an overview of the home batteries currently available and those expected to enter the Dutch market within five years, a questionnaire was developed and distributed among parties affiliated with EnergyStorage NL[2] (trade association for the Dutch energy storage sector). The questionnaire was designed to gather information on, among others, battery technologies, technical specifications, and each company's role (*i.e.*, manufacturer, distributor or installer). Only four out of fifteen companies completed the questionnaire, all of which were manufacturers or sellers to consumers; installers did not participate. The battery technologies mentioned, include lithium-ion batteries with lithium-iron-phosphate (LFP) cathodes, lithium-ion batteries with nickel-manganese-cobalt (NMC) cathodes, and gel lead-acid batteries. An online scan confirmed that lithium-ion home batteries with LFP cathodes currently dominate the Dutch market. Semi-structured interviews were conducted with the Consumentenbond, Milieu Centraal and CE Delft to obtain additional insights into the home batteries landscape.

The Consumentenbond reported that installers estimate about one in four new solar panel systems are installed together with a battery. Three developments are driving this demand: (1) the termination of the net metering scheme from 2027, making self-consumption financially more attractive; (2) stricter capacity tariffs and higher grid management costs that increase charges on peak consumption[3]; (3) tightened safety and insurance standards following a NIPV report on fire risks associated with home batteries (NIPV, 2024). The Consumentenbond started testing plug-and-play home batteries, which show large consumer interest and market uptake. Plug-and-play home batteries are expected to become more popular.

Milieu Centraal reports that most home batteries are lithium-ion batteries with LFP cathodes, with a smaller share using NMC or nickel-cobalt-aluminium (NCA) chemistries. Although home batteries aim to help address grid congestion, they may contribute to local grid congestion issues if large numbers of batteries are charged or discharged simultaneously. In 2023, an estimated 40.000 home batteries were installed in the Netherlands (Dutch New Energy Research, 2024). This number reached 163.500[4] in 2025 indicating rapid market growth.

CE Delft confirms that the market is dominated by lithium-ion batteries, while the development of two new types of home batteries is also observed: sodium-ion batteries and saltwater batteries. CE Delft also foresees local grid congestion problems if home batteries are installed at scale. They note that there is currently no viable business case for home batteries, with payback periods varying widely (from 1–10 to 10–22 years), which makes it an uncertain investment. From a sustainability perspective, CE Delft takes an ambivalent stance: using electric vehicles for dual purposes is more energy efficient, although it does result in increased battery wear and tear.

Characteristics of various types of (home) batteries

Lithium-ion batteries. A lithium-ion battery is a rechargeable battery in which lithium ions move between two electrodes via an electrolyte. The anode (negative electrode) is usually made of graphite, while the cathode (positive electrode) is often made from a lithium metal oxide. The electrolyte enables lithium-ion transport and ensures stability and is typically an organic liquid containing lithium salts, such as dimethyl carbonate ($C_3H_6O_3$) with lithium hexafluorophosphate ($LiPF_6$).

[2] Website Energy Storage NL

[3] Vervolgonderzoek Energietarieven in Transitie

[4] https://allesoververduurzamen.nl/thuisbatterij-statistieken/

For home energy storage, the two most relevant types of lithium-ion batteries are NMC and LFP. Both usually use graphite for the anode, but differ in the cathode material:
NMC (Lithium-Nickel-Manganese-Cobalt Oxide) batteries have a cathode composed of a combination of nickel, manganese, and cobalt in varying proportions. NMC batteries are widely used in electric vehicles because they offer a good balance between high energy density, long lifespan, and safety.
LFP (Lithium-Iron-Phosphate) batteries have a cathode made from lithium-iron-phosphate ($LiFePO_4$). LFP batteries have a lower energy density than NMC batteries, but they provide both higher thermal stability and a longer lifespan.

While lithium-ion batteries are generally safe, they can experience thermal runaway. This is an uncontrolled rise in temperature caused by, among others, internal short circuits, overcharging, high temperatures, or physical damage, which can lead to fire or explosion. Aging, too rapid charging, overcharging, or charging at too low temperatures can cause metallic lithium to deposit on the graphite anode surface, a process known as lithium plating. This reduces battery capacity and may cause dendrite (needle) formation on the anode, that can create short circuits and can also trigger thermal runaway.

Sodium-ion batteries. A sodium-ion battery operates on the same basic principle as a lithium-ion battery but uses sodium ions as charge carriers. The cathode is typically made from sodium-rich transition metal oxides, such as sodium manganese oxide ($NaMnO_2$), sodium iron phosphate ($NaFePO_4$) or Prussian blue analogues ($Na_xM[Fe(CN)_6]$, with M= Fe, Mn, Ni, etc.) The anode is usually composed of hard carbon. The electrolyte consists of a sodium salt dissolved in an organic solvent, which provides high ionic conductivity, although it is flammable. Sodium is abundant and inexpensive, unlike lithium. Additionally, some sodium-ion battery chemistries, similar to LFP lithium-ion batteries, are less prone to thermal runaway. At present, sodium-ion batteries have lower energy density and a shorter lifespan compared to lithium-ion batteries. Sodium-ion batteries are poised to take over the market thanks to better cold performance and greater material availability. Because they are initially more expensive to produce than traditional lithium-ion batteries, large-scale development is slowed (Yao et al., 2025).

Gel lead-acid batteries. A gel lead-acid battery is a type of lead-acid battery that uses a gel-like electrolyte (thickened sulfuric acid with silica) which prevents leakage and makes the battery maintenance-free. The anode is typically made of lead dioxide (PbO_2), while the cathode consists of spongy lead (Pb). Gel lead-acid batteries are less prone to overheating, fire, or explosion compared to lithium-ion batteries. They are more tolerant of improper charging, pose a lower fire risk, and are relatively simple and efficient to recycle. Gel lead-acid batteries do not use rare earth metals, but they are heavy, less powerful, and have a shorter lifespan than lithium-ion batteries. Gel lead-acid batteries are more sensitive to deep discharge and are more likely to suffer permanent damage compared to other battery types.

Saltwater batteries. A saltwater battery (aqueous sodium-ion battery, ASIB) is an electrochemical battery that uses an aqueous salt solution as its electrolyte. This makes the battery non-toxic, non-flammable, and environmentally friendly. At equal capacity, a saltwater battery is typically larger and heavier than sodium-ion, lithium-ion batteries and gel lead-acid batteries. The cathode is usually made of activated carbon or a metal oxide, while the anode is often carbon or another environmentally friendly material.

Saltwater batteries contain only salt, water, and carbon. In principle, such materials are easy to recycle or can be safely disposed. Saltwater batteries can be discharged to 100%

depth of discharge without damage, which is unique among battery types. However, they charge more slowly than lithium-ion batteries. Although they can withstand many charge-discharge cycles, their lifespan in years is sometimes shorter than that of the best lithium-ion batteries. Given that the electrolyte is water-based, saltwater batteries are less suitable for use below freezing temperatures. There are few suppliers, and one of the few, Greenrock, recently went bankrupt[5].

Solid-state batteries. A solid-state battery operates on the same basic principle as a conventional lithium-ion battery but uses a solid electrolyte (usually ceramic or polymer) instead of a liquid organic electrolyte. The cathode is often similar to those used in lithium-ion batteries. The anode can be graphite; the use of metallic lithium or silicon as an anode is promising, thanks to the stability provided by the solid electrolyte. The non-flammable, solid electrolyte significantly reduces the risk of fire, short circuits, or leakage. Using lithium metal as the anode enables much higher energy density, resulting in lighter and smaller batteries with greater capacity. Solid-state batteries experience less chemical degradation of the electrolyte and electrodes, leading to a longer lifespan and more charge cycles. They can often operate at higher and lower temperatures without performance loss or risk of thermal runaway. With no liquid organic solvents, they offer improved safety and environmental benefits. In addition, ion conduction in solid electrolytes is generally lower than in liquid electrolytes, which can limit charging speed, though new materials are improving this aspect. The technology is still in development; mass production and large-scale commercial applications are currently limited. Nonetheless, several companies, including Toyota, Nissan, BYD, and CATL, are actively working on advancing solid-state battery technology[6].

Battery management system and location of home batteries

The Battery Management System (BMS) can play a role in monitoring and managing battery safety. The BMS, once a simple protection against overcharging and over-discharging, now acts as the brain of the battery; monitoring, optimizing, and communicating with other systems. This complexity makes modern batteries more vulnerable to cyberattacks. Compromising the BMS can lead to physical damage such as overheating or fires. The role of batteries in smart grids and critical infrastructure increases these risks, and robust cybersecurity measures are therefore essential to prevent operational failures.

Some factors are important for all type of batteries. The *location* of a home battery is for example important for safety in the event of thermal runaway. Several considerations may limit the available options: a. Do not place the battery in an escape route; b. The immediate surroundings should be constructed from non-combustible materials and have sufficient ventilation; c. Protect the battery from physical damage, heat, cold, flooding, moisture, snow, and direct sunlight (e.g. attics are an unsuitable location, because they can become excessively warm; d. Outdoors, batteries must be actively protected against low temperatures (e.g. with heating elements). *Wall mounting*: home batteries are often securely mounted to the wall, but this makes it difficult for emergency services to remove the battery during a fire (removal is sometimes the best way to fight the fire (NIPV, 2026)). Mobile plug-in home batteries usually do not meet the same safety standards as fixed installations which are installed by certified professionals (NEN 1010/AREI). However, in case of emergency, they are generally easier to remove.

[5] GREENROCK zoutwaterbatterij: duurzame off-grid oplossing

[6] https://electrek.co/2026/06/25/catl-solid-state-battery-level-4-2030/

3. Characteristics of an ideal home battery

Relevant SSbD frameworks

There are several SSbD-methods and criteria available. We mention here two most relevant methods that are useful for the development of a practical screening method for an ideal home battery.

European Commission's (EC) revised SSbD framework. This builds on the 2022 JRC proposal and the accompanying Commission Recommendation. A key innovation is the introduction of SSbD Fundamentals, which provide the conceptual backbone for assessing safety and sustainability throughout the innovation process. The revised framework starts with a structured scoping analysis to identify and prioritize the most relevant issues for each innovation, emphasizing early engagement across the life cycle. Safety is evaluated through an integrated assessment of intrinsic hazards and exposure in occupational, consumer, and environmental contexts, while process-related risks linked to alternative production routes are also considered. Environmental sustainability is assessed using life-cycle methods, with screening shortcuts and benchmarks to support early-stage innovation. The socio-economic sustainability component addresses social fairness, supply chain vulnerabilities, life-cycle costs, and competitiveness. To support decision-making, the framework features a dashboard-style visualisation to highlight trade-offs, uncertainties, and priority areas.

RIVM report 'Towards safe and sustainable battery innovation: A conceptual framework'. RIVM published a battery-specific conceptual framework for responsible battery development that builds on SSbD principles. The framework aligns with the EU's Competitiveness Compass (2025), which identifies responsible battery innovation as a key driver of Europe's industrial strength, clean-energy transition, and cross-value-chain collaboration. The revised EC SSbD framework offers valuable building blocks, but it is not sufficient for the battery sector, which should also address battery-specific challenges such as criticality, circularity, and cybersecurity. This framework consists of three core elements:

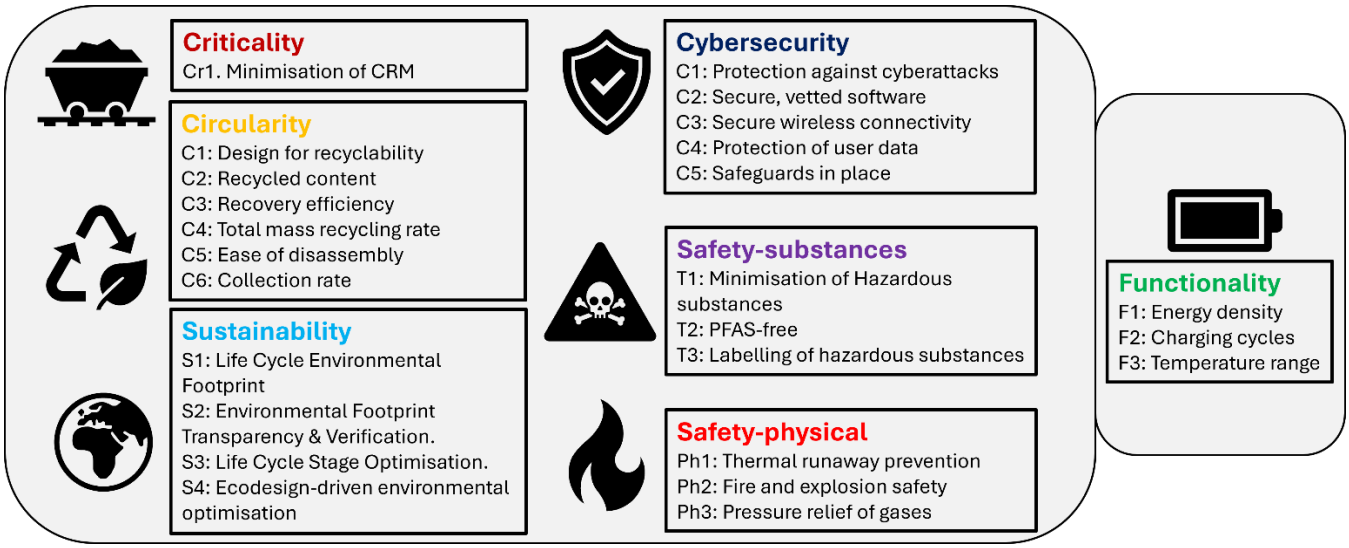
1. *Scoping, design, and scenario formulation.* The process begins by defining the battery type, intended applications, and performance goals, and identifying which components require redesign. Early multi-stakeholder engagement is essential to build shared understanding and align expectations across the value chain.
2. *Defining ambitions and information needs for responsible design.* Ambitions are translated into concrete requirements across five design principles: safety, sustainability, circularity, criticality, and cybersecurity. Information needs evolve with technological maturity.
3. *Gathering and assessing information for responsible design.* Data on the five design principles are collected and assessed to inform decisions. These insights guide whether and how development should continue, ensuring alignment with societal expectations, regulatory requirements, and business viability.

SSbD-criteria for defining an ideal home battery

All SSbD approaches share the principle of steering innovation with a multi-dimensional compass that spans the entire life cycle and value chain. Based on the RIVM report for safe and sustainable battery innovation, seven criteria or design principles were identified for defining an ideal battery: functionality, safety (substances), safety (physical risks), sustainability, circularity, criticality, and cybersecurity. In this study, functionality is treated as a separate criterion, and safety is divided into two types: safety related to hazardous substances and safety related to physical effects. These criteria jointly operationalize SSbD, providing a framework for assessing and developing an ideal home battery. Figure 1 presents the seven main parameters and accompanying criteria identified that are relevant for innovation and assessment of home batteries. For each criterion, an ideal direction of performance was defined. Such a practical approach with main and sub-criteria serves as an

SSbD compass for batteries making trade-offs visible, highlighting hotspots, and guiding iterative redesign.

Figure 1. Criteria for a practical SSbD approach for home batteries.



Functionality

SSbD begins with the intended function and use context. For batteries, this includes energy storage performance (capacity, power, lifetime, efficiency), as well as form factor, operating conditions, and integration into systems (*e.g.*, EVs or consumer electronics). With a clear 'functional unit', alternatives can be meaningfully compared, and trade-offs in safety and sustainability can be properly evaluated. Functionality is closely linked to life-cycle sustainability and circularity. The most important functionality parameters are:

- Criterion F1: energy storage capacity matched to household usage: 5-10 kWh.
- Criterion F2: lifetime measured in charging cycles (#).
- Criterion F3: safe operating temperature range (in °C), for outdoor placement.

The ideal home battery has a high capacity relative to the cost, weight of materials or environmental impact, a long lifetime (>10.000 charging cycles or 15+ years) and is resistant to a wide temperature range.

Safety-substances (intrinsic and exposure-related)

This refers to the intrinsic toxicity of active materials, electrolytes, binders, additives, and degradation products, as well as the potential exposure of workers, consumers and the environment across the battery's life cycle. Toxicity of substances is important at all lifecycle stages: mining, manufacturing, use, repair, second life and recycling. Toxicity can hinder safe reuse and recycling or require costly protective measures. Reducing toxicity is therefore a precondition for high-quality circular loops.

Criterion T1: minimisation of hazardous substances. The Battery Regulation only restricts the use of mercury in batteries above a concentration of 0,0005 wt.%. Lead and cadmium are also restricted (to 0,01 wt.% and 0,002 wt.% respectively), but only in portable batteries. Other hazardous substances are not restricted but do require labelling. (Regulation (EU) 2024/2865; EU, 2024)

Criterion T2: PFAS-free. Per- and polyfluoroalkyl substances (PFAS) are a large group of synthetic chemicals that are persistent in the environment and have been linked to adverse health and environmental effects. According to the universal PFAS restriction proposal (2025

update), batteries are included under the third restriction option (RO3): non-time limited derogations. These have been proposed for specific uses where substitution is (currently) not possible. Although the use of PFAS in batteries will not be fully restricted (permitted, albeit under certain conditions), the ideal home battery should be free from PFAS.
Criterion T3: labelling requirements. If hazardous substances cannot be replaced and are used in the battery, the ideal home battery should at provide clear documentation and labelling of all hazardous substances present ánd in which part of the battery.

Safety-physical (system, operational and societal safety)
Batteries introduce fire, explosion, and thermal runaway risks at cell, pack, vehicle, building, and grid level, leading to flammable and toxic gases that can be rapidly expelled from the battery. The following criteria are important for the design and use of batteries:
Criterion Ph1: Thermal runaway prevention. This depends on:

- *1a. Large safe operating region* (voltage and temperature). The voltage is managed by the BMS. The temperature also depends on the location. The ideal battery has a safe charge and discharge operating region of -20 to +60 °C;
- *1b. Physical robustness and compartmentalisation.* The ideal battery should be designed with sufficient physical robustness to resist external damage, and with internal compartmentalisation to limit the spread of failures or incidents. Failure by electromagnetic fields in and around the battery should also be prevented.
- *1c. Characteristics of BMS.* The BMS should include, among others, overcurrent protection, short circuit protection, overcharge and overdischarge protection, temperature monitoring, cell balancing, state of charge and state of health monitoring, isolation monitoring, and error reporting to ensure safe operation.
- *1d. sensitivity to lithium plating and dendrite formation.* Ideal batteries have no dendrite formation. This is also influenced by charging conditions and aging.

Criterion Ph2: fire and explosion safety. This depends on:

- *2a. Pressure relief of gases*. The battery system contains *small* amounts of flammable electrolytes (e.g. alkyl carbonates) and must be equipped with adequate ventilation and pressure relief mechanisms to safely release any overpressure and gases in case of malfunction or thermal events.
- *2b. fire suppression and detection.* The ideal battery has no internal fire risk or can at least detect and suppress fires within its enclosure, e.g. by compartmentalising with fire barriers or aerosol extinguishing systems.

Criterion Ph3: Toxic emissions. The ideal battery produces during thermal runaway limited volumes of smoke gasses (only released after extensive heating). Smoke contains limited amounts of corrosive smoke particles (like lithium hydroxide) and does not rapidly produce carbon monoxide and corrosive gasses (like hydrogen chloride, hydrogen fluoride).

Sustainability (environmental)
For life-cycle environmental performance, life cycle assessment (LCA) serves as the backbone of environmental sustainability, covering multiple impact categories, including at least climate change, resource use, water use, land use, and pollution across all lifecycle stages. For (home) batteries, this is essential because many impacts are upstream (mining, refining) or downstream (recycling, disposal).
Criterion S1: life cycle environmental footprint. This is defined as the total environmental impacts per functional unit (*e.g.,* kWh over the battery's service life) across all life cycle stages: raw material extraction, manufacturing, distribution, use, and end-of-life. The Battery Regulation requires the carbon footprint to be calculated and reported for each battery model and production plant. It focuses primarily on carbon footprint (kg CO_2-eq) and energy consumption, but other impact categories are also relevant: water use, resource

depletion, human toxicity and ecotoxicity (EU Environmental Footprint (EF) methodology[7]).
Criterion S2: Environmental Footprint Transparency & Verification. This is defined as the availability, completeness, and public accessibility of a verified environmental footprint declaration for each battery model and manufacturing site. This criterion reflects compliance with EU requirements for reporting and verification, supporting both consumer awareness and regulatory oversight. An ideal home battery should have a full and verified environmental footprint declaration via QR code compliant with the Battery Regulation.
Criterion S3: Life Cycle Stage Optimisation. This is defined as the distribution of environmental impacts across the battery's entire life cycle. The ideal home battery should demonstrate the absence of dominant avoidable hotspots, where impacts are minimized across all life cycle stages through design and process choices (Battery Regulation, Annex II; Soeteman-Hernandez et al., 2023)
Criterion S4: Ecodesign-driven environmental optimisation. This is defined as the extent to which the battery's environmental performance is actively optimized through product design choices. This includes material efficiency and energy-efficient production as specified in EU directives and initiatives. The ideal home battery should be designed to optimize environmental performance (Soeteman-Hernandez et al. 2023).

Circularity
Given the significant environmental impact of battery materials, circularity strategies (reuse, repair, remanufacturing, recycling) are essential for sustainable battery design. Circularity is closely linked to product life and waste management, and is enforced by EU policy (*e.g.*, Batteries Regulation). Based on requirements from this Regulation and literature addressing battery design, dismantling, and recovery performance (*e.g.*, Harper et al., 2019; Bielewski et al., 2021), circularity is operationalised with six criteria.
Criterion C1: design for recyclability. This criterion focuses on how material selection, component integration, and joining techniques influence recovery yields under current industrial conditions. Although Harper et al. (2019) analyse lithium-ion batteries from electric vehicles, their discussion of design-related barriers to disassembly and separation is relevant for stationary storage systems. The authors argue that permanent adhesives, composite structures, and highly integrated cell designs can substantially reduce recyclability, even when established recycling routes exist. Following Bielewski et al. (2021), design for recyclability also includes features that facilitate access to hazardous and valuable components (e*.g.*, reversible joints). This criterion captures intrinsic design properties with implications for recyclability.
Criterion C2: Recycled content. This is defined as the proportion of recycled materials, such as plastics, cobalt, lithium, nickel and lead, used in batteries, in accordance with the reporting and minimum-content requirements set out in the Battery Regulation. It requires manufacturers to document the percentage of recycled content for each metal using a mass-balance method. (e.g. minimum levels are from 2036 at least 26% recycled cobalt, 12% recycled lithium, 15% recycled nickel, and 85% recycled lead for industrial and electric vehicle batteries placed on the EU market).
Criterion C3: Metal-specific recovery efficiency. This refers to the percentage of a given metal that can be recovered from a battery at the end-of-life through established recycling techniques (*e.g.*, mechanical, metallurgical, pyrometallurgical treatment (Harper et al., 2019)). This criterion captures downstream recovery of specific metals under current recycling conditions (not material inputs) and therefore also depends on the recycling process used. EU regulatory targets (at least 80% of lithium and 95% of the cobalt, nickel, lead and copper in 2031) can be used as benchmark values (Regulation (EU) 2023/1542; European Commission, 2025).

[7] Environmental Footprint Methods - Green Forum - European Commission

Criterion C4: Total mass recycling rate. This criterion is defined as the percentage of the overall battery mass that can be recovered through established recycling techniques. It captures the broader end-of-life performance of recycling operations by assessing how much of the total battery is diverted from collection. The Battery Regulation sets targets for different types of batteries by 2030 (*e.g.*, by average weight at least 75% of lead-acid batteries, 70% of lithium-based batteries, and 80% of nickel-based batteries).
Criterion C5: ease of dismantling and disassembly. This is defined as the extent to which a home battery can be safely, efficiently, and non-destructively removed from its installation (dismantling) and separated into modules, cells, and component (disassembly) using existing manual or automated techniques. This is important for the repairability and maintenance. This reflects how design choices made earlier in the chain (Criterion C1), translate into operational performance. Wu *et al.* (2023) show that disassembly is essential for direct recycling and for reducing hazards during pretreatment, while Hansen *et al.* (2025) demonstrate that irreversible joints, obstructed layouts, and highly integrated assemblies impede automated dismantling. This criterion captures the safety of dismantling and disassembly and influences Criterion C3 and C4.
Criterion C6: collection rate. This involves the percentage of home batteries that are collected at end-of-life and reflects the extent to which batteries are returned to authorised handlers. The minimum collection targets for portable and light-means-of-transport batteries (*e.g.*, 80% by 2031) may be considered a relevant benchmark. Criterion 6 is a precondition for the recovery outcomes described in Criteria 3 and 4. Both can only be measured when batteries are returned to authorised collection channels.

Criticality.
Batteries rely on a range of critical raw materials (CRMs). This raises concerns about material supply risks and the need for strategic autonomy within Europe[8]. Several materials usin batteries are included on the EU's list of critical and strategic raw materials: aluminium, antimony, cobalt, copper (strategic), lithium, manganese, natural graphite, nickel (strategic), phosphorous, silicon, and heavy rare earth elements.
Criterion Cr1*:* Presence of critical or strategic raw materials. The ideal home battery should minimise the use of CRMs.

Cybersecurity.
In the context of battery systems, cybersecurity involves safeguarding the BMS and its data from digital threats that could impact safety, performance, privacy, or compliance. To address these risks, the ideal home battery and its BMS should adhere five criteria.
Criterion Cs1: protection against cyberattacks. As BMS become more complex and connected, there is an increased vulnerability to cyberattacks, exposing systems to malware, electromagnetic interference, manipulation of sensor data, fault injection, and wireless jamming. The system should be strongly protected against such attacks.
Criterion Cs2: secure, vetted software. By installing batteries in critical infrastructure like the energy grid, new vulnerabilities are introduced. Only secure, vetted software, preferably developed and audited within the EU, should be used.
Criterion Cs3: secure wireless connectivity. Wireless BMS eliminate the need for physical wiring and improve reliability but also introduce new security. Using wireless BMS, secure communication with robust encryption and authentication protocols must be ensured.
Criterion Cs4: protection of user data. The BMS collects sensitive data, including user behaviour, charging habits, and vehicle usage. Compliance with relevant data protection regulations is necessary to prevent data breaches.

[8] Critical raw materials - Internal Market, Industry, Entrepreneurship and SMEs

Criterion Cs5: safeguards in place. The system should be designed to maintain performance and safety even in the event of attempted cyberattacks, with safeguards in place to detect and respond to unauthorized changes in battery data, thereby preventing impacts on battery performance, lifespan, and efficiency.

4. Comparison of type of batteries for relevant criteria

To evaluate the selected battery types against the SSbD-criteria, extensive data are required. Some data are available in literature, while other aspects rely on expert judgement. Due to limitations in available data and scope of this study, an extensive assessment of all battery types was not feasible. Therefore, this study presents an exploratory assessment, describing the available information for each set of design criteria across battery types. The criteria are assessed provisionally, as the analysis is based on an initial scoping exercise rather than a systematic literature review. For each criterion, the assessment may vary depending on battery type, can be independent of battery type (*e.g.*, the BMS) or can be brand specific. The criteria can be used to compare products and to identify innovation areas contributing to a more ideal battery.

Functionality, The functionality varies by battery type, but is also strongly influenced by various usage factors, such as deep discharging, charging and discharging rates, and environmental factors such as humidity, vibrations and elevated temperatures. To provide a general impression of performance, the table below presents an overview of the properties of different battery types. For some types, limited literature is available.

Table 1. Functionality characteristics (relative) of existing and potential home battery technologies

Battery type	**Energy density (Wh/kg)**	**Cycle life**	**High temperature (discharge)**	**Low temperature (discharge)**
Lithium-ion (LFP)	+	+ up to +++[1]	++	-
Lithium-ion (NMC)	++	+	+/-	+/-
Sodium-ion*	+	+	++	+
Lead-gel	+/-	+/-	+/-	+/-
Saltwater	+/-	++	+++	+/-[2]
Solid-state *	+++ (expected)	++ (expected)	++ (expected)	- up to +++ [3] (expected)

1: Cycle life depends, among other factors, on type of anode.
2: Good properties above 0°C; not very suitable at temperatures below 0°C.
3: Functionality at low temperatures is highly dependent on the materials and design.
* Sodium-ion and solid-state technologies are still emerging; the indicated properties reflect current prototypes and early commercial systems and may change as the technology matures.

Safety-substances. Salt-water batteries are the safest in terms of used substances, as they only use non-toxic materials and do not contain or use PFAS (Criterion T2) or other hazardous substances (Criterion T1) (Park et al., 2016). Whereas lead-gel batteries are also free from PFAS, they contain lead, which is highly toxic and environmentally persistent, and use sulfuric acid, which is highly corrosive. However, lead in these batteries can be efficiently recovered through established recycling processes, and the sulfuric acid is normally contained (Wang et al., 2026). The use of hazardous substances (Criterion T1) is minimised in sodium-ion batteries compared to lithium-ion batteries containing nickel and cobalt (in NMC cathodes). Nickel and cobalt are considered as environmentally persistent metals. Both lithium- and sodium-ion batteries generally contain PFAS (Criterion T2), although there are exceptions (Xi et al., 2026). Additionally, they use organic solvents. The

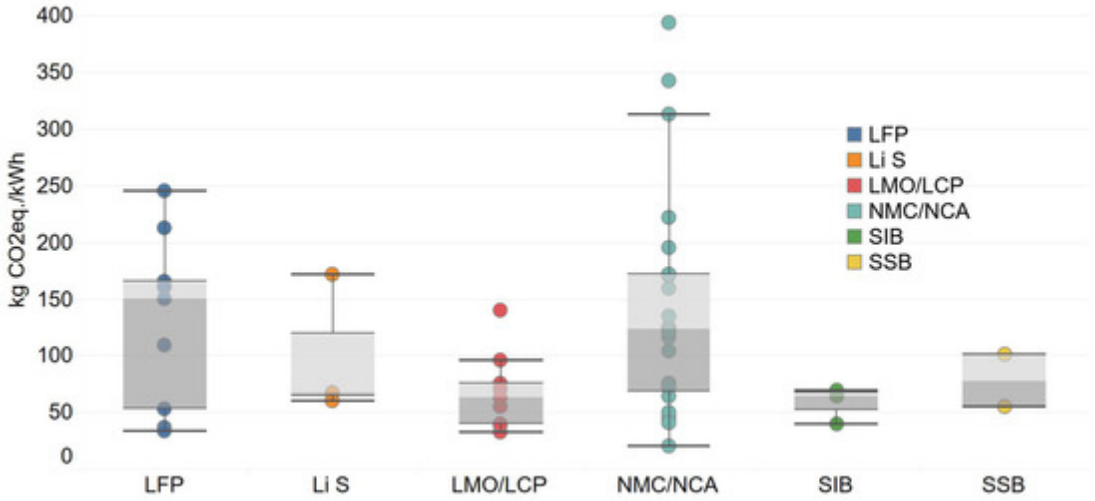
safety profile of solid-state batteries depends on the specific chemistry used; when NMC or LFP cathodes are used, their hazards are similar to conventional lithium-ion batteries. As solid-state batteries are still under development, manufacturers have the opportunity to make them PFAS-free by design.

Safety-physical. Saltwater batteries and lead-gel batteries exhibit the lowest risk: they contain little to no flammable or volatile substances, resulting in a very low risk of explosion or fire in the event of a defect or damage (Criterion Ph2). Moreover, the chance of thermal runaway with these batteries is minimal (Criterion Ph1), and hardly any toxic substances are released in case of an incident (Criterion Ph3). LFP batteries are known as the safest lithium-ion variant; they are thermally stable and much less susceptible to thermal runaway relative to NMC batteries, which can ignite or explode more easily if damaged or overcharged (Criterion Ph2). In incidents involving LFP batteries, the amount of toxic gases released is somewhat lower compared to NMC batteries, but in practice this does not make a major difference (Criterion Ph3). Sodium-ion batteries are similar to lithium-ion LFP batteries in terms of safety: they are less reactive and contain fewer flammable components than lithium-ion NMC (Criterion Ph2), and the risk of thermal runaway is lower (Criterion Ph1). Emissions of chemical substances are also relatively limited (Criterion Ph3), although this technology is still fairly new. In theory, solid-state batteries offer the highest safety of lithium-based batteries, because their solid electrolyte is non-flammable. The risk of thermal runaway, explosion, or fire is significantly lower than with conventional lithium-ion batteries (Criteria Ph1 & Ph2). In addition, fewer fumes are released in the event of an incident (Criterion Ph3). However, solid-state batteries are still under development, and their real-world safety has yet to be fully demonstrated.

Sustainability. Battery technologies are compared solely on life cycle environmental footprint per kWh and charging cycles, as this is the only criterion that distinguishes between battery chemistries. Findings from different studies sometimes contradict one another, often due to methodological inconsistencies. Figure 2 presents the greenhouse gas emissions of several of the technologies discussed in this report, as reported in the literature (Ankathi et al., 2024). The considerable spread in reported values, as well as differences in system boundaries and underlying assumptions, make it difficult to derive robust, unequivocal conclusions. Nevertheless, based on the current body of literature, a few cautious generalisations can be formulated.
Among commercially mature options, LFP batteries are often the most environmentally favourable, as these avoid cobalt and nickel (CRM), have a long cycle life, and perform well across most impact categories (Jasper et al.,2022). NMC batteries offer higher energy densities but have a greater environmental footprint due to more critical material use (compared with LFP) and shorter lifespan, partially offset by better recycling potential (Ankathi et al., 2024; Zhang et al., 2023). Sodium-ion batteries show lower mineral resource impacts and no dependence on critical materials, although at commercial scale the overall climate impact is still uncertain (Wickerts et al., 2024; Guo et al., 2023). Lead-gel batteries have low production of greenhouse gasses, but the worst life cycle performance compared to the other types due to frequent replacements (Yudhistira et al., 2022). Saltwater batteries mainly use abundant, non-toxic materials, but require more material per kWh due to low energy density and generally do not have lower greenhouse gas emissions compared to lithium-ion batteries. However, since most of the emissions originate from the polytetrafluoroethylene (PTFE) binder used in the electrolyte pellets, replacing this binder with alternative materials would greatly improve the overall environmental performance (Peters et al., 2017; Zheng et al., 2024). As shown in Figure 2, few studies have conducted LCAs on lab-scale solid-state batteries. The results of comparisons with LFP batteries are also contradictory, largely due to methodological differences. While solid-state batteries

offer high energy density and long lifetimes, their sustainability advantages remain unproven at this stage (Liu et al., 2024; Degen et al., 2025).

Figure 2. Greenhouse gas emissions per kWh of different battery technologies: LFP, NMC, sodium-ion (SIB) and solid state (SBB), not specific for home batteries. Ranges are partly due to differences in scope. Lead-gel batteries and saltwater batteries are not part of this overview. Reproduced from Ankathi, et al., 2024.



Circularity. For lead-gel batteries, a plausible proxy for the 'total mass recycling rate' (Criterion C4) is available, based on the achieved 81% recycling rate for lead-acid batteries in the Netherlands in 2023 (Eurostat, 2025). When compared with the 2025 minimum target set in the Battery Regulation (*i.e.*, 75% recycling for lead-acid), this suggests that the current recycling rate for lead-gel batteries is favourable. For the other five battery types, no reliable figures (and recycling technologies) for Criterion C4 were identified in this initial exploration. For sodium-ion batteries, the literature indicates that the economic incentive to use recycled content (Criterion C2) in batteries is low, due to the relatively low prices of primary materials, such as sodium and iron (Mashfy et al., 2026; Cai et al., 2024). No data were found for the criteria design-for recyclability (Criterion C1), ease of dismantling and disassembly (Criterion C5) and collection rate (Criterion C6). Nevertheless, it may reasonably be assumed that design choices, adequate collection, and feasible dismantling processes are essential to enable recycling (Criterion C3 and Criterion C4) and the use of recycled content (Criterion C2) in batteries. The Battery Regulation does set a minimum collection target (Criterion C6) for portable and light-means-of-transport batteries: 80% by 2031. The most recent collection rate for portable batteries and accumulators (hence, no specific battery types) was 46.5% in in the Netherlands in 2023, compared to 43% in 2012 (Eurostat, 2025). These figures cannot be applied directly to the six home-battery types, but they do suggest that the collection rate in the Netherlands shall remain far below the European minimum target by 2031. If it would be obligatory to hand in end-of-life home batteries this could change.

Criticality. In terms of strategic and critical raw materials, lead-gel and salt-water batteries are more ideal, as they do not contain *critical or strategically sensitive* materials. Sodium-ion batteries follow, as they may use some critical materials, but *having a* lower *reliance* than lithium-ion batteries. Among lithium-ion batteries, those with LFP cathodes require fewer critical raw materials than those with NMC cathodes. Solid-state batteries are more difficult to rank*:* their criticality depends on the specific chemistry used. Solid-state batteries

do not necessarily reduce dependence on critical materials compared to conventional lithium-ion batteries, and demand for lithium may even increase due to the use of lithium metal anodes instead of graphite (Bron: IEA).

5. Conclusions and recommendations

The central question in this report is in what direction innovation and use of home batteries should evolve ('ideal battery') and what information is needed if policy wants to influence this direction. To provide relevant information, the goal of this study was to apply the SSbD approach to develop a description of the parameters and criteria that define an ideal home battery. In this way an integrated, practical SSbD-based assessment framework for home batteries is introduced. By applying this framework to current and emerging technologies, the opportunities for improvement and the main knowledge gaps are revealed.
It was concluded that the ideal characteristics of home batteries can be described across seven main categories: functionality, safety-substances, safety-physical, criticality, circularity, sustainability and cybersecurity. These characteristics can be applied early in the development process and used in a practical approach for the assessment of safety and sustainability of home batteries and their innovation. A part of the criteria depend on the battery type (*e.g.*, operating temperature), but others are independent of battery type (*e.g.*, BMS), or may be specific to the producers (*e.g.*, transparency in environmental impact).
For all criteria a qualitative level or direction for the ideal battery is given (e.g. minimisation of hazardous substances and of critical raw materials, low thermal risk, high recyclability rates, and low life cycle environmental impact). A quantitative target threshold value for the criteria could not be set for all parameters and can be improved in a dedicated follow-up study. For circularity for example, it is referred to the EU-regulatory targets for batteries in general. The current framework provides a structured basis for such target setting and for comparing existing and emerging battery technologies against the qualitative ideal.
Comparing available data on home batteries currently on the market and those potentially available in the coming years, provides a qualitative view of the distance between these batteries and the ideal battery. However, a practical limitation was the lack of readily available and validated information for different battery types, such as data on ease of dismantling and disassembly. This initial exploration shows that the assessment of design criteria across battery types remains largely incomplete or is dependent on assumptions and general reference figures. A robust evaluation requires a more extended systematic approach that integrates literature, empirical data and expert judgement across the design criteria for the different types of home batteries.

Despite these limitations, the comparison gives direction towards efficient innovations in home battery technology. Cycle life (functionality) can differ strongly between type of battery. Some batteries contain fewer or no hazardous substances (safety-substances); the risk of a thermal run-away or fire shows a clear difference between battery types (safety-physical); four out of six batteries contain critical raw materials to different extents (criticality); data on the recyclability of home batteries is still lacking (circularity); and a comprehensive study comparing the environmental impacts of different type of home batteries is missing, preventing sound conclusions being drawn on the sustainability of the production and use per functional unit (sustainability).
Depending on the location and intended use of a home battery, different characteristics and safety or sustainability criteria could be more or less important for further innovation or selection towards and ideal battery. This could lead to different choices for the ideal battery in a specific situation. This practical approach may also serve as a basis for application to other energy transition technologies, support SSbD for batteries, and contribute to knowledge development for current safety and sustainability regulatory frameworks.

Recommendations

The criteria of an ideal battery across the seven parameters can be used as a starting point in discussions with stakeholders on SSbD and innovation of home batteries. Additionally, these criteria could guide the procurement of home batteries by companies, government and retailers. At the same time further elaboration is needed to define specific targets for ideal home batteries.

Furthermore, we recommend a more detailed study to examine differences in sustainability of the production and use, in particular the climate-change impact of new type of batteries compared to mainstream home batteries, next to gathering data on recyclability. Given the ongoing innovation and rapid pace of implementation of battery systems, more attention is needed for the sustainability and circularity of home battery types to help policymakers understand how policy options can shape the safety, sustainability and circularity of home batteries as part of our energy system.

The price of battery capacity (kWh) was not considered in this study. However, this could be an additional factor for selection next to the criteria mentioned. Furthermore, energy security during power outages is often cited as a key argument for home battery adoption, but most current systems do not function as emergency backup. An ideal home battery should include a backup inverter or gateway, ensuring continued power supply.

6. References

Ankathi, S.K., et al. (2024). Beyond tailpipe emissions: life cycle assessment unravels battery's carbon footprint in electric vehicles. World Electric Vehicle Journal, 15(6), 245.

Bielewski, M., et al. (2020). Analysis of sustainability criteria for lithium-ion batteries including related standards and regulations, EUR 30597 EN, Publications Office of the European Union, Luxembourg, 2021.

Cai, X., et al. (2024). Challenges and industrial perspectives on the development of sodium ion batteries. Nano Energy, 129, 11052.

Costa, R. (2025). Life Cycle Assessment (LCA) Challenges in Evaluating Emerging Battery Technologies: A Review. Materials, 18(18), 4321.

Degen, F., et al. (2025). Comparative life cycle assessment of lithium-ion, sodium-ion, and solid-state battery cells for electric vehicles. Journal of Industrial Ecology, 29(1), 113-128.

Dutch New Energy Research & Solar365 (2024). Het Nationaal Smart Storage Trendrapport. Nationaal Smart Storage Trendrapport | Dutch New Energy

EU, 2023. Regulation (EU) No 2023/1542, 12 July 2023 concerning batteries and waste batteries.

EU, 2024. Regulation (EU) 2024/2865, 23 October 2024 amending Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures.

EU, 2024a. Regulation (EU) 2024/1252, 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials.

EU, 2024b. Regulation (EU) 2024/1781, 13 June 2024 establishing a framework for the setting of Ecodesign requirements for sustainable products.

EU, 2025a. European commission Brussels, 26.2.2025 com(2025) 85 final communication the clean industrial deal: a joint roadmap for competitiveness and decarbonisation.

EC, 2025. New rules to boost recycling efficiency from waste batteries - Environment

Eurostat. (2025). Waste statistics - recycling of batteries and accumulators - Statistics Explained - Eurostat. Retrieved May 5, 2026,

Guo, W., et al. (2023). Comparative life cycle assessment of sodium-ion and lithium iron phosphate batteries in the context of carbon neutrality. Journal of Energy Storage, 72, 108589.

De Haan, F., et al. (2026). Implementatie kleinschalige batterijen. Rijksdienst voor Ondernemend Nederland. Geraadpleegd op 1 juni 2026 via: https://www.rvo.nl/nieuws/overbelast-elektriciteitsnet-biedt-kansen-voor-batterijopslag.

Hansen, S., et al. (2025). Design for automated disassembly: A comparative study of different battery component designs. International Journal of Sustainable Engineering, 18(1), 2504388.

Harper, G., et al. (2019). Recycling lithium-ion batteries from electric vehicles. Nature, 575, 75–86.

Jasper, F., et al. (2022). Life cycle assessment (LCA) of a battery home storage system based on primary data. Journal of cleaner production, 366, 132899.

JRC, 2025. Safe and Sustainable by Design Chemicals and Materials. Revised framework (2025), Bracalente, G., Abbate, E. and Garmendia Aguirre, I. (editors), Publications Office of the European Union, Luxembourg, 2025.

Liu, Z., et al.(2024). Are solid-state batteries absolutely more environmentally friendly compared to traditional batteries-analyzing from the footprint family viewpoint. Journal of cleaner production, 447, 141452.

Mashfy, M.M., et al. (2026).8 Sodium-ion batteries: A sustainable alternative to lithium-ion batteries with an overview of market trends, recycling, and battery chemistry. Next Energy, 10, 100478.

NIPV, 2024. P. van Rede, B. Riemersma. Thuisbatterijen en brandveiligheid. Nederlands Instituut Publieke Veiligheid (NIPV). Nederlands.

NIPV, 2026. Incidentbestrijding lithium-ion thuisbatterijen. 20260326-NIPV-Rapport-Incidentbestrijding-Thuisbatterijen.pdf

Park, S., et al. (2016). Saltwater as the energy source for low-cost, safe rechargeable batteries. J. Mater. Chem. A, 4 (19), 7207–7213.

Peters, J. F., & Weil, M. (2017). Aqueous hybrid ion batteries–An environmentally friendly alternative for stationary energy storage? Journal of Power Sources, 364, 258-265.

Soeteman-Hernández, L.G., et al. 2023. Life cycle thinking and safe-and-sustainable-by-design approaches for the battery innovation landscape. iScience, Volume 26, Issue 3, 17 March 2023, 106060.

Soeteman-Hernández, L.G., S. Ouhajji, C.W. Noorlander, A.J.A.M. Sips, 2025. Towards safe and sustainable battery innovation, A conceptual framework. RIVM letter report 2025-0119. RIVM, Bilthoven.

Wang, H., et al. (2026). Recycling of lead-acid batteries: A review, Energy Storage Materials, 85, 104895.

Wickerts, S., et al. (2024). Prospective life cycle assessment of sodium-ion batteries made from abundant elements. Journal of Industrial Ecology, 28(1), 116-129.

Wu, S., Kaden, N., & Dröder, K. (2023). A systematic review on lithium-ion battery disassembly processes for efficient recycling. Batteries, 9(6), 297.

Xi, G., et al. (2026). A critical review of PFAS in lithium-ion batteries: application, monitoring, exposure and health risk. Energy Environ. Sci., 19 (8), 2396–2419.

Yao, A., et al. (2025). Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. *Nat Energy* 10, 404–416.

Yudhistira, R., et al. (2022). A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage. Journal of Cleaner Production, 358, 131999.

Zhang, H., et al. (2023). Life cycle environmental impact assessment for battery-powered electric vehicles at the global and regional levels. Scientific Reports, 13(1), 7952.

Zheng, S., et al. (2024). A review of equivalent-circuit model, degradation characteristics and economics of Li-ion battery energy storage system for grid applications. Journal of Energy Storage, 101, 113908.