

September 2023

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# Alternative Battery Technologies Roadmap 2030+

# Index of Abbreviations

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3C	Consumer, computing, and communication	NCA	Lithium nickel cobalt aluminum oxides
AAM	Anode active material	Me-ion	Metal-ion
AIB	Aluminum-ion battery	Me-air	Metal-air
BEV	Battery electric vehicle	Me-S	Metal-sulfur
CAGR	Compound annual growth rate	MIB	Magnesium-ion battery
CAM	Cathode active material	Na-S HT	Sodium-sulfur high temperature
CAS	Chinese Academy of Sciences	Na-S RT	Sodium-sulfur room temperature
cEV	Commercial electric vehicle	NiCd	Nickel-cadmium
CNT	Carbon nanotube	NiMH	Nickel metal hydride
DOD	Depth of discharge	NMC	Lithium nickel manganese cobalt oxides
EPO	European Patent Office	NMP	N-methyl-2-pyrrolidone
ESS	Electrical energy storage (stationary storage)	OEM	Original equipment manufacturer
EV	Electric vehicle	PbA	Lead acid
eVTOL	Electric vertical take-off and landing aircraft	pEV	Electrified passenger vehicle
GDE	Gas diffusion electrode	PHEV	Plug-in hybrid electric vehicle
GWP	Global warming potential	RFB	Redox flow battery
HAPS	High altitude pseudo-satellites	RLA	Revealed Literature Advantage
HALE	High altitude long endurance	RPA	Revealed Patent Advantage
HC	Hard carbon	RT	Room temperature
HT	High temperature	RTO	Research and technology organization
IPC	International Patent Classification	SHE	Standard hydrogen electrode
IPCEI	Important project of common European interest	SIB	Sodium-ion battery
IRA	Inflation Reduction Act	SIB Salt	Sodium-ion saltwater battery
KPI	Key performance indicator	SOH	State of health
Li-air	Lithium-air	SSB	Solid-state battery
LIB	Lithium-ion battery	WIPO	World Intellectual Property Organization
Li-S	Lithium-sulfur	WPI	World Patents Index
LCA	Life cycle analysis	TPB	Three-phase boundary
LFP	Lithium iron phosphate	TRL	Technology readiness level
LMFP	Lithium manganese iron phosphate	ZIB	Zinc-ion battery
LTO	Lithium titanate	Zn-air	Zinc-air

# Alternative Battery Technologies Roadmap 2030+



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# Preface

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This “Alternative Battery Technologies – Roadmap 2030+” was developed as part of the accompanying project BEMA II, which is funded by the German Federal Ministry of Education and Research (BMBF) under the “Battery 2020” initiative. Fraunhofer ISI is supporting German battery research with a roadmap and monitoring process, strategic information processing and status seminars for the exchange of information on scientific progress and technology transfer. As part of the accompanying project, updates are made to the roadmap “High-energy batteries 2030+ and prospects for future battery technologies” (2017) and earlier roadmaps from 2010 to 2015. In addition to this roadmap, a solid-state battery roadmap was published in 2022 and an update on high-energy LIB will be made in 2023 (to be published by 2024). The roadmaps also complement and support the competence clusters funded under the BMBF’s umbrella concept “Battery Research Factory” (Dachkonzept Forschungsfabrik Batterie).

The BMBF has realigned its battery research activities with its umbrella concept for battery research – released in early 2023 – with the aim to secure Germany’s technological sovereignty in this field in the long term. This umbrella concept encompasses basic competence building as well as industrial application and production. It focuses on material and component development, process and production technology, recycling and the circular economy, as well as digitalization and scaling research. There is also a greater emphasis on the transition from academic research to industrial development and the subsequent transfer to application than in the previous umbrella concept. Greater attention is also given to the societal and industrial needs (e.g., of small and medium sized enterprises).

The BMBF’s umbrella concept considers lithium-ion and other battery systems (promising technology variants of the future, e.g., solid-state batteries, sodium-ion batteries and other chemistries and concepts). This “Alternative Battery Technologies – Roadmap 2030+” thus fits into the BMBF’s realigned umbrella concept and addresses the role of alternative battery technologies within the context of and in relation to the aim to achieve technology sovereignty.

# Vorwort

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Die vorliegende „Alternative Battery Technologies – Roadmap 2030+“ wurde im Rahmen der Begleitmaßnahme BEMA II entwickelt, welche vom Bundesministerium für Bildung und Forschung (BMBF) im Rahmen der Initiative „Batterie 2020“ gefördert wird. Das Fraunhofer ISI unterstützt die deutsche Batterieforschung mit einem Roadmapping- und Monitoring-Prozess, strategischer Informationsaufbereitung und Statusseminaren zum Austausch von Informationen über den wissenschaftlichen Fortschritt und Technologietransfer. Im Rahmen der Begleitmaßnahme sollen u.A. Updates der Roadmap „Hochenergiebatterien 2030+ und Perspektiven für zukünftige Batterietechnologien“ (2017) sowie von früheren Roadmaps aus den Jahren 2010 bis 2015 entstehen. Neben dieser Roadmap wurde 2022 eine Roadmap zu Feststoff-Batterien veröffentlicht, in 2023 wird eine Aktualisierung zu „Hochenergie LIB“ erarbeitet (Veröffentlichung bis 2024). Die Roadmaps ergänzen und unterstützen hierbei auch die im Rahmen des Dachkonzepts Forschungsfabrik Batterie geförderten Kompetenzcluster.

Mit dem Anfang 2023 veröffentlichten Dachkonzept Batterieforschung hat das BMBF seine Batterieforschung neu ausgerichtet, um die Technologiesouveränität Deutschlands langfristig zu sichern. Dieses Dachkonzept reicht vom Aufbau grundlegender Kompetenzen bis zur industriellen Anwendung und Produktion. Schwerpunkte sind die Entwicklung von Material- und Bauteilen, Prozess- und Produktionstechnik, Recycling und Kreislaufwirtschaft sowie Digitalisierung und Skalierungsforschung. Zudem wird der Transfer von der akademischen Forschung zur industriellen Entwicklung und anschließend in die Anwendung im Vergleich zum früheren Dachkonzept zunehmend betont. Auch die gesellschaftlichen und industriellen Bedürfnisse (z.B. von kleinen und mittleren Unternehmen) werden stärker berücksichtigt.

Im BMBF-Dachkonzept werden sowohl Lithium-Ionen-Systeme als auch weitere Batteriesysteme (zukunftssträchtige Technologievarianten, z.B. Feststoffbatterien, Natrium-Ionen-Batterien und weitere Chemien und Konzepte) berücksichtigt. Die vorliegende „Alternative Battery Technologies – Roadmap 2030+“ fügt sich somit in das neu ausgerichtete Dachkonzept des BMBF ein und adressiert die Frage nach der Rolle alternativer Batterietechnologien im Kontext und mit dem Ziel der Erreichung von Technologiesouveränität.

# Executive Summary



## Motivation

Lithium-ion batteries (LIBs) are currently the dominant battery technology and address a global market that is expected to reach nearly one TWh in 2023. In the coming decade, LIBs will essentially be the only scaled technology besides lead-acid (PbA) batteries. LIBs exhibit the highest growth rates and have even overtaken PbA batteries owing to their use in electric passenger cars, commercial vehicles and many other mobility concepts, stationary applications and of course continue to be used in mobile (consumer) devices.

While world regions are currently in the critical phase of building up their battery ecosystems based on LIBs, parallel political and geopolitical tensions are setting a new framework. The leading Chinese position in particular is being critically observed. Measures such as the European Battery Regulation to shape the conditions for a European battery value chain (with mandatory sustainability and safety requirements) or the US Inflation Reduction Act (IRA) to re-industrialize the USA and attract direct investments into the region are thought to increase the resilience and sovereignty of those regions.

In this context, a new focus on industrial policies and concentrated funding can be observed in all world regions and countries. Strategic agendas have been formulated recently and have been partly updated to take into account the existing and increasing geopolitical dependencies and market structures.

In terms of European technology sovereignty, the main questions revolve around a resilient and sustainable circular battery ecosystem which requires access to the supply chain. From raw materials and components through to establishing cell production capacities to meet the increasing demand from automotive industries as well as other system integrators and users. There are strategies to ease the raw material dependencies through mining projects in Europe (especially lithium) or recycling of LIBs. These can only however partially solve the problem of dependencies and/or will only have a substantial impact in 10 years or more (e.g., in the case of recycling). Limiting the resources used (e.g., by reducing scrap in battery production or by using more efficient processes with smart, digital production) or reducing the batteries needed (through the promotion/support of sustainable use and end-consumer behavior, e.g., sharing) are some of the measures which can help to reduce technology dependencies on LIBs.

However, the battery demand will still increase tenfold in the coming decade and potentially even beyond that. With this huge demand on the one hand and only one battery technology available on a large scale on the other, the question of alternative battery technologies available is more than justified.

In addition to LIBs, there are at present many other alternative battery technologies that are still being developed or are about to enter the market. Therefore, this roadmap focuses on those alternative battery technologies that seem promising for one or more applications with a more medium- to long-term perspective, i.e., on batteries that have not yet been commercially established on a large scale. The roadmap covers the following alternative battery technologies:

- Metal-ion (Me-ion)
  - Sodium-ion batteries (SIBs)
  - Sodium-ion saltwater batteries (SIBs Salt)
  - Magnesium-ion batteries (MIBs)
  - Zinc-ion batteries (ZIBs)
  - Aluminum-ion batteries (AIBs)
- Metal-sulfur (Me-S)
  - Lithium-sulfur (Li-S)
  - Sodium-sulfur room temperature (Na-S RT)
  - Sodium-sulfur high temperature (Na-S HT)
- Metall-Luft (Me-air)
  - Lithium-air (Li-air)
  - Zinc-air (Zn-air)
- Redox flow batteries (RFBs)

The roadmap provides a systemic perspective and covers technical (KPIs and potential developments), economic (cost, markets, production, supply chains), and ecological aspects (e.g., resource availability and ecologic footprint of battery materials) and compares them with the benchmark of LIBs. In doing so, this roadmap also intends to contribute to current discussions such as European technology sovereignty and geopolitical aspects. The insights summarized and discussed are based on an extensive literature review, an online survey and an in-depth expert consultation process.

## Key Results

The roadmap on alternative battery technologies addresses a number of questions:

### What are technology specific advantages of alternative battery technologies?

#### Me-ion batteries

SIBs are very similar to LIBs in terms of structure and operating principles. However, they are less resource dependent and offer the potential for better sustainability and cost benefits. ZIBs have a much lower energy density than LIBs but at the same time a much lower environmental footprint owing to the water-based electrolyte used. MIBs have the potential to provide the missing high gravimetric and volumetric energy density which could exceed that of LIBs. AIBs can be designed to have a significantly higher power density than LIBs, a higher energy density than capacitors as well as a high cycle life and a high C-rate. However, their energy density is much lower than most other Me-ion battery technologies.

#### Me-S batteries

Promising technologies also exist in the field of Me-S batteries. Li-S batteries have the potential for higher gravimetric energy density than LIBs, although volumetric energy density and cycle stability are likely to be lower. In addition, due to the high energy density and the low cost of S, there is also the potential to achieve low cost per kWh. Improvements in cycle stability and power density are required. Na-S HT batteries achieve a slightly lower gravimetric energy density than LIBs. Na-S HT batteries may have a lower CO<sub>2</sub> footprint than LIBs, owing to the materials used. However, system efficiency and comparatively higher costs are both a definite challenge. In this respect, the Na-S RT battery is substantially more advantageous and could also achieve a similar gravimetric energy density to LIBs in the long term.

#### Me-air batteries

Among the Me-air batteries considered, Li-air batteries in particular have a low technology readiness level (TRL) and a correspondingly high need for research. In theory, however, Li-air batteries could have an extremely high gravimetric energy density at potentially slightly lower cost than that of LIBs. But for this to be realized the cycle stability problem needs to be solved. Zn-air batteries can be considered to be more advanced than Li-air with a higher TRL, in addition they could also achieve relatively high energy density comparable to that of LIBs.

Furthermore, they may even deliver lower costs and a smaller CO<sub>2</sub> footprint. Their power density, however, is relatively low. Although a Zn-air flow battery design has been on the verge of commercialization for many years according to company announcements, it has not yet been able to establish itself on the market as a viable alternative battery technology.

#### RFBs

RFBs based on vanadium are already established on the market, but still offer potential for improvement (e.g., through material substitution, in particular of vanadium) in order to further reduce the cost and the CO<sub>2</sub> footprint.

Hence, some of the alternative battery technologies considered are particularly suitable if low cost (e.g., Zn-based cells) or high resource availability (in particular Na- or Mg-based cells) is desired, while their technical KPIs mainly determine their suitability for specific applications.

### Which applications might be addressed first by alternative battery technologies?

Owing to the technical, economic and ecological differences between the alternative battery technologies they are suitable for very different areas of application and are expected to be available for commercialization at different times (due to different TRLs and technical challenges). Thus, there is not one technology that addresses all applications and market demands.

#### Mobile Applications

Currently, in mobile applications requiring high energy and power density, none of the alternative technologies under consideration is used. SIBs are likely to be used first, as they are close to commercialization and can achieve similar KPIs to lithium iron phosphate (LFP) cells, depending on the electrode material. They may also be advantageous in hybridization with high energy LIB cells such as lithium nickel manganese cobalt oxides (NMCs), owing to their good performance at low temperatures, for example. Recent announcements indicate that SIBs will be used mainly in 2–3 wheeled vehicles and small cars, an area in which they will compete with LFP-based LIBs. Looking further ahead, MIBs could be used in larger vehicle sectors owing to their potential for high energy density, possibly from 2040 onwards. Li-S batteries could be used in larger drones by the middle of the next decade and even in electric vertical take-off and landing aircrafts (eVTOLs) around 2040.



**Alternative battery chemistries show first evidence that they may become reality. They make use of abundant, cost-effective and non-toxic materials and have the potential to mitigate availability issues of critical raw materials and cut geopolitical dependencies.«**

**Prof. Dr. Maximilian Fichtner,**

Helmholtz Institute Ulm & Spokesman of  
the POLiS Cluster of Excellence

eVTOLs could also be an interesting area of application for Zn-air batteries where they would have a lower power and energy density than Li-S batteries, but offer advantages in terms of CO<sub>2</sub> footprint and possibly cost. Li-air batteries might also play a role at an even later stage (and when research challenges are overcome) owing to their exceptionally high energy density. However, due to the high uncertainties regarding the future development of this technology, any assessment with regard to time to market and addressed application would be speculative. Rather, this technology might have spillover effects with further R&D.

#### Stationary Applications

Requirements for some key KPIs, such as energy density, are typically lower in stationary applications (ESS) than in mobile ones, but more stringent in other aspects such as cycle life or cost per kWh charging cycle. Hence, alternative battery technologies are likely to play a more prominent role here. In addition to the storage systems that are already partially available on the market, such as RFBs, saltwater or Na-S HT batteries, SIBs are likely to be adopted in the near future owing to their high resource availability, safety and deep discharge capability. Between 2025 and 2030, the low-cost and environmentally friendly ZIBs could also enter the market, which are more suitable for large ESSs than for mobile applications due to their limited energy density and high volume requirements. MIBs are more likely to be used in stationary applications as a stepping stone to mobile applications. In the case of Me-air batteries,

Zn-air batteries could already be considered for large buffer storage systems in the medium term. From 2035, Na-S RT could enable the use of Me-S technology in smaller storage systems, something that is not possible/economical with today's Na-S HT batteries. Lastly, from 2025–2030, AIBs could be used primarily in highly cyclical applications with a high C-rate, such as for grid stabilization or peak shaving, and later also as buffer storage for fast charging.

#### How is Europe positioned/specialized in terms of technology development?

Analyses of patents and publications indicate that Europe is better positioned for the technological development of some of the alternative battery technologies than it is currently for LIBs, e.g., RFBs, Li-air and AIBs – with Japan and China remaining the leading countries in patent and publication activities, respectively. For some of the alternative battery technologies, the EU28 has publication and patent shares of approximately 15–20 % of global R&D activities and in some cases high dynamics with annual growth rates between 10–50 %, whereas with LIBs as a benchmark, the EU28 has a share of about 15–18 % in R&D activities and 10 % growth. However, the absolute level of activity for LIBs is about 5 to 30 times higher in terms of the number of publications and patents compared to alternative battery technologies.

### **Are there alternative battery technologies that can significantly reduce dependencies on raw materials?**

Basically, all non Li-based battery technologies need less critical raw materials and could help reduce dependencies. However, in the absence of large applications and markets comparable to LIBs, the production and supply of lithium, nickel, cobalt will remain critical (especially in the next 5–10 years). In addition, most of the alternative technologies considered have a lower energy density than LIBs, meaning that a larger amount of raw materials is usually needed to achieve the same storage capacity.

### **Are there alternative battery technologies on the horizon, which are producible and scalable like LIBs?**

Me-Ion batteries other than LIBs have the closest production steps to LIBs and are therefore generally more attractive, as it will be advantageous to be able to use and adapt existing production technologies (drop-in technologies) and environments – in the coming decade at least.

### **Can alternative battery technologies be cheaper than LIBs?**

Alternative battery technologies have potentially lower material costs than LIBs. In scaled production technologies, the share of material costs is always higher compared to other cost factors (e.g., energy, equipment, labor, etc.). Most recently, for example, the high LIB raw materials prices led to an increase of LIB cell costs. For alternative battery technologies, initial costs are expected to be higher than the cost of LIBs due to low production scales. At scaled production, however, cost benefits are expected to be realized. Therefore, it is more a matter of identifying sufficiently large markets and applications on the GWh scale to realize such economies of scale and cost reductions.

### **How can supply chains be established for alternative battery technologies?**

Since alternative batteries will essentially always be competing with LIBs as a benchmark, an orientation with regard to standards and compatibility will be important. This means keeping as close as possible to the production steps from components to cells, cell formats and battery systems in order to potentially replace LIBs in certain applications. In so doing, existing supply

chains can be maintained and would not have to be created from scratch. Establishing entirely new supply chains would only be realistic for technology with a dedicated use case, i.e., with a sufficiently large market and application, and in the medium-to-long term.

### **How large are the potential markets for alternative batteries?**

While dependencies on LIBs and their supply chains will remain high due to their wide range of applications, the battery market is expected to become increasingly diversified in terms of the technologies used in the medium-to-long term. Alternative battery technologies can complement LIBs in specialized markets (e.g., certain stationary storage applications or hybrid forms in combination with LIBs in passenger cars) or new ones (e.g., eVTOLs). These specialized markets seem to provide good opportunities for alternative battery technologies to enter and exploit their specific advantages.

In the next 5–10 years, several GWh-markets or better concrete applications will emerge which could be large enough as application scenario for certain alternative battery technologies with suitable KPIs addressing the application requirements. LIBs can contribute to the growth of these markets before alternative battery technologies are commercialized. Alternative battery technologies, however, will only be a part of the future battery landscape, while LIBs will continue to play a prominent role, other new concepts such as solid state batteries (SSBs) are also emerging.

### **Points of action for the EU and Germany**

To tap into the potential of alternative battery technologies and thereby a more resilient and technologically sovereign battery system from a German and European perspective, additional policy support might be needed. In this initial phase, when the market developments and framework conditions set by policymakers are still uncertain, the local industry might need to be incentivized.

While a solid R&D base already exists for alternative battery technologies, an integrative policy approach could boost key technologies towards market readiness and deployment. This approach should cover the entire supply chain including basic R&D to address technological challenges, continued build-up

of a patent portfolio or intellectual property in general, development and qualification of production processes, securing of resources, and incorporation of an end user to test and commercialize the practical application. It is important to attract not only big firms, who have traditionally shaped battery ecosystems, but also SMEs and startups, which could become key players in the relevant specialized markets with a manageable size (e.g. via high funding rates and multistage funding processes).

However, such an integrative approach is characterized by high cost and risk and can therefore only be applied to a limited number of technologies. The selection of key technologies would require systematic and regular screening processes, as well as criteria for selection and potentially also for the termination of funding.

In addition to alternative battery technologies, particularly SSBs or high energy LIBs, may develop and serve as alternatives to state-of-the-art LIB in the future. There is still a great need for R&D and advances in new materials and cell concepts for future battery applications, even beyond the alternative battery technologies considered in this roadmap. This R&D could also allow for potential spillover effects between the different battery types. In addition, markets and supply chains may be affected by political and geopolitical tensions as well as the increasing importance assigned to environmental friendliness.

It is therefore essential to define milestones for development and market relevance, as well as to monitor and roadmap the progress of alternative battery systems accordingly.

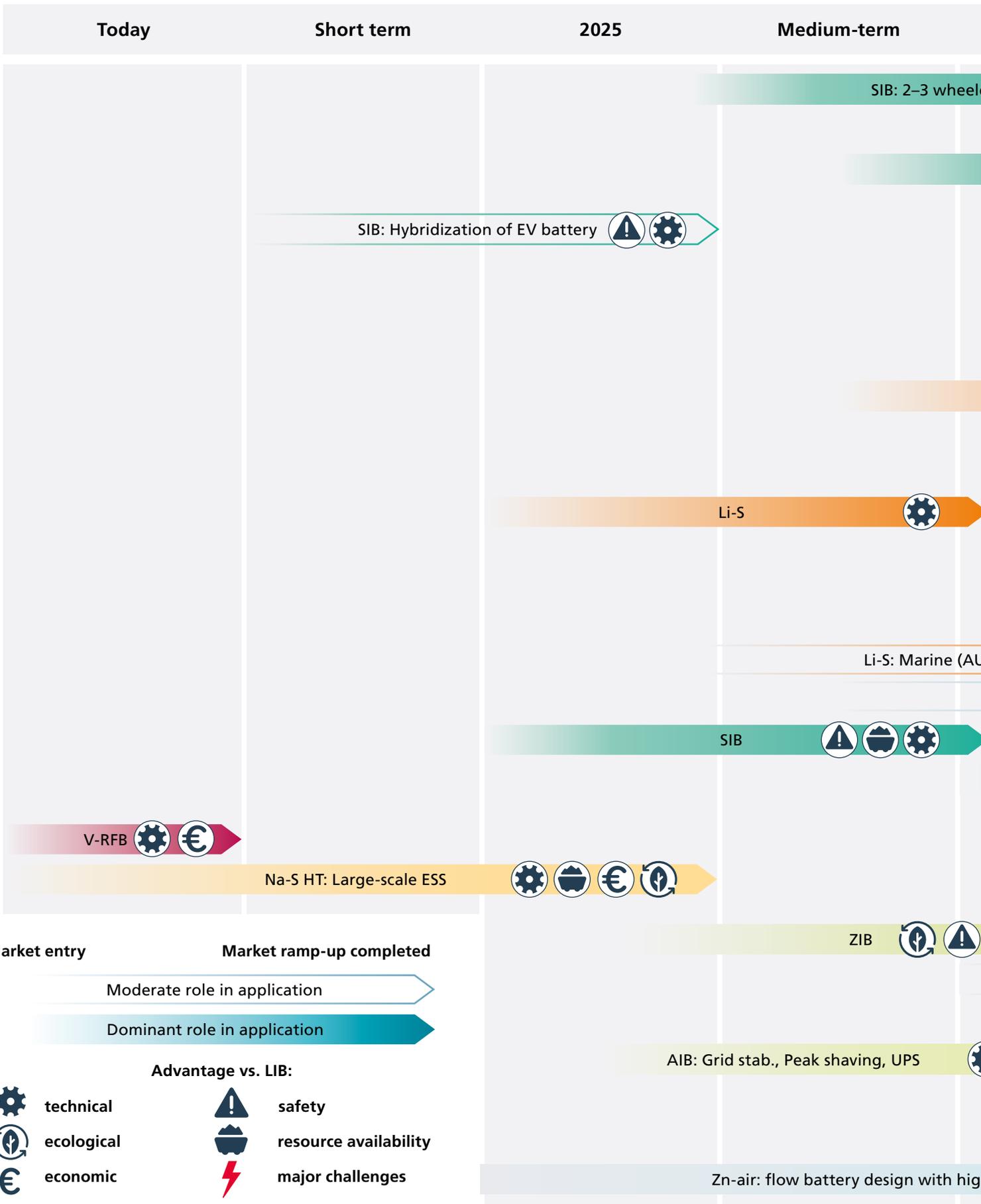
# Alternative battery technology roadmap – KPIs and challenges

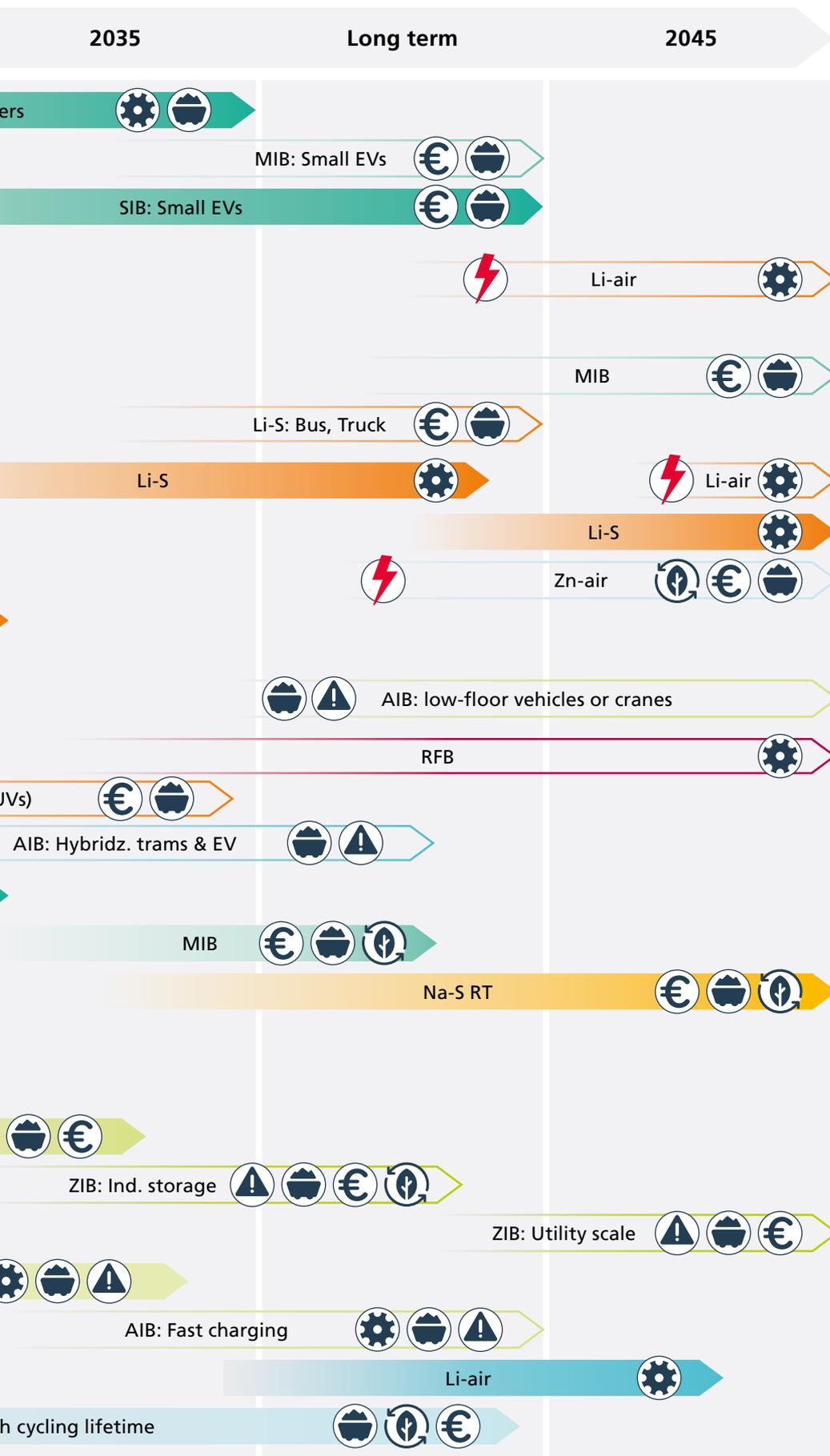
		Today & Short term	2025
	<b>LIB</b>	200–300 Wh/kg, 600–750 Wh/l 90–175 €/kWh	
<b>Me-ion</b>	<b>SIB</b>	140–160 Wh/kg, 250–300 Wh/l 80–120 €/kWh	
	<b>SIB–Salt</b>	< 150 Wh/kg, 10–25 Wh/l 700–1000 €/kWh*	Incre
	<b>MIB</b>	50–150 Wh/kg, 150–300 Wh/l	
	<b>ZIB</b>	30–60 Wh/kg, 40–100 Wh/l	
	<b>AIB</b>	30–35 Wh/kg, 35–50 Wh/l, but 9,000 W/kg and >20,000 cycles	
<b>Me-S</b>	<b>Li-S</b>	> 300 Wh/kg, 300–450 Wh/l	
	<b>Na-S RT</b>	> 300 Wh/kg	Multiple
	<b>Na-S HT</b>	180–268 Wh/kg, 300–414 Wh/l, long calendar and cycle lives 300–450€/kWh*	
<b>Me-air</b>	<b>Li-air</b>	<= 500 Wh/kg, but with a very low cycling stability	Safet
	<b>Zn-air</b>	100–200 Wh/kg, only flow design with pot. high cycling stability 100–150 €/kWh	No sta
	<b>V-RFB</b>	22–30 Wh/kg, > 10 000 cycles, 20 years calendar life	Improved op

\* Cost on system level

Medium-/long term	2035	Vision
Continuous improvement	320–360 Wh/kg, 800–960 Wh/l 45–90 €/kWh	
Optimizing material combinations	> 200 Wh/kg, > 400 Wh/l < 40 €/kWh	
Increasing operating voltage and reducing costs	< 200 €/kWh*	
Stable cathode-electrolyte combination	> 300 Wh/kg, > 400 Wh/l < 40 €/kWh	
Stability of electrodes and electrolyte	50–120 Wh/kg, 80–200 Wh/l	
Highly corrosive electrolyte	45–50 Wh/kg, 45–80 Wh/l, but > 10,000 W/kg and > 50,000 cycles; 10–20 % cost saving compared to LIBs	
Cycling stability and power density	550 Wh/kg, 700 Wh/l 50 €/kWh	
Challenges especially on cathode and anode side	> 350 Wh/kg	
Cost reduction and safety improvements	220–300 Wh/kg, 320–440 Wh/l, long calendar and cycle lives < 300 €/kWh*	
Energy efficiency, unhealthy side reactions	theoretical: 3500 Wh/kg practical: 1230 Wh/kg	
Stable planar cell design, low power performance	200–300 Wh/kg, 2000–14000 cycles 10–100 €/kWh	
Operational temperature and automated cell stacking	> 35 Wh/kg, > 10 000 cycles, 20 years calendar life	

# Alternative battery technology roadmap – applications





2-3 wheelers	Road
Light vehicles	
Cars	
Heavy vehicles	
Drones	Air
eVTOLs	
HALE/HAPS	Others
Logistics	
Ships	
Trains	
Stationary	

# Zusammenfassung



## Motivation

Aktuell stellen Lithium-Ionen-Batterien (LIBs) die vorherrschende Batterietechnologie dar. Im Jahr 2023 wird die globale Marktnachfrage voraussichtlich eine Kapazität von fast eine TWh erreichen. Zudem sind LIBs, neben Blei-Säure-Batterien (PbA-Batterien), für das nächste Jahrzehnt im Wesentlichen die einzige skalierbare Technologie und weisen zudem die höchsten Wachstumsraten auf. Aufgrund ihres breiten potentiellen Einsatzspektrums in Elektro-Pkw, Nutzfahrzeugen und weiteren mobilen Anwendungen sowie in stationären und selbstverständlich auch weiterhin in mobilen (Verbraucher-) Geräten haben LIBs die PbA-Batterien mittlerweile überholt.

Während sich viele Regionen der Welt derzeit in der kritischen Aufbauphase ihrer LIB-basierten Batterie-Ökosysteme befinden, verändern parallel dazu geopolitische Spannungen die Rahmenbedingungen. Insbesondere die Führungsrolle Chinas wird kritisch beobachtet. Darum sollen Maßnahmen wie die europäische Batterieverordnung zur Schaffung der Voraussetzungen für eine europäische Batteriewertschöpfungskette (mit verbindlichen Nachhaltigkeits- und Sicherheitsanforderungen) oder der US Inflation Reduction Act (IRA) zur Reindustrialisierung der USA und zur Förderung von Direktinvestitionen die Resilienz und Souveränität dieser Regionen erhöhen.

In diesem Zusammenhang ist in vielen Regionen und Ländern der Welt eine neue Ausrichtung auf industriepolitische Maßnahmen sowie konzentrierte Förderung zu beobachten. Mithilfe kürzlich erstellter bzw. aktualisierter strategischer Aktionspläne sollen bestehende und zunehmende geopolitische Abhängigkeiten und Marktstrukturen berücksichtigt werden.

Im Hinblick auf die europäische Technologiesouveränität drehen sich die wichtigsten Fragen um ein resilientes und nachhaltiges zirkuläres Batterie-Ökosystem. Dies erfordert auch den Zugang zu Lieferketten: von Rohstoffen und Komponenten bis hin zum Aufbau von Zellproduktionskapazitäten, die in der Lage sein müssen die steigende Nachfrage aus der Automobilindustrie sowie die weiteren Systemintegratoren und Nutzer decken zu können. Es gibt Strategien, die Rohstoffabhängigkeit durch Bergbauprojekte in Europa (insbesondere Lithium) oder durch Recycling von LIBs zu verringern. Diese können das Problem der Abhängigkeiten jedoch nur teilweise lösen und/oder werden erst in 10 Jahren oder mehr (z. B. im Falle des Recyclings) einen wesentlichen Einfluss entfalten. Weitere Maßnahmen, wie die Begrenzung des Ressourcenverbrauchs (z. B. durch die Verringerung des Abfalls bei der Batterieproduktion

oder durch effizientere Prozesse mit Hilfe intelligenter, digitalisierter Produktion) oder die Verringerung der benötigten Anzahl an Batteriezellen (durch die Förderung einer nachhaltigen Nutzung und eines nachhaltigen Verhaltens der Endverbraucher, z. B. Sharing), können dazu beitragen, die Technologieabhängigkeit von LIBs zu verringern.

Nichtsdestotrotz wird sich die Nachfrage nach Batterien im kommenden Jahrzehnt und möglicherweise sogar darüber hinaus verzehnfachen. Angesichts dieses enormen Bedarfs einerseits und nur einer in großem Maßstab verfügbaren Batterietechnologie andererseits ist die Frage nach alternativen Batterietechnologien mehr als berechtigt.

Neben LIBs befinden sich derzeit noch viele weitere alternative Batterietechnologien in der Entwicklung oder stehen kurz vor der Markteinführung. Diese Roadmap konzentriert sich daher auf diejenigen alternativen Batterietechnologien, die für eine oder mehrere Anwendungen mit eher mittel- bis langfristiger Perspektive vielversprechend erscheinen, d. h. auf Batterien, die noch nicht in großem Maßstab kommerziell etabliert sind. Konkret umfasst die vorliegende Roadmap die folgenden alternativen Batterietechnologien:

- Metall-Ionen (Me-ion)
  - Natrium-Ionen-Batterien (SIBs)
  - Natrium-Ionen-Salzwasser-Batterien (SIBs Salt)
  - Magnesium-Ionen-Batterien (MIBs)
  - Zink-Ionen-Batterien (ZIBs)
  - Aluminium-Ionen-Batterien (AIBs)
- Metall-Schwefel (Me-S)
  - Lithium-Schwefel (Li-S)
  - Natrium-Schwefel Raumtemperatur (Na-S RT)
  - Natrium-Schwefel Hochtemperatur (Na-S HT)
- Metall-Luft (Me-air)
  - Lithium-Luft (Li-air)
  - Zink-Luft (Zn-air)
- Redox-Flow-Batterien (RFBs)

Die Batterietechnologien werden dabei aus einer systemischen Perspektive heraus betrachtet, die technische (KPIs und Entwicklungspotenziale), ökonomische (Kosten, Märkte, Produktion, Lieferketten) und ökologische Aspekte (z. B. Ressourcenverfügbarkeit und ökologischer Fußabdruck von Batteriematerialien) berücksichtigt und diese Aspekte mit dem Benchmark LIB vergleicht. Auf diese Weise will diese Roadmap auch einen Beitrag

zu aktuellen Diskussionen wie der europäischen Technologiesouveränität und geopolitischen Aspekten leisten. Die Erkenntnisse beruhen auf einer umfassenden Literaturrecherche, einer Online-Umfrage, einer ausführlichen Expertenbefragung sowie einem Experten-Workshop.

## Zentrale Ergebnisse

In der vorliegenden Roadmap für alternative Batterietechnologien wird insbesondere auf die folgenden Fragen eingegangen:

### **Was sind die technologiespezifischen Vorteile alternativer Batterietechnologien?**

#### **Metall-Ionen-Batterien**

SIBs sind in Bezug auf ihren Aufbau und Funktionsprinzipien den LIBs sehr ähnlich. Sie sind jedoch weniger abhängig von bestimmten Ressourcen und bieten sowohl Potenzial für mehr Nachhaltigkeit als auch Kostenvorteile. ZIBs haben eine deutlich geringere Energiedichte als LIBs, weisen dafür aber einen ebenso deutlich geringeren ökologischen Fußabdruck auf, insbesondere aufgrund der auf wasserbasierten Elektrolyten. MIBs können hohe gravimetrische und volumetrische Energiedichten erreichen, die sogar die von LIBs übertreffen. AIBs hingegen können potentiell eine deutlich höhere Leistungsdichte als LIBs, eine höhere Energiedichte als Kondensatoren sowie eine hohe Zykluslebensdauer und eine hohe C-Rate erreichen. Jedoch liegt ihre Energiedichte deutlich unter der der meisten anderen Me-Ionen-Batterietechnologien.

#### **Metall-Schwefel-Batterien**

Vielversprechende Technologien gibt es auch auf dem Gebiet der Me-S-Batterien. Die Li-S-Batterien haben das Potenzial für eine höhere gravimetrische Energiedichte als die der LIBs, aber sowohl die volumetrische Energiedichte als auch die Zyklusstabilität sind wahrscheinlich geringer. Aufgrund der hohen Energiedichte und der niedrigen Kosten von Schwefel können voraussichtlich geringe Kosten pro kWh erreicht werden, jedoch sind hierzu weitere Verbesserungen in der Zyklusstabilität und der Energiedichte erforderlich. Na-S HT erreichen eine etwas geringere gravimetrische Energiedichte als LIBs. Während Na-S HT-Batterien aufgrund der verwendeten Materialien zwar einen geringeren CO<sub>2</sub>-Fußabdruck als LIBs aufweisen, stellen die Effizienz des Batteriesystems und die vergleichsweise hohen Kosten eine Herausforderung dar. In dieser Hinsicht zeigt sich die Na-S RT-Batterie deutlich vorteilhafter und könnte auch

langfristig eine den LIBs ähnliche gravimetrische Energiedichte erreichen.

#### **Metall-Luft-Batterien**

Unter den betrachteten Me-Luft-Batterien weisen vor allem Li-Luft-Batterien ein niedriges Technology Readiness Level (TRL) und einen dementsprechend hohen Forschungsbedarf auf. Jedoch könnten Li-Luft-Batterien eine sehr hohe theoretische gravimetrische Energiedichte erreichen, möglicherweise zu etwas geringeren Kosten als LIBs. Hierfür muss jedoch eine stabile Zyklenfestigkeit gewährleistet werden. Zn-Luft-Batterien können als fortschrittlicher als Li-Luft-Batterien mit einer höheren TRL angesehen werden, außerdem könnten sie eine relativ hohe Energiedichte erreichen, die mit der von LIBs vergleichbar ist. Darüber hinaus bieten sie Potenzial für niedrigere Kosten und einen geringeren CO<sub>2</sub>-Fußabdruck als LIBs. Sie haben jedoch den Nachteil einer relativ geringen Leistungsdichte. Obwohl Unternehmensangaben seit vielen Jahren darauf hindeuten, dass ein Zn-Luft-Flow-Batteriekonzept kurz vor der Kommerzialisierung steht, konnten sich sekundäre Zn-Luft-Batterien bisher nicht als wirtschaftliche Alternative etablieren.

#### **Redox-Flow-Batterien**

Auf Vanadium basierende RFBs sind bereits auf dem Markt verfügbar, bieten jedoch noch Verbesserungspotenzial (z. B. durch Materialsubstitution, insbesondere von Vanadium), um die Kosten und den CO<sub>2</sub>-Fußabdruck weiter zu reduzieren.

Zusammenfassend lässt sich feststellen, dass die Eignung der betrachteten alternativen Batterietechnologien im Wesentlichen durch die technischen KPIs bestimmt wird. Einige der Technologien können besonders attraktiv sein, wenn beispielsweise niedrige Kosten (z. B. Zn-basierte Zellen) oder eine hohe Verfügbarkeit von Ressourcen (insbesondere Na- oder Mg-basierte Zellen) erreicht werden sollen.

### **Welche Anwendungen kommen für alternative Batterietechnologien zuerst in Frage?**

Aufgrund der technischen, wirtschaftlichen und ökologischen Unterschiede zwischen den betrachteten alternativen Batterietechnologien eignen sich diese auch für sehr unterschiedliche Anwendungen. Unterschiedliche TRLs und technologische Herausforderungen lassen vermuten, dass die alternativen Batterietechnologien voraussichtlich zu unterschiedlichen Zeiten für den Markteintritt zur Verfügung stehen. Dementsprechend gibt es unter den betrachteten Technologien keine den LIBs vergleichbare Technologie, welche für die gesamte Anwendungsbreite und Marktanforderungen geeignet ist.



## **Alternative Batteriechemien scheinen nun bereits Realität zu werden. Sie nutzen häufig vorkommende, kosteneffiziente und ungiftige Materialien und haben das Potenzial, Probleme bei der Verfügbarkeit von Rohstoffen zu entschärfen und geopolitische Abhängigkeiten zu verringern.«**

**Prof. Dr. Maximilian Fichtner,**  
Helmholtz-Institut Ulm & Sprecher  
des Exzellenzclusters POLiS

### **Mobile Anwendungen**

Mobile Anwendungen erfordern eine hohe Energie- und Leistungsdichte, weswegen derzeit keine der betrachteten alternativen Technologien in mobilen Anwendungen eingesetzt wird. SIBs stehen jedoch kurz vor der Kommerzialisierung; sie werden voraussichtlich als erste der betrachteten alternativen Batterietechnologien in mobilen Anwendungen zum Einsatz kommen. Zudem können SIBs abhängig vom Elektrodenmaterial ähnliche KPIs wie Lithium-Eisenphosphat-Zellen (LFP) erreichen. Eine weitere Möglichkeit wäre der hybride Einsatz von SIBs zusammen mit Hochenergie-LIBs wie Lithium-Nickel-Mangan-Kobalt-Oxiden (NMCs), da SIBs beispielsweise auch bei niedrigen Temperaturen eine gute Performance aufweisen. Jüngste Ankündigungen deuten darauf hin, dass SIBs hauptsächlich in motorisierten Zwei- und Dreirädern und in Kleinwagen eingesetzt werden. Dort würden sie entsprechend mit den LFP-basierten LIBs konkurrieren. Längerfristig könnten MIBs aufgrund ihrer potenziell hohen Energiedichte auch in größeren Fahrzeugbereichen eingesetzt werden, möglicherweise ab 2040. Li-S-Batterien könnten ab Mitte des nächsten Jahrzehnts in größeren Drohnen und ab 2040 sogar in eVTOLs (electric vertical take-off and landing) zum Einsatz kommen. Letztere könnten auch einen interessanten Anwendungsfall für Zn-Luft-Batterien darstellen, da diese zwar eine geringere Leistungs- und Energiedichte als Li-S-Batterien aufweisen, aber Vorteile in Bezug auf den CO<sub>2</sub>-Fußabdruck und möglicherweise auch auf die Kosten haben. Zu einem noch späteren Zeitpunkt (und nach Überwindung der bestehenden

Forschungsherausforderungen) könnten auch Li-Luft-Batterien aufgrund ihrer außergewöhnlich hohen Energiedichte dort eine Rolle spielen. Aufgrund der großen Unsicherheiten hinsichtlich der zukünftigen Entwicklung von Li-Luft-Batterien ist jedoch eine Einschätzung hinsichtlich der Markteinführung und der angesprochenen Anwendung spekulativ. Vielmehr könnte diese Technologie Spillover-Effekte zu anderen F&E-Fragestellungen ermöglichen.

### **Stationäre Anwendungen**

Die Anforderungen an einige wichtige Kennzahlen, wie z. B. die Energiedichte, sind bei stationären Anwendungen (ESS) in der Regel niedriger als bei mobilen Anwendungen, können in Bezug auf andere Aspekte, wie die Lebensdauer oder die Kosten pro kWh-Ladezyklus, aber auch strenger sein. Daher werden alternative Batterietechnologien in stationären Anwendungen wahrscheinlich eine größere Rolle als in mobilen Anwendungen spielen. Neben den teilweise bereits auf dem Markt befindlichen Speichersystemen wie RFBs, Salzwasser- oder Na-S HT-Batterien dürften auch SIBs aufgrund ihrer guten Ressourcenverfügbarkeit, Sicherheit und Tiefentladefähigkeit in naher Zukunft zunehmend relevant werden. Zwischen 2025 und 2030 könnten auch die kostengünstigen und umweltfreundlichen Zn-Ionen-Batterien auf den Markt kommen, die aufgrund ihrer begrenzten Energiedichte und des hohen Volumenbedarfs eher für große stationäre Anwendungen als für mobile Anwendungen geeignet sind. Der Einsatz von MIBs in stationären Anwendungen könnte als Sprungbrett für einen

Einsatz in mobilen Anwendungen dienen. Als Vertreter der Me-Luft-Batterien könnten Zn-Luft-Batterien bereits mittelfristig für große Pufferspeicher in Frage kommen. Ab 2035 könnten Na-S RT Batterien den Einsatz der Me-S Technologie in kleineren Speichersystemen ermöglichen, der derzeit nicht möglich/wirtschaftlich ist. Ab 2025/2030 könnten zudem AIBs vor allem in Anwendungen mit hoher Zyklanzahl und C-Rate eingesetzt werden, beispielsweise zur Netzstabilisierung oder zum Glätten von Lastspitzen, später auch als Pufferspeicher für Schnellladungen.

#### **Wie ist Europa in Bezug auf die alternativen Batterietechnologien aufgestellt/positioniert?**

Patent- und Publikationsanalysen deuten darauf hin, dass Europa bezüglich der Entwicklung einiger alternativen Batterietechnologien besser aufgestellt ist als derzeit für LIBs, beispielsweise für RFBs, Li-Luft- und Al-Ionen-Batterien – wobei Japan und China die führenden Nationen in Patent- und Publikationsaktivitäten bleiben. Bei einigen der alternativen Batterietechnologien hält die EU28 Veröffentlichungs- und Patentanteile von ca. 15–20 % an den weltweiten FuE-Aktivitäten und verzeichnet zum Teil eine hohe Dynamik mit jährlichen Wachstumsraten zwischen 10–50 %, während die EU28 bei LIBs einen Anteil von etwa 15–18 % an den FuE-Aktivitäten und ein Wachstum von 10 % aufweist. Jedoch ist dabei zu bedenken, dass das absolute Aktivitätsniveau für LIBs bezüglich der Anzahl der Publikationen und Patente im Vergleich zu alternativen Batterietechnologien 5 bis 30 Mal höher liegt.

#### **Gibt es alternative Batterietechnologien, die die Abhängigkeit von Rohstoffen deutlich verringern?**

Die meisten Batterietechnologien, welche nicht auf Li basieren, benötigen weniger kritische Rohstoffe und könnten somit dazu beitragen, Abhängigkeiten zu reduzieren. Mangels großer Anwendungsgebiete und Märkte, die mit LIBs vergleichbar sind, wird die Produktion und Versorgung mit Lithium, Nickel und Kobalt jedoch kritisch bleiben (insbesondere in den nächsten 5 bis 10 Jahren). Darüber hinaus weisen die meisten der betrachteten alternativen Batterietechnologien eine geringere Energiedichte auf als LIBs, weswegen typischerweise eine größere Menge an Rohstoffen benötigt wird, um die gleiche Speicherkapazität zu erzielen.

#### **Sind alternative Batterietechnologien absehbar, welche ähnlich wie LIBs produzierbar und skalierbar sind?**

Zumindest im kommenden Jahrzehnt sind hier weitere Metallionen Batterien, die nicht zu den LIBs gehören, im Vorteil. Ihre Produktionsschritte sind denen der LIBs sehr ähnlich, weswegen bestehende Produktionstechnologien und -umgebungen direkt genutzt werden könnten (Drop-in-Technologien) oder nur begrenzt angepasst werden müssen.

#### **Können alternative Batterietechnologien günstiger als LIBs werden?**

Alternative Batterietechnologien weisen potenziell niedrigere Materialkosten als LIBs auf. Zudem ist bei skalierten Produktionstechnologien der Anteil der Materialkosten im Vergleich zu anderen Kostenfaktoren (z. B. Energie, Ausrüstung, Arbeit usw.) höher. Beispielsweise haben kürzlich die hohen Rohstoffpreise für LIBs zu einem Anstieg der LIB-Zellkosten geführt. Bei alternativen Batterietechnologien dürften die Zellkosten zunächst aufgrund des geringen Produktionsumfangs höher sein. Jedoch können durch eine Skalierung der Produktion Kostenvorteile erreicht werden. Um diese Größenvorteile und Kostensenkungen zu realisieren sind entsprechend ausreichend große Märkte und Anwendungsfälle im GWh-Maßstab notwendig.

#### **Wie können Lieferketten für alternative Batterietechnologien aufgebaut werden?**

Da alternative Batterien im Grunde immer mit LIBs als Benchmark konkurrieren werden, ist eine Orientierung an Standards und Kompatibilität wichtig. D. h. die Produktion von Komponenten sowie Batteriezellen, die Zellformate und Batteriesysteme sollten sich an denen der LIBs orientieren, sodass bestehende Lieferketten, sofern möglich, beibehalten werden können und nicht neu aufgebaut werden müssen. Der Aufbau neuer Lieferketten wäre nur für Technologien mit speziellen Anwendungsfällen realistisch, insbesondere solche mit einer mittel- bis langfristig ausreichend großen Nachfrage.

#### **Wie groß sind die potenzielle Märkte für alternative Batterietechnologien?**

Während die Abhängigkeit von LIBs und ihren Lieferketten aufgrund ihres breiten Anwendungsspektrums hoch bleiben

wird, ist mittel- bis langfristig mit einer zunehmenden Diversifizierung des Batteriemarktes im Hinblick auf die verwendeten Technologien zu rechnen. Alternative Batterietechnologien können LIBs in bestimmten Märkten (z. B. bestimmte stationäre Speicheranwendungen oder hybrid in Kombination mit LIBs in PKWs) oder neuen Märkten (z. B. eVTOLs) ergänzen. Diese Märkte können eine gute Gelegenheit für den Markteintritt alternativer Batterietechnologien bieten, um dort ihre spezifischen Vorteile zu nutzen.

In den nächsten 5 bis 10 Jahren werden unterschiedliche GWh-Märkte bzw. konkrete Anwendungsbereiche entstehen, die aufgrund ihrer KPIs für bestimmte alternative Batterietechnologien geeignet sind und ausreichende Volumina aufweisen. LIBs können zur Entwicklung dieser Märkte beigetragen, bis die alternativen Batterietechnologien anschließend auf den Markt kommen. Neben LIBs, die weiterhin eine zentrale Rolle spielen werden, werden sich auch andere aussichtsreiche Konzepte wie Feststoff-Batterien (SSBs) etablieren. Es ist daher davon auszugehen, dass die in dieser Roadmap betrachteten alternativen Batterietechnologien nur einen Ausschnitt der zukünftigen Batterielandschaft darstellen werden, die vielfältiger sein wird als heute.

### **Handlungsfelder für die EU und Deutschland**

Um das Potenzial alternativer Batterietechnologien und damit ein aus deutscher und europäischer Sicht belastbareres und technologisch souveränes Batterie-Ökosystem zu erschließen, bedarf es zusätzlicher politischer Unterstützung. Gerade in der Anfangsphase, in der die zukünftige Marktentwicklung und die von der Politik gesetzten Rahmenbedingungen noch ungewiss sind, müssen möglicherweise Anreize für die lokale Industrie geschaffen werden.

Aufbauend auf der bereits existierenden soliden F&E-Basis für alternative Batterietechnologien, könnte ein ganzheitlicher politischer Ansatz helfen, Schlüsseltechnologien zur Marktreife zu führen und zum Einsatz zu bringen. Dieser Ansatz sollte die gesamte Lieferkette umfassen, einschließlich der Grundlagenforschung zur Bewältigung technologischer Herausforderungen, des kontinuierlichen Aufbaus eines Patentportfolios oder geistigen Eigentums im Allgemeinen, der Entwicklung und Qualifizierung von Produktionsprozessen, der Sicherung von Ressourcen und der Berücksichtigung von Endnutzenden zur Erprobung und Kommerzialisierung der Anwendung. Dieser

Ansatz sollte nicht nur große Unternehmen, die traditionellerweise das Batterie-Ökosystem prägen, sondern auch KMUs und Start-ups, die bei überschaubarer Größe (z. B. durch hohe Finanzierungsquoten und mehrstufige Finanzierungsprozesse) zu wichtigen Akteuren auf den jeweiligen Spezialmärkten werden könnten, berücksichtigen.

Ein solcher ganzheitlicher Ansatz ist jedoch mit hohen Kosten und Risiken verbunden und kann daher nur auf eine begrenzte Anzahl von Technologien angewendet werden. Systematische und regelmäßige Screening-Prozesse für die Auswahl von Schlüsseltechnologien sowie Kriterien für eine mögliche Beendigung der Förderung wären notwendig.

Darüber hinaus ist davon auszugehen, dass sich auch andere Batterietechnologien, insbesondere SSBs oder Hochenergie-LIBs, weiterentwickeln und in Zukunft auch als Alternativen zu den modernen LIBs zur Verfügung stehen. Auch über die in dieser Roadmap betrachteten alternativen Batterietechnologien hinaus besteht noch ein erheblicher F&E- und Weiterentwicklungsbedarf bei neuen Materialien und Zellkonzepten für zukünftige Batterieanwendungen. Diese F&E könnte auch mögliche Spillover-Effekte zwischen den verschiedenen Batterietypen ermöglichen. Darüber hinaus können politische und geopolitische Spannungen sowie die zunehmende Bedeutung von Umweltschutz und Nachhaltigkeit, Märkte und Lieferketten beeinflussen.

Aus diesem Grund ist es wichtig, Meilensteine für die Entwicklung und Marktrelevanz zu definieren und den Fortschritt alternativer Batteriesysteme entsprechend zu begleiten und zu planen.

# 1. Introduction

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The Paris Agreement requires that countries to decrease their greenhouse gas emissions as soon as possible in order to achieve climate-neutrality by the middle of this century. To decarbonize carbon-intensive sectors, such as energy and transportation, batteries are a key technology and are driving the transformation in these sectors toward a broad diffusion of electric mobility and stationary storage concepts.

Lithium-ion batteries (LIBs) have become the leading battery technology, surpassing the demand for lead acid (PbA) batteries and serving a global market of between one-half and one TWh. In the coming decade, LIBs will be essentially the only scaled battery technology and will be mainly used and will diffuse in electric passenger cars, commercial vehicles and many other mobility concepts, stationary applications and, of course, will still be needed for mobile (consumer) devices.

While many world regions are currently at a critical phase in building up their battery ecosystems (based on LIBs), political and geo-political tensions are setting a new framework at the same time. Within this framework, China's leading position in particular is viewed critically. Measures such as the European Battery Regulation to shape the conditions for a European battery value chain (with mandatory sustainability and safety requirements) or the US Inflation Reduction Act (IRA) to re-industrialize the USA and direct investments into the region are intended to increase the resilience and sovereignty of those regions.

In this context, a new focus on industrial policies and concentrated funding can be observed across world regions and countries. Strategic agendas have been formulated recently and are currently being updated in some cases, taking into account the increased geo-political dependencies and market structures.

Main questions arising with respect to LIBs:

- Is access to raw materials (in particular lithium, cobalt, nickel) assured and at controlled costs? The leading suppliers here are world regions such as South America, Africa, Australia, but also China (in the case of graphite). Activities to determine the mining potential of certain raw materials (e.g., Lithium) in Europe are increasing and aim to reduce global dependencies.
- Is access to technology and cell production ensured and sustainable (e.g., energy-efficient production of LIB cells)? In addition to Korean and Japanese cell producers, Chinese producers in particular dominate the global LIB market and are currently developing production capacities in Europe. Energy prices (also in the context of the Russia-Ukraine war as an accelerator to the energy crisis) are impacting the choice of production location as are international re-industrialization policies such as the IRA from the USA.
- Are the supply chains for LIB stable and secured? The leading component suppliers are companies from China, South Korea and Japan. There is still a dependency along the battery value chain besides the supply of raw materials and cell manufacturing. For Europe, supply chains for LIBs and any other future battery technology would have to be built up, or at least access along the value chain secured.
- Are batteries a sustainable solution and can regional ecosystems be established competitively? In addition to questions concerning the supply of battery raw materials, components and cells, a circular economy for battery production is also becoming more important. This includes recycling batteries at their end of life to reduce raw material dependencies by using secondary raw materials. The EU Battery Regulation aims to support battery recycling and reduce the overall CO<sub>2</sub> footprint (e.g., with the battery passport). However, a circular battery economy still has to be established and prove its competitiveness in Europe.

## Motivation for this roadmap

Against this background and against the benchmark of LIBs, the question arises whether there are potentially alternative technologies to LIBs that could ease the raw material situation and dependency, where scaled production of the technology is possible, and competitive supply chains can be built up. When could alternative battery technologies come to market and can they address similar (broad) applications similar to LIBs?

For established battery technologies such as lead acid (Pb), but also nickel cadmium (NiCd), nickel metal hydride (NiMH), etc., performance parameters such as energy densities, but also cost aspects, sustainability aspects or relevant markets were limiting factors, which led to the widespread use of LIBs today. But perhaps alternative technologies may appear on the horizon in the future?

## Focus of this roadmap

This roadmap thus focuses on alternative battery technologies that appear to be promising for one or more applications with a longer-term perspective, i.e., on batteries that are not yet commercially established – in general or in Europe.

The roadmap covers metal-ion (Me-ion), metal-sulfur (Me-S), metal-air (Me-air) and redox flow batteries (RFBs), with sodium-ion batteries (SIBs) (in general and saltwater, SIB Salt), magnesium-ion batteries (MIBs), zinc-ion batteries (ZIBs), aluminum-ion batteries (AIBs), lithium-sulfur (Li-S), sodium-sulfur at room and high temperature (Na-S RT and HT), lithium-air (Li-air), zinc-air (Zn-air) and RFBs investigated in more detail.

The roadmap takes a holistic perspective and covers

- technical aspects (KPIs, TRL levels, potential future developments),
- economic aspects (costs, potential applications and markets, production, supply chains), and
- ecological aspects (e.g., resource availability, sustainability)

In doing so, this roadmap also intends to contribute to current discussions such as European technology sovereignty and geopolitical aspects. Accordingly, the advantages and potentials of the individual technologies for Europe will be discussed and compared with LIBs as a benchmark.

Finally, with a cross-comparison of the different technologies based on the above-mentioned aspects, the roadmap aims to answer the question whether technology candidates are in sight that could aid technology sovereignty, especially in Europe.

## 1.1. Market Developments

The global secondary battery demand arises from various sectors and markets. Currently, lead acid (PbA) and lithium-ion batteries (LIBs) cover most applications, with the latter exhibiting the highest growth rates (annual growth between 30 % and 50 %), driven by the increasing global market for electric vehicles (EVs). The global demand for LIBs reached 600 to 700 GWh in 2022. Initial calculations for the year 2022 indicate a capacity demand of around 680 GWh.

Currently, LIBs are used in various sectors and for a variety of applications. Hence, both the achievable performance of the applications and their price are determined by LIB development. However, the requirements of the various applications differ substantially. In addition, new applications might emerge with completely different requirements. From a demand perspective, therefore, there is a need for more specific LIBs or alternatives to LIBs.

Within this market analysis, we focus on LIB demand projections. However, these forecasts are based on the assumption that no additional alternative technologies will become widely available in the future. In principle, the projected demand should be interpreted with a corresponding openness to technology. Alternative battery technologies that meet the specific requirements of certain applications could satisfy parts of the demand.

### Market development

By 2030, global demand for LIBs could reach more than 3 TWh per year (Figure 1) [1]. Most technical reports and market forecasts predict a global demand of 2 to 4 TWh in 2030, reaching up to 6 TWh in maximum scenarios. After 2030, the market will continue to grow. By then, new markets, e.g., individual passenger aviation and many others could reach relevant market shares, which will further increase demand. In the long term, a global battery demand of more than 10 TWh per year is considered realistic. [1]

The European demand for LIB cells is estimated at 20–30 % of the global demand. In Europe, electric mobility is an even stronger driver of LIB demand than it is globally, driven by the high sales figures of car manufacturers from Germany and France, for example.

### Application sectors with the highest battery demand

The main driver behind the growing global LIB market is electric mobility in the form of EVs. The market for electric passenger cars generates the highest demand among LIB applications today (Figure 1). In addition to electric cars, other LIB applications include commercial EVs (cEV), stationary storage (electrical energy storage, ESS) and portable/wearable devices for consumer, computing, and communications (3Cs).

Electrified passenger cars (pEVs) such as battery EVs (BEVs) or plug-in hybrid EVs (PHEVs) already account for more than 70 % of LIB demand today. The global demand for LIBs for electric cars increased from 130 GWh in 2020 to more than 500 GWh in 2022.

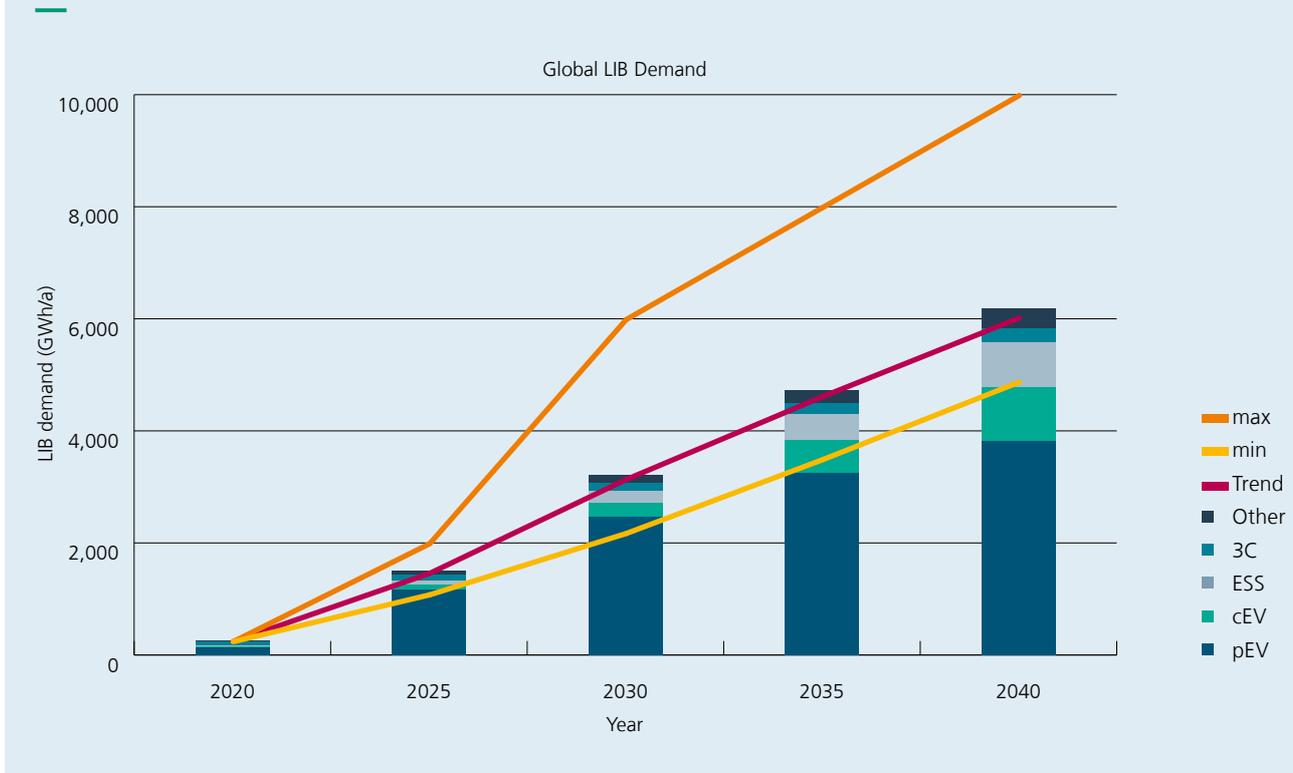
cEVs (e.g., electric buses or electric trucks) do not yet play a major role, but could develop into another main market by 2030 and beyond. There are smaller numbers of heavy-duty cEVs, but they have substantially higher battery capacity. Sales of light cEVs like delivery vans or vehicles for craftspeople are increasing rapidly. The battery capacities of such vehicles are comparable with those of passenger cars [1].

The market for ESS is growing strongly, but at a low overall level. According to rather conservative forecasts, the annual demand from stationary applications could amount to about 100 GWh in 2030. More optimistic forecasts project a demand of 200 to 300 GWh per year by then. [1]

3C applications are already established LIB markets that will continue to grow. Smaller single-digit growth rates are projected for the established market of laptops, tablets and mobile phones. The segment of power tools and portable household applications is considered a strong growth market in the years to come, with annual growth rates of 15–20 %. Other electronic and consumer applications such as cameras and drones are currently comparatively small, but could develop much more dynamically in the future.

Micromobility applications such as eBikes or eScooters also represent a growing market. The compound annual growth rates (CAGRs) to date have ranged between 8 % and 14 %. Demand could roughly double by 2030.

Other transport sectors, e.g., trains, ships and airplanes, will begin or continue to push electrification efforts in the next few years. In addition to purely electric alternatives, hybridization of propulsion systems may be a frequent option in shipping,

**Figure 1: Illustration of the demand for LIB between 2020 and 2040 by market segment.**

for example. In aviation, the need for batteries will probably only increase on a large scale after 2030 [1]. The battery demand for the categories micromobility and other transport sectors is comparatively low and is assigned to the category "Other" in Figure 1.

### Global and regional developments of cell and component production

Given the predicted increase in demand for battery cells, global production capacities will have to increase substantially in the future. According to initial calculations, more than 1 TWh of production capacity was installed at the end of 2022. Most of the factories are located in Asia, especially China, South Korea, and Japan. The capacities announced for the future suggest installations of around 4 TWh by 2025 and the share of production in Europe and the United States will increase by then. By 2030, production capacities may exceed 6.5 TWh. In total, a cumulated production capacity of more than 12 TWh has been announced by different companies up to 2030. However, a consolidation of these announcements and stakeholders is expected, and these capacities might only be realized well beyond 2030. [1]

It is likely that Europe will develop production capacities of up to 1.7 TWh by 2030, partly built by Asian stakeholders, but increasingly also by European stakeholders. Due to this trend, Europe's capacities will account for approximately one third of global production by 2030.

### Market revenues and battery cost developments

In total, the LIB cells sold in 2022 had a market value of 80 billion EUR. Due to the predicted growth of the market, revenue may increase to 125–225 billion EUR by 2030 [1]. Studies assume current average cell costs of approximately 115 EUR/kWh for state-of-the-art LIBs [2]. Although the raw material situation for LIBs is currently quite tense, forecasts still predict an overall downward trend for cell cost in the future. The material components for the cell (anode, cathode, separator and electrolyte) account for the largest share of cell cost. The market share of these components exceeded 43 billion euros in 2021 and will increase to over 150 billion euros by 2030. The most expensive cell component is the cathode as it typically contains valuable raw materials such as cobalt or nickel. Currently, the cathode accounts for more than half of the material costs. Compared to material costs, manufacturing costs make up a smaller share of the total cell cost. The added monetary value of cell production (without materials etc.) will be

approximately 35 billion euros in Europe and 65 billion euros worldwide in 2030.

Beyond battery cell fabrication, the assembly of cells to modules and packs is another important market. The costs for battery pack assembly amount to 14 to 30 EUR/kWh [3]. Other markets affected are the machinery and equipment manufacturers producing the systems needed for highly automated cell production. The costs of installing production lines in all the cell factories which have been announced amount to approximately 300 billion euros worldwide until 2030. In Europe, battery manufacturers will have to invest approximately 80 billion euros by 2030. According to announcements in Germany, more than 17 billion euros will be invested in production lines by then.

### Addressable markets for alternative battery technologies

Alternative battery technologies can address individual or multiple key performance indicators such as technical, cost, safety or sustainability aspects. Although electric mobility has been a core driver of battery development in the past, current battery technology developments also specifically address other markets.

Since the major car manufacturers have committed themselves to the use of lithium iron phosphate (LFP) or lithium nickel manganese cobalt oxides (NMCs) technologies for the next few years, it is likely that only selected alternative battery technologies will be used in the BEV mass market in the near future. If key performance indicators (KPIs) of a new and commercialized technology are comparable to those of today's LIBs, alternative technologies can address a potential market in the double- to triple-digit GWh range.

In the case of premium BEVs, alternative technologies with substantial performance improvements in energy density and charging speed could play a role. While customers in this market segment are less price-sensitive than in other markets, this market accounts for only a share of the total EV market.

For cEVs, alternative battery technologies can reduce product cost or increase operational lifetime. While similar developments can be expected for light cEVs as for pEVs, batteries for heavy duty vehicles continue to compete with technologies such as internal combustion engines or fuel cells.

Alternative technologies might also be able to address the needs of new kinds of mobile applications such as battery-electric aircraft and space applications, ships or trains. However, in the near future, only a fledgling market in the

MWh range, i.e., for testing, can be assumed for alternative battery technologies. However, if technologies prove to be feasible and promising, markets in the GWh range could be possible in the long term.

For ESS, batteries with high cycle stability or high power are required – energy density is less important. Hence, alternative technologies addressing these requirements may be even more favorable than LIBs. A distinction can be made between smaller residential home storage systems and large (grid-scale) industrial ESS. For residential home storage systems, lead-acid batteries have been replaced by LIBs for several years, and LIBs are unlikely to be replaced by alternative battery technologies in the near future. It is therefore likely that only MWh ranges will be addressed for the time being in smaller, residential home storage systems. For large (grid-scale) ESS, a mix of technologies such as PbA, redox flow and high-temperature batteries (e.g., Na-S or ZEBRA) have already been announced or employed in large-scale ESS projects. It is likely that new alternative battery technologies in this market segment will continue to find their way up to application scale in the future and could also capture further market shares once they have achieved increasing lifetime, lower cost and economics of scale. Therefore, the potential market might be in the double- to triple-digit GWh range here.

For consumer electronics, fast charging and downsizing are important trends. While in the future, flexible cell design and increasing miniaturization could become more important, it is expected that LIBs will continue to be the dominant technology for typical consumer electronics applications.

Whether and to what extent alternative battery technologies can capture market shares depends on various criteria such as performance, cost, production scalability or sustainability aspects. These criteria may vary by country, company or specific application and therefore increase uncertainty about future market developments, in particular for alternative battery technologies.

## 1.2. Roadmap Approach

A number of interrelated methods were used to draw up this roadmap, building on each other sequentially (Figure 2).

### Desk Research

A scientific literature review of the state-of-research on a multitude of alternative battery technologies such as metal-ion batteries, metal-sulfur batteries or flow batteries, marked the start of the activities, which began in May 2022. This review was continued throughout the elaboration of the roadmap to include and update important literature. The aim was to identify the most important and promising alternative battery technologies and cell concepts undergoing research, including their individual advantages and bottlenecks as well as potential solutions for these bottlenecks. Furthermore, first performance parameters were extracted, e.g., in terms of stability and cycle life, energy (density), cost and regarding the availability of raw materials.

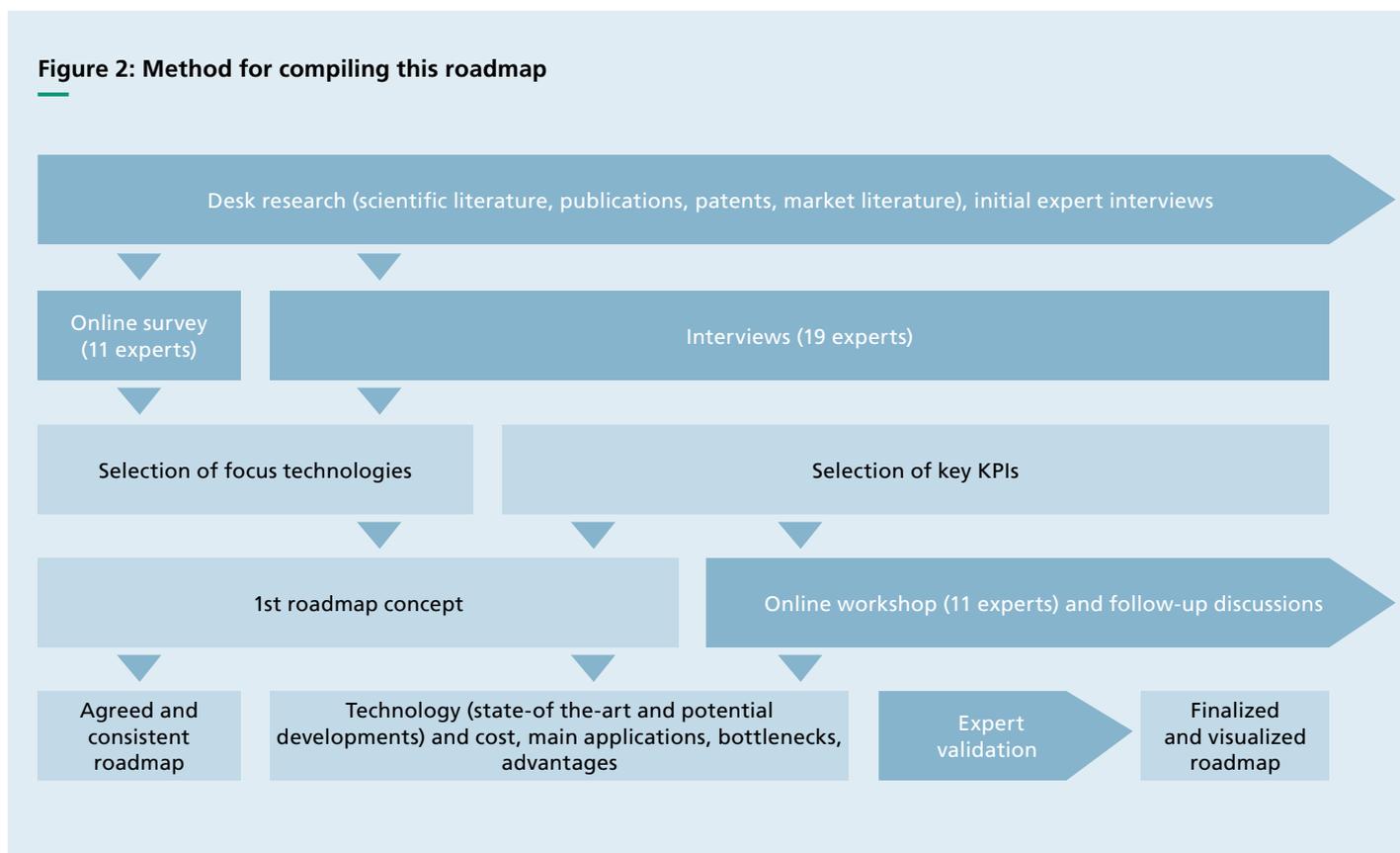
Together with initial expert interviews and an online survey (see below), this review led to the initial selection of alternative

battery technologies and a first outline of a roadmap including time frames and scope.

A market literature review performed during the process in order to obtain market data on LIBs as a benchmark for any alternative system complemented the scientific literature review, and helped to identify applications that could potentially benefit from non-LIB technologies. The sources used included market studies, technology reports, articles and information from company websites.

On a more aggregated level, publication and patent analyses were used to identify past R&D dynamics, current trends, and competitors at regional, country, and organizational level. The peer-reviewed publications were extracted from the Web of Science using a keyword-based search. This approach was intended to identify “key publications”, which allow for a comparison of R&D activities between countries and key players. Patent applications were identified via a keyword search in the World Patents Index (WPI) database. Both analyses covered the last five years. To narrow the search to patent applications with relatively high economic value, our analysis focused

**Figure 2: Method for compiling this roadmap**



on transnational patent applications, i.e., patent applications either submitted to the European Patent Office (EPO) or the World Intellectual Property Organization (WIPO), because these are always aimed at several foreign patent offices and require a high investment in the patent application process. Moreover, the use of transnational patents enables a fair country comparison, as differences in national patenting systems lead to the overvaluation of certain countries if only national patent applications are regarded. The publication and patent activities indicate the position of German and EU28 activities in an international context, taking LIB as a benchmark, and are strategically important to assess the competition as well as potential partnerships.

### Survey

Complementing the first insights from the literature, an online survey was conducted in June 2022 to identify the most promising alternative battery technologies, which should become the focus of this report. National battery experts from industry and academia pre-assessed the relevance of alternative battery technologies using a three-step scale. The term ‘relevance’ was not defined in the survey to allow a broad perspective and encompass various dimensions including technical, economic and ecological ones. In total, 11 experts pre-assessed the technologies, many of whom also served as experts in the interviews conducted (see below).

### Interviews

Interviews with 19 mostly national experts were conducted during the roadmapping process, some of whom we talked to twice. The first set of interviews was intended to outline the roadmap concept and to answer questions insufficiently addressed in the literature. A second set of expert interviews was conducted once the list of alternative battery technologies was finalized in order to complement extant findings and prepare the expert workshop (see below). Finally, a third set of interviews followed after the workshop to address any open questions. The expert interviews covered the different alternative battery technologies and the cell concepts focused on in this roadmap. Therefore, the interviews also served to shape the roadmap’s structure and content. While this approach ensured that the roadmap was in line with the scientific community, the interviews also served to check the validity and consistency of outcomes from other data sources and pinpoint major uncertainties and areas of broad consensus.

### Expert workshop

The insights gathered through desk research and the interviews were complemented by an expert workshop, which was conducted online in October 2022 with 11 national experts for alternative battery technologies from science and industry, and the roadmap team. During the workshop, the state of research for each alternative battery technology was discussed using a collaborative real-time online whiteboard. The workshop focused on discussing the challenges and related solutions concerning the battery components and how they function, as well as the respective time frames for development and commercialization. Additional aspects covered in this roadmap were debated, such as resource availability, production processes, market readiness, and the developments of markets and target applications, as well as implications for industry, policy and R&D. This workshop served to validate the roadmap, but also to supplement and correct it by including recent inputs, updates and harmonization.

In total, more than 20 experts contributed to the roadmap. The roadmap team and authors of this report then finalized the roadmap including the latest literature reviews, figures, and consolidating texts. Parts of the document were sent to the experts for validation.

This roadmap is to be understood as a technology roadmap with an international perspective, which is not restricted to the national or European level. While the screened literature and markets were international in scope, the experts contributing to the roadmap were mainly from Germany, and might have a certain bias with respect to their background and perspective.

## 1.3. Benchmark: LIBs

LIBs currently represent the benchmark for many different applications from consumer products (phones, laptops, etc.), power tools, and stationary storage systems to mobility applications (electric bikes, scooters, buses and trucks, and especially passenger cars). In the future, other battery technologies such as solid-state batteries (SSBs) might become the benchmark in certain applications, but for the time being, emerging battery technologies have to compete with the current benchmark – liquid electrolyte LIBs.

### General structure of lithium-ion batteries and active materials

LIBs typically consist of stacked foil electrodes, i.e., the anode and the cathode. Each of them is composed of a metallic current collector foil, an anode active material / cathode active material (AAM/CAM) and inactive materials such as binders and conductive agents. A separator in-between the electrodes and a liquid organic electrolyte provide ionic conductivity and prevent electronic conductivity.

The lithium storage mechanism of most CAM is to provide a host structure for Li intercalation. Two groups of CAM are in use today [4]: layered transition-metal oxides  $\text{Li}(\text{Mn},\text{Co},\text{Ni},\text{Al})\text{O}_2$  with  $\text{LiMn}_x\text{Co}_y\text{Ni}_{1-x-y}\text{O}_2$ ,  $x < 1$ ,  $y < 1$  (NMC) and  $\text{LiCo}_x\text{Ni}_{1-x-y}\text{Al}_y\text{O}_2$ ,  $x < 0.2$ ,  $y < 0.1$  (NCA) being the most prominent sub-classes, and olivine structured transition metal phosphates  $\text{Li}(\text{Mn},\text{Fe},\text{Co},\text{Ni})\text{PO}_4$  with  $\text{LiFePO}_4$  (LFP) currently being the only commercially applied material in this group. The oxides have an intercalation potential of 3.8 V vs.  $\text{Li}/\text{Li}^+$  and a specific capacity of 150 to 200 mAh/g. LFP has a specific capacity of almost 170 mAh/g at a potential of 3.4 V vs.  $\text{Li}/\text{Li}^+$ . Approaches to further develop oxide materials either increase the nickel content 1-x-y to so-called Ni-rich materials [5] or use Li- and Mn-rich oxides that have high theoretical capacities [6]. LFP is currently being improved by substituting iron with manganese to form  $\text{LiFe}_{1-x}\text{Mn}_x\text{PO}_4$  (LMFP), which increases cell voltage.

The CAM typically consists of sub-micrometer primary particles that aggregate to micrometer-sized secondary particles. Nano- to micro-sized carbon additives, which cover the CAM particle surface and result in a conductive network, enable electronic conductivity. Polymer binders provide the mechanical stability of these particle-based layers.

The AAM typically consists of either spherical or plate-like graphite particles. Depending on the desired power capability, smaller or larger particles are used. Similar to the CAM, binders and carbon additives are added.

In the future, Si-based materials are likely to provide high-capacity alternatives to graphite [7, 8] either as mixtures of graphite and Si or as  $\text{SiO}_x$  nanoparticles or as completely Si-based systems. Silicon forms an alloy with lithium at a voltage of 0.3 V vs.  $\text{Li}/\text{Li}^+$ . With a theoretical capacity of more than 3500 mAh/g, it could significantly increase the energy density of LIBs, although there are major technological challenges associated with the high volume change during the reaction and electrochemical stability. The active materials in LIBs account for 60 to 80 % of the total cost.

### Key performance indicators – today and in the future

The range of possible performance characteristics for LIB is very high. With the right material selection and cell design, it is possible, for example, to produce high-performance cells with charge and discharge rates of up to 10C ( $\text{Li}_4\text{Ti}_5\text{O}_{12}$ , lithium titanate (LTO)-based LIB), high-duty cells with a lifetime of several thousand cycles, or high-energy cells with a gravimetric and volumetric energy density of more than 250 Wh/kg and 700 Wh/l (e.g., NCA-LIB). However, all of the maximum values mentioned cannot be realized simultaneously in a single cell.

Depending on the application, there are different development trends for further optimization of the relevant KPI(s). For electronics applications, energy density is to be optimized by increasing the cell voltage to  $> 3.9$  V while simultaneously increasing the capacity. For many mobile applications, e.g., from the power tools sector, the focus is on the cost-effective development of fast-charging cells. Two strands are currently being pursued in the automotive sector: increasing energy density at cell level through the latest high-energy materials (Ni-rich NMCs or NCAs) and increasing energy density at pack level through safe large-format cell technologies (e.g., LFP-based).

In addition to the availability of ever more powerful materials, energy density is also likely to be improved by increasingly efficient cell design, or by reducing the amount of passive components in the battery cells, e.g., by reducing the thickness of separator layers, increasing the active material content, or reducing porosity. Already today, up to 60 % of the energy density at material level can be transferred to the cell level. This is due to thin current collector foils and a loading of 4 to 5 mAh/cm<sup>2</sup>. By 2030, electrode loading could increase to capacities of over 7 mAh/cm<sup>2</sup>, leading to energy densities of  $> 300$  Wh/kg and  $> 900$  Wh/l [9].

## Lithium-ion battery cell production

The general fabrication of LIB cells from thin coated electrode foils and subsequent stacking or winding processes allow continuous roll-to-roll production, at least until cell assembly.

While some parts of production, such as formation and aging, are still very time-consuming, process developments have led to high throughputs enabling very efficient factories producing LIBs at GWh-scale (so-called “gigafactories”). Today, cell manufacturing costs account for substantially less than 20 % of the total costs of LIB cells. Nevertheless, the manufacturing process includes some critical steps which, among others, affect the environmental footprint of LIBs [10]: the use of toxic solvents, the need for atmospheric conditioning to low dew points, and the generally very high use of energy in material production, electrode fabrication, and cell formation. While many new technologies are being developed to address these issues [11], various challenges seem inherently linked to the characteristics of LIBs, so that production cannot be optimized at will.

## Limitations of lithium-ion batteries and general challenges

The use of intercalation materials, i.e., more or less stable host structures for the Li-ions, enables a very stable and high-performance electrochemical system, but necessarily results in very high material overheads and thus limits the achievable energy density of LIBs. Strictly speaking, the use of Si as an anode material is already a step away from the Li-ion battery towards a Li battery. However, a further increase in energy density is unlikely to be possible with pure intercalation “ion systems”.

Regardless of the active materials chosen, the electrochemical system poses fundamental challenges that affect, for example, the environmental footprint. The stable operation of LIBs depends substantially on the interfacial chemistry between electrodes and electrolyte. Liquid organic electrolytes seem to be the only commercially ready option so far. However, they are toxic, flammable and extremely water-sensitive, and are also very difficult to recycle. From an ecological point of view, aqueous electrolytes would be highly desirable. However, their use in LIBs is associated with enormous challenges [12]. The materials used and the structure of LIBs also pose safety risks. The flammability or reactivity of the materials and the thin layer structures result in a high hazard potential, which must be countered by special efforts at pack level.

By weight, lithium is only present in LIBs in small percentages due to its small mass, but the material and its extraction contribute greatly to the overall cost and environmental footprint of LIBs. It is also still being debated whether lithium is available in sufficient quantities. Lithium recycling can play a significant role in alleviating this problem, however not in the short and medium term [13].

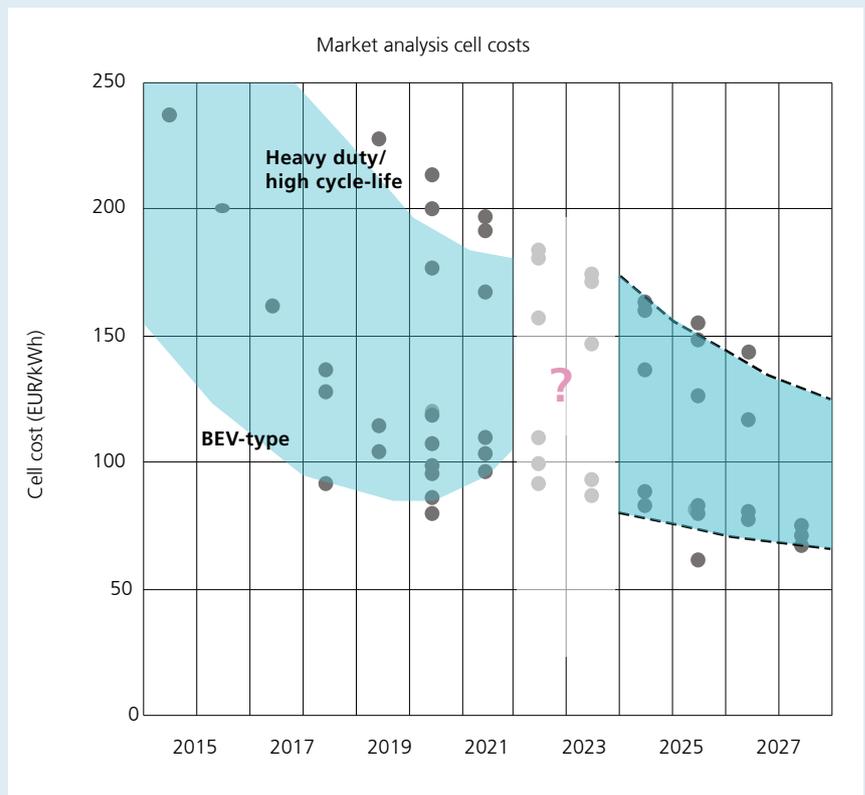
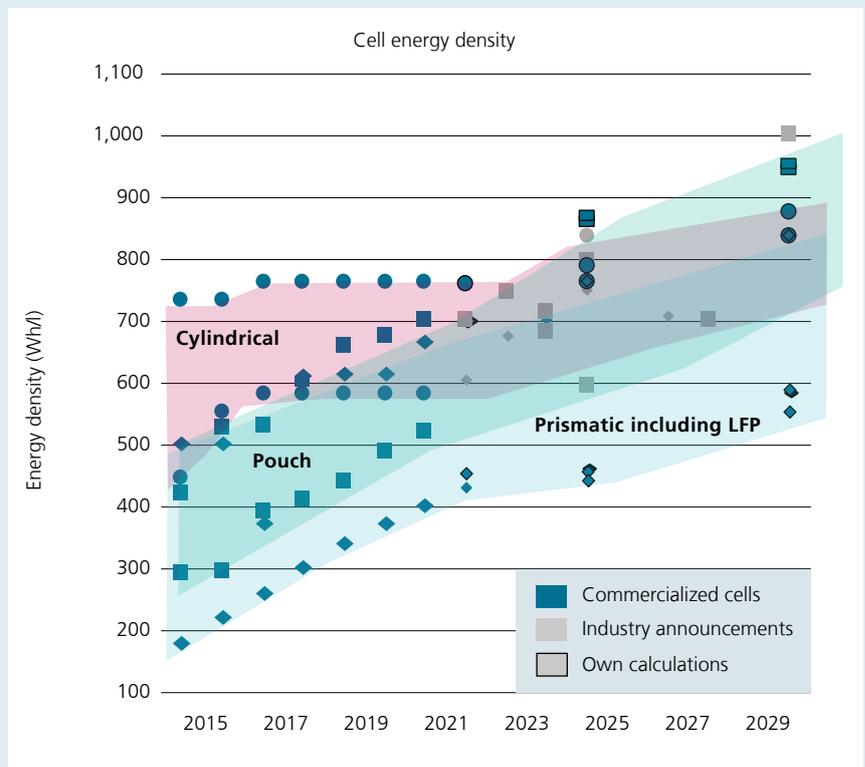
## Lithium-ion battery cost

As a result of high Li demand and supply shortages, the Li price has rocketed over the last 2 years. This trend can also be observed for other important precursor materials such as Co- and Ni-sulfate.

The increase in raw material costs has driven the price of CAMs. While this is the biggest cost component of LIBs, energy, labor, R&D, depreciation and other factors also contribute to their cost. Energy costs have increased in many LIB-producing countries, particularly in 2022. Similarly, investment costs for production equipment have increased due to the high demand and scale-up of new gigafactories. As a result, the price of BEV-type LIB cells rose from close to 100 USD/kWh in 2020/21 to over 120 USD/kWh in 2022 [2, 14]. Earlier cost targets for LIBs of less than 80 EUR/kWh for this decade [15, 16] have thus become a distant prospect. The technologies mentioned above for increasing energy density are therefore subject to economic viability. If the high price pressure continues, this would favor the cheaper and not necessarily the most efficient LIB technologies.

Due to the above mentioned limitations of LIBs with respect to cost, sustainability and performance, research is focusing on alternative battery technologies with the main goal of developing batteries with a smaller ecological footprint that ideally use abundant materials and simultaneously have sufficiently high performance to be used in various applications. Each alternative battery technology will, however, have to compete with LIBs in the specific application and will need to substantially outperform LIBs in at least one KPI to gain relevant market shares.

**Figure 3: Energy densities and cell costs of LIBs** Left: Industry announcements and our density development for LIBs. Right: Analysis of LIB cell cost forecasts by different analysts [17–21] and effect of raw material cost increase in 2021/22.



## 2. Alternative Battery Technologies

### 2.1. Overview of Alternative Battery Technologies

Many of the properties of lithium are advantageous for battery design and have led to the establishment of lithium-ion battery (LIB) technology alongside other systems such as lead acid (PbA) or nickel metal hydride (NiMH) batteries. Li is light (specific weight), small (ionic radius) and has a very low electrode potential (vs. standard hydrogen electrode / SHE), so a broad range of potential electrode (host) materials with high specific capacity are available and high voltage is achievable at the cell level. Although there are no suitable and intrinsically stable electrolytes for most electrode combinations, stable operation could be achieved with organic electrolytes.

In principle, alternative battery systems to LIBs, and thus Li intercalation in electrode materials, are conceivable in different ways:

- by utilizing alloying or conversion or deposition reactions at the electrodes,
- by completely different electrode concepts, e.g., with gaseous oxygen at the cathode, or
- by using other charge-carrying elements / ions.

However, many of the alternatives to Li have either a less favorable electrode potential or a larger ionic radius (Table 1). Although both parameters do not directly describe the performance of these ions in batteries, they are indicators of the cell voltage that can be achieved and the volume required for storage.

Nevertheless, many of the possible alternative battery systems could be highly interesting for specific applications. In addition to the fundamental properties of the ions, technical solutions must be found at all levels and life cycle stages of a battery that are feasible in practice: suitable active materials and electrolytes with high kinetics and stability, scalable manufacturing processes and, last but not least, strategies for handling the batteries after their end of life.

This roadmap focuses on those alternative battery technologies that seem to be promising for one or more applications, where promising covers different dimensions such as performance, economic and ecological aspects. Moreover, this roadmap focuses on long-term developments and consequently on

batteries that have not been commercially established yet – in general or in Europe. Based on insights from previous roadmaps [15] and the literature, as well as on an online survey conducted with national battery experts, this roadmap focuses on metal-ion (Me-ion), metal-sulfur (Me-S), metal-air (Me-air) and redox flow batteries (RFBs) and selected sub-technologies (Table 2).

#### Metal-ion batteries

Me-ion batteries are systems for electrochemical energy storage in which ions shuttle back and forth between the negative and positive electrodes during discharging and charging [22]. They usually consist of a particular cathode material and an anode material, each typically deposited on a metallic current collector foil. The two electrodes are separated by a microporous separator, while ion transport is enabled by a typically liquid electrolyte. Me-ion batteries can be considered state-of-the-art in many applications, with LIBs being the best-known representative, but not the only one. The other Me-ion batteries follow the same shuttle principle as LIBs, but use metals such as sodium, aluminum, zinc or magnesium instead of lithium. Although the way a cell is built up is quite similar when different metals are used, the resulting battery systems differ in terms of their respective KPIs (as Table 1 indicates) and can therefore be used in different specific applications.

#### Metal-sulfur batteries

Sulfur can react with Li, Na, Mg and other metals to form metal-sulfides, making it a promising, low-cost, and highly abundant cathode active material. Me-S batteries typically use metallic anodes (in molten or solid form) and liquid (room temperature Me-sulfur batteries) or solid electrolytes (high-temperature Me-sulfur batteries). In addition to high temperature (HT) Me-S batteries, room temperature (RT) Me-S batteries are also likely in the future. Due to the low electronic conductivity of sulfur, the material requires functionalization in room temperature concepts, e.g., through embedding in a conductive carbon matrix. Battery cells with a metallic Li or Na anode promise high gravimetric energy densities. The stability and

power performance of such systems, however, pose severe challenges. The development of suitable cell components such as electrolytes, membranes and specialized carbons is a prerequisite for future commercialization. High-temperature concepts utilizing molten sulfur and sodium have already been commercialized, but require a special system set-up with external heating and ceramic components.

### Metal-air batteries

Me-air batteries consist of a metal electrode (e.g., lithium or zinc), an electrolyte and the gas diffusion electrode (GDE), which enables the supply of the active oxygen component from either the surrounding air or an oxygen tank. The electric energy results from a chemical reaction between the metal and oxygen. Hence, the cell capacity is primarily defined by the metal used. The main advantages of Me-air batteries are the theoretically high energy density and potential low cost. A variety of technological challenges along the entire cell design spectrum results in major disadvantages for the cell's stable operation (cycle life, efficiency), which still need to be overcome.

### Redox flow batteries

Redox flow batteries (RFBs) consist of two electrolyte tanks, in which the electrical energy is stored in the form of redox couples, typically in an aqueous solution. A battery cell, through which the electrolytes are pumped, converts the electrical energy into chemical energy and vice versa. Different chemical redox systems exist for RFBs, among which the vanadium/vanadium is the most mature electrochemical system. High cycle stability as well as readily recyclable electrolyte materials are advantages of RFBs.

**Table 1: Ionic radius and SHE of different ions**

Element, ion	Ionic radius (pm)	Potential vs. SHE (V)
<b>Aluminum, Al<sup>3+</sup></b>	54	-1.66
<b>Magnesium, Mg<sup>2+</sup></b>	72	-2.37
<b>Zinc, Zn<sup>2+</sup></b>	74	-0.76
<b>Lithium, Li<sup>+</sup></b>	76	-3.04
<b>Vanadium, V<sup>2+</sup></b>	79	-1.18
<b>Calcium, Ca<sup>2+</sup></b>	100	-2.87
<b>Sodium, Na<sup>+</sup></b>	102	-2.71
<b>Potassium, K<sup>+</sup></b>	138	-2.93

**Table 2: Overview of alternative battery technologies that form the focus of this roadmap**

Focus battery technology groups	Focus battery technologies
<b>Me-ion</b>	<ul style="list-style-type: none"> <li>▪ SIB</li> <li>▪ SIB Salt</li> <li>▪ MIB</li> <li>▪ ZIB</li> <li>▪ AIB</li> </ul>
<b>Me-S</b>	<ul style="list-style-type: none"> <li>▪ Li-S</li> <li>▪ Na-S RT</li> <li>▪ Na-S HT</li> </ul>
<b>Me-air</b>	<ul style="list-style-type: none"> <li>▪ Li-air</li> <li>▪ Zn-air</li> </ul>
<b>RFB</b>	No specific focus

## 2.2. Publications and Patents

The number of scientific publications and patent applications in specific fields of science and technology are a measure of the R&D efforts and commercial interest in this field.

The publication analyses were based on peer-reviewed publications in Web of Science. Different keyword-based search strategies were used to identify the respective key publications. The patent analyses were performed using mixed IPC class (International Patent Classification) and keyword-based search strategies in the Derwent Worlds Patents Index (WPI) database hosted by the Scientific & Technical Information Network. The searches were limited to transnational patent applications to the European Patent Office (EPO) or the World Intellectual Property Organization (WIPO), as these require a high level of investment in the patent application process and enable a fair comparison between countries. Taking national patents into account can lead to distorted statistics due to inequalities in the effort required for national patent applications. Thus, in both publication and patent analyses, we identified activities that are comparable at international level allow for comparisons between countries as well as technologies.

The technologies considered include: Metal-ion (Me-ion) batteries with LIBs as a benchmark, focusing on the battery technologies of sodium-ion batteries (SIBs), magnesium-ion batteries (MIBs), zinc-ion batteries (ZIBs), aluminum-ion batteries (AIBs), metal-sulfur (Me-S) batteries, focusing on the technologies of lithium-sulfur (Li-S) and sodium-sulfur (Na-S) batteries, and metal-air (Me-air) batteries with the focus on lithium-air (Li-air) and zinc-air (Zn-air) batteries. In addition, redox flow batteries (RFBs) are considered. Solid-state batteries (SSBs) were discussed and analyzed in the corresponding roadmap from 2022 but are partially indicated in the analyses to provide an overview of the intensity and dynamics of different technologies in comparison. In this context, lead acid (PbA) batteries are also partially indicated in our analyses, as they still have a large market share (e.g., in stationary applications) and, depending on the applications, can also be partly regarded as a benchmark.

### Technology publication shares and dynamics

The number of LIB publications grew exponentially from around 2008 until around 2014 and then followed a rather linear growth until 2020. After 2020, new and stronger growth can be observed. The number of publications increased from 500 to 2,000 between the years 2000 and 2010 and since then around 1,000 additional articles have been published every year, i.e., already 12,000 in 2020 alone.

Compared to this LIB benchmark, alternative battery technologies have developed since 2012, starting from shares of a few percent and increasing to shares of around 10–20 % (most specifically SIBs, Li-S batteries). More recently, publications on ZIBs and Zn-air batteries have grown strongly and indicate that a share of 10 % could be reached in the next few years (Figure 4). RFBs show similar growth rates to those of LIBs. Na-S batteries have higher growth rates but with shares below 1 %. The number of publications on Li-air batteries are currently declining.

### EU28 publication shares and dynamics

The share of EU publications ranges from 10 % to 25 % depending on the alternative technologies (Figure 5). For LIBs, the share is 18 % and the recent 11 % annual growth rates are slightly higher than the growth rates of global LIB publications. Besides Li-air batteries with negative growth rates (below –10 %), all other alternative battery technologies show higher growth rates compared to the LIB benchmark (especially ZIB and Zn-air battery publications). There are some technologies, such as RFBs, AIBs, Na-S batteries or SSBs, for which the EU28 has higher shares in global publication activities.

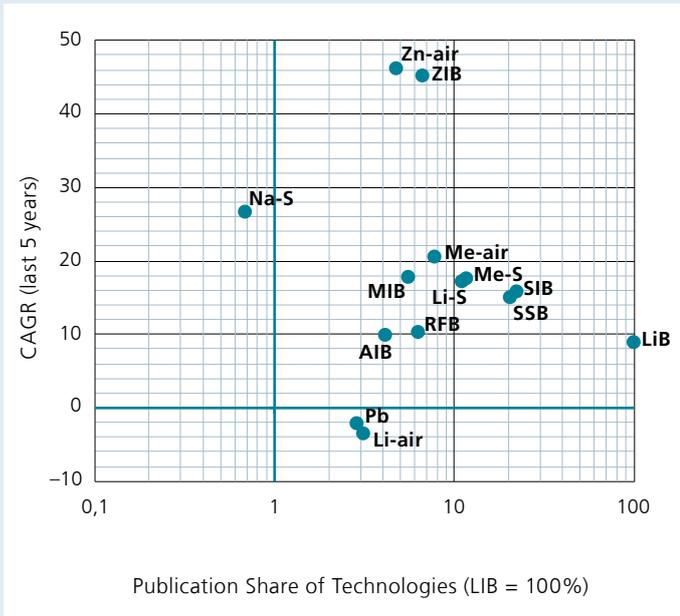
### Country shares and players

China is a leading player across all the technologies considered, with over 30 % to almost 80 % shares depending on the technology (Figure 8). For LIBs, its share is around 55 %.

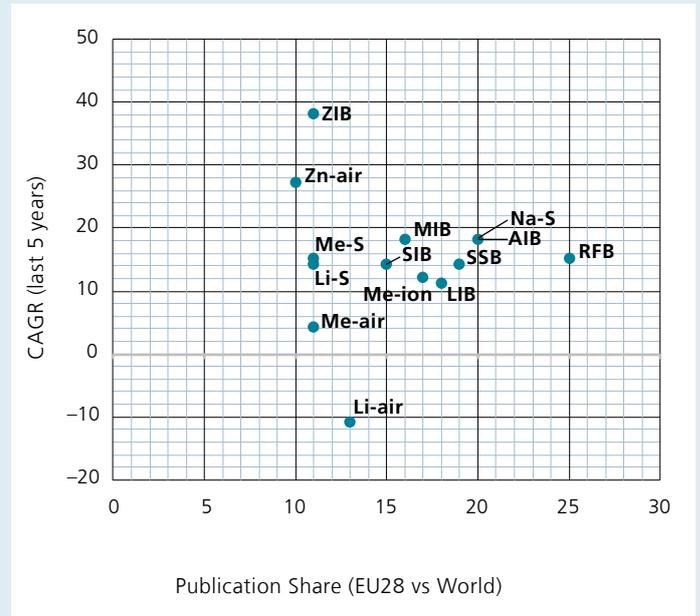
It can be observed that the Chinese Academy of Sciences (CAS) plays a prominent role in publication activities in China as well as in global cooperation with other countries and world regions. In addition, a large number of leading universities in China contribute to the enormous publication activities. In the US, there are leading universities and research labs that contribute between 10 and 25 % shares to publication activities depending on the technology. The EU28 also have publication shares of around 10–25 %, quite similar to the US. In Europe, leading research centers (especially KIT and FZ Jülich in Germany, but also CNRS, for example, in France and other research centers), as well as leading European universities are among the hotspots with regard to research activities.

The leading universities and research institutes in South Korea contribute between 5 and more than 10 % of publications and those in Japan with less than 5 to less than 10 %. The publication share of Germany is typically somewhere between that of

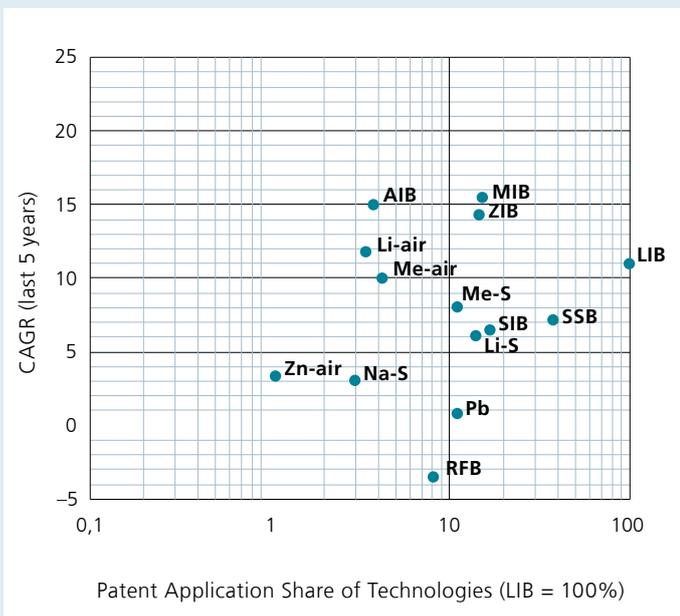
**Figure 4: Share of peer-reviewed publications for alternative battery technologies (using the benchmark LIBs = 100%) vs. average Compound Annual Growth Rate of the past 5 years.**



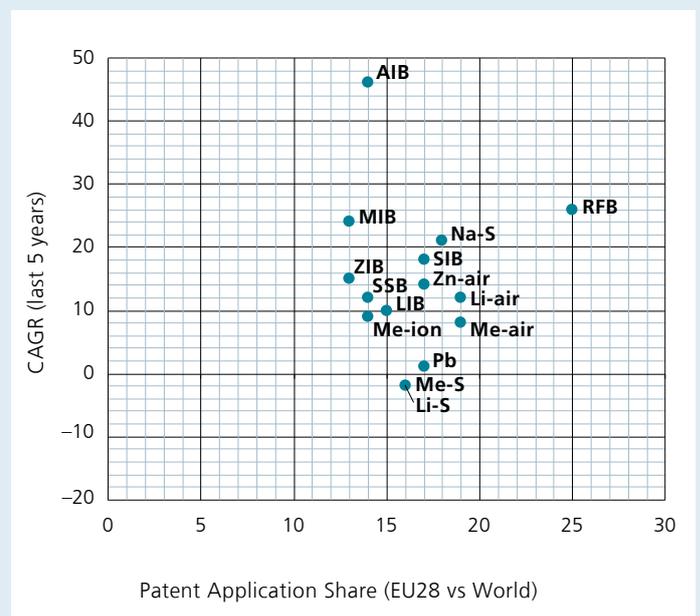
**Figure 5: EU28 share of global peer-reviewed publications for alternative battery technologies vs. average Compound Annual Growth Rate of the past 5 years.**



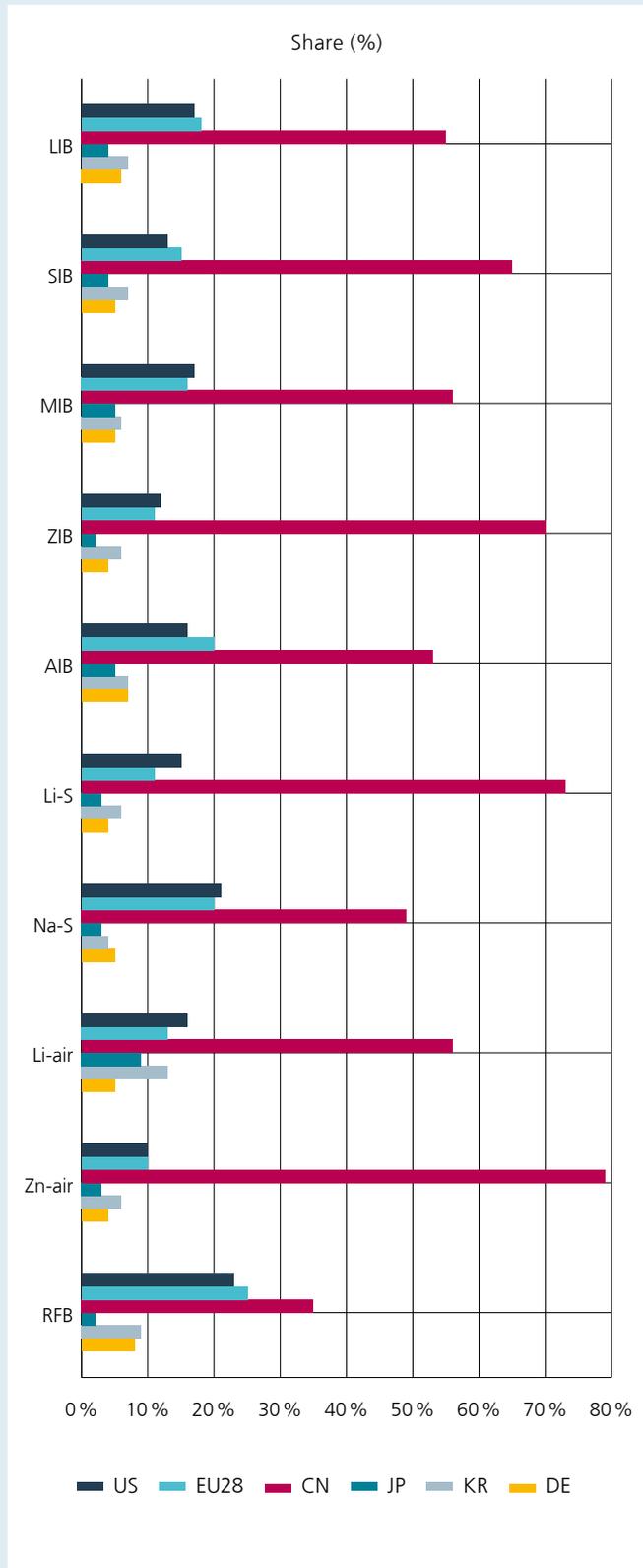
**Figure 6: Share of transnational patent applications for alternative battery technologies (using the benchmark LIBs = 100%) vs. average Compound Annual Growth Rate of the past 5 years.**



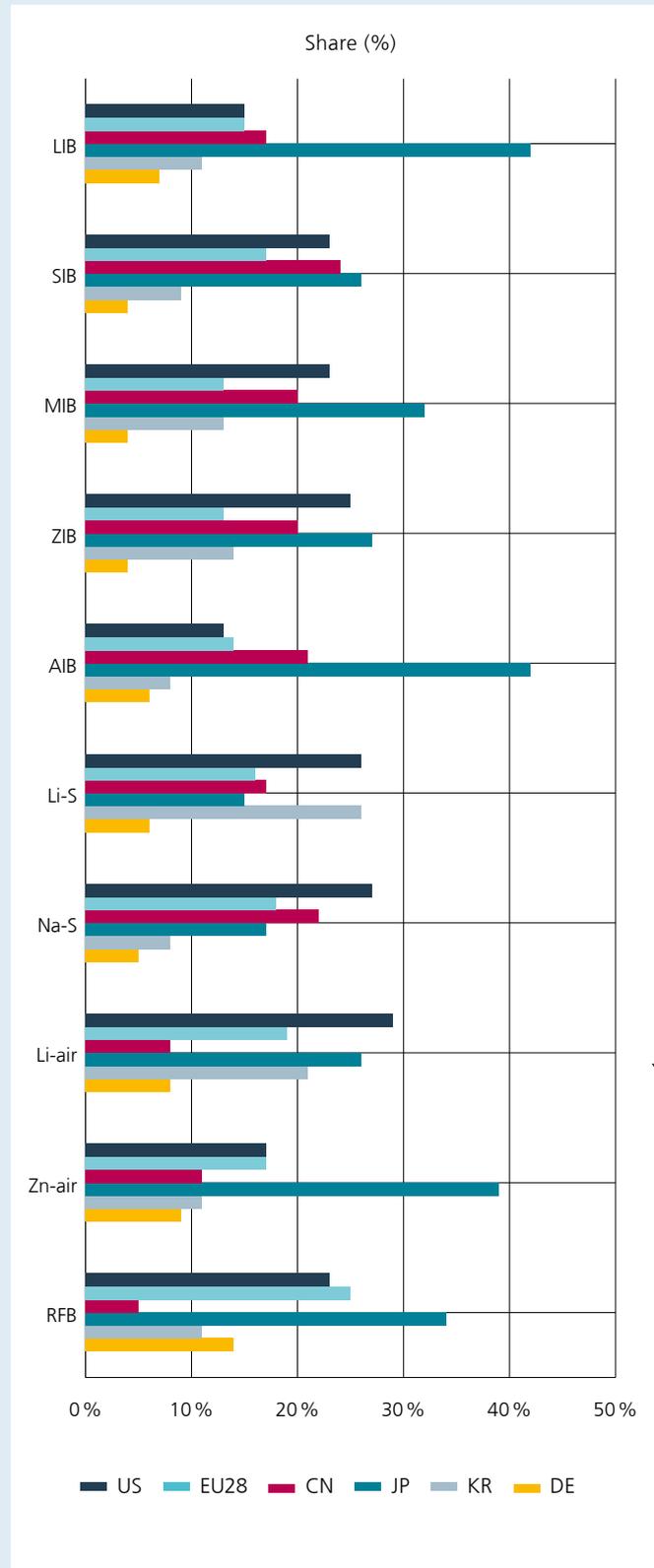
**Figure 7: EU28 share of global transnational patent applications for alternative battery technologies vs. average Compound Annual Growth Rate of the past 5 years.**



**Figure 8: Share of global peer-reviewed publications for alternative battery technologies by country and world region (over the past 5 years).**



**Figure 9: Share of global transnational patent applications for alternative battery technologies by country and world region (over the past 5 years).**



Japan and South Korea and thus (besides China and US) on a par with leading countries globally when considering individual countries.

### Technology patent shares and dynamics

Patent applications for LIBs grew from 200 to 1,000 (in the years from 2000 to 2010) with a peak in the year 2012 (with almost 1,600 applications). A stagnation and partial decrease was observed until 2017. Since then, new growth has been seen.

Using the above as a benchmark, it can be observed that alternative battery technology patents increased more when LIB patent applications were stagnating. In the past few years, some alternative technologies have stagnated (e.g., RFBs) whilst others have experienced lower and higher growth rates in comparison to LIBs, i.e., 5 to 15 % growth compared to 11 % for LIBs (Figure 6).

Compared to LIBs, the share and growth of Na-S battery patent applications is smaller. Since research on Na-S HT batteries has matured and research on Na-S RT is still in its infancy, this is the most likely explanation in particular for the smaller growth rates. The share of patent applications for Zn-air batteries is about 1 %, up to 10 % for Li-air and AIBs, and RFB technologies, and 10–20 % for Li-S batteries, MIBs, ZIBs or SIBs. For SSBs, the share is even up to 40 %, compared to recent LIB patent applications.

### EU28 patent shares and dynamics

The share of EU patent applications ranges from 13 to 19 % for most of the alternative technologies with a benchmark of 15 % for LIBs (Figure 7). There is however a 25 % share for RFBs.

With regard to growth rates, and thus the dynamics of applications, the alternative technologies show varying rates from below 10 to over 20 %, while LIBs as a benchmark have 10 % growth rates. Me-S patent applications have recently started declining and AIB patent applications show the highest growth rates with over 45 %.

### Country shares and players

Japan is a leading player across almost all the considered technologies, with a share of patent applications ranging from 25 to over 40 %. Japan has the highest share for LIBs as a benchmark, but also for AIBs with 42 %. Only in the case of Li-S batteries are South Korea and the US ahead of Japan with over 25 %. For Li-air, the US is also ahead of Japan with a share of almost 30 % (Figure 9).

For LIBs, China, the US and EU28 have similar shares of around 15–17 %. However, China has recently shown the highest growth rates and patent application dynamics with almost 30 %, compared to 10 % for EU28 and 4 % for the US. South Korea with an 11 % share and Germany with a 7 % share of patent applications still feature among the five leading countries, but with patent growth rates below 10 %. All the other countries together have a share of 5 % in global patent applications, but a very high growth rate of 70 %.

The shares and dynamics of these countries and world regions are in general quite similar across the alternative technologies. Compared to the LIB benchmark, the following divergences can be observed:

High shares of patent applications for the US and South Korea for Li-S batteries with 26 % and lower shares for Japan, China, and EU28 with around 15 % (the rest of the world has a 30 % growth rate with a low share of patent applications). The US and Japan have the highest shares of patent applications for Me-air batteries (US higher for Li-air and Japan higher for Zn-air). China has a 9 % share for Me-air batteries but > 80 % growth, and the rest of the world has a 44 % growth for Me-air batteries.

Among Me-ion batteries: for SIBs, Japan, China, and US have shares of around 25 % and the EU has 17 %. Germany has only a 4 % share but a 34 % growth rate. For MIBs, Japan (32 %), the US (23 %), and China (20 %) have higher shares than the EU (13 %). For AIBs, the EU, China, South Korea have growth rates above 40 % and Germany even has a growth rate of 86 %.

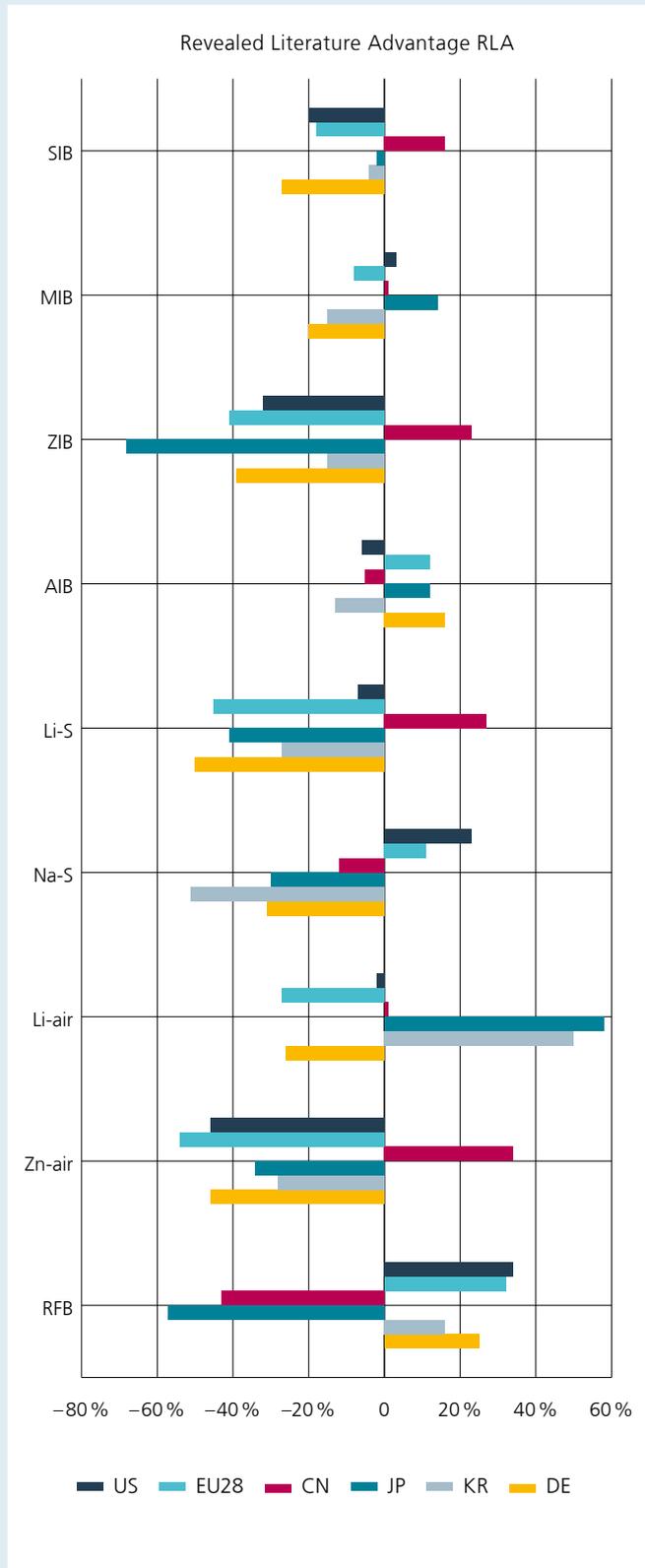
For RFBs: Japan, the EU, and the US have shares ranging from 23 % to 34 %. Germany has a high share with 14 % and 50 % growth. China shows a low level of activity for RFBs.

Concerning the players and patent applicants, we observe that, for Japan, leading cell manufacturers (such as Panasonic, GS Yuasa, etc.) as well as a diverse range of suppliers along the battery value chain are contributing to patent activities. For South Korea as well, cell manufacturers (such as LG, SDI, SK) and suppliers are the leading patent applicants.

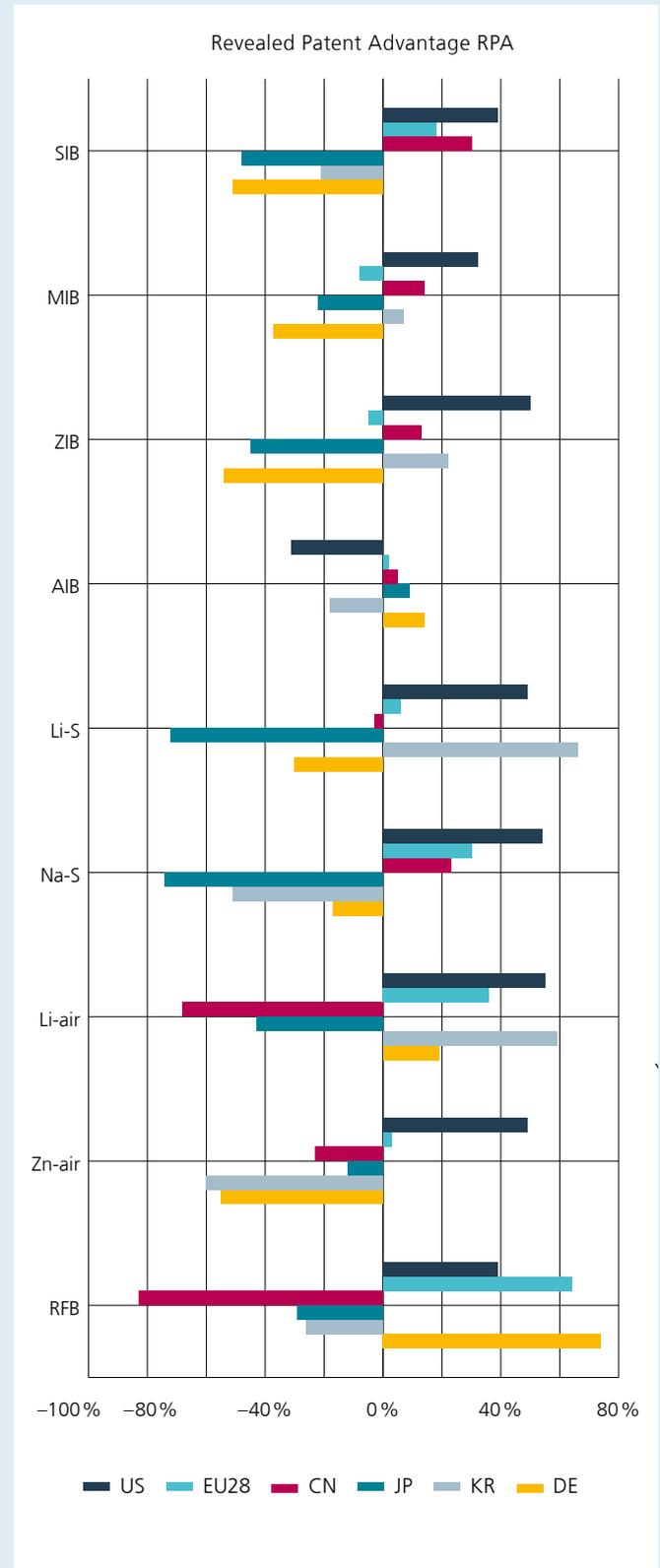
In China, companies like CATL, BYD, etc. are leading the patent application activities complemented by activities from suppliers along the battery value chain. In the US, the applicants range from material suppliers to battery integrators but also include universities.

In Europe, large companies along the battery value chain (especially material/chemistry companies such as BASF, Umicore) and OEMs are leading applicants. In some cases, leading applicants also include cell manufacturers, occasionally research organizations (RTOs) and less frequently universities.

**Figure 10: Revealed Literature Advantage of countries for alternative battery technologies (based on peer-reviewed publications 2017–2021) compared with LIBs as a benchmark.**



**Figure 11: Revealed Patent Advantage of countries for alternative battery technologies (based on transnational patent applications 2018–2020) compared with LIB as a benchmark.**



## Specialization and technology portfolio of countries

The specialization indices RLA (Revealed Literature Advantage) for publications and RPA (Revealed Patent Advantage) for patents are defined as:

$$RPA_{kj} = 100 * \tanh \ln \left[ \frac{(P_{kj} / \sum_j P_{kj})}{(\sum_k P_{kj} / \sum_k \sum_j P_{kj})} \right]$$

with  $P_{kj}$  indicating the number of publications or patent applications of country  $k$  in the technology field  $j$ .  $k$  sum up to the global activities and  $j$  are related to LIB activities as a benchmark.

Positive values indicate that the respective technology has a higher weight in the portfolio of the country than its weight in the world (all publications/patent applications from all countries). Negative values indicate below average specializations. Values around zero indicate that the specialization in a technology is similar to LIBs as the benchmark. Extreme values of around  $\pm 100$  typically indicate that the numbers are very low and the technology has to be treated with caution as part of the countries portfolio.

The RLA and RPA enable a better and more balanced comparison between technologies and counterbalance the weight of leading countries with extremely high shares (such as China for publications and Japan for patent applications).

It can be observed that although China has LIB publication shares of above 50 %, there are still positive specializations, e.g., for Zn-air, Li-S, ZIBs or SIBs (Figure 10). Japan has no corresponding specializations for patents apart from AIBs (Figure 11). Germany and the EU28 specialize in RFBs, and Li-air for patents, whereas the EU are specialized in AIBs, and SIBs for publications.

## 2.3. Resource Availability

A variety of materials are required for the production of LIBs. At the beginning of the production chain are both ores and crude oil. Especially the cathode material for LIBs contributes substantially to their material footprint because of its high weight. For the transition metal-based cathode active materials (CAMs), it is necessary to extract e.g., Mn, Fe, Co or Ni compounds from ores, and Li salts from salines or ores. But also passive components of LIB cells such as Cu or Al current collectors or the casing made of aluminum or steel contribute to the material demand. The solvents for the electrolyte and the separator foils are petrochemical products. The anode material, graphite, can be mined or produced synthetically from petrochemical precursors.

The precise material and ore requirements depend very much on the cell chemistry of the respective LIB. In addition to the pure material, demand and the finite nature of the raw materials, the ecological footprint associated with mining and processing and the geographical location of the reserves also play an increasingly important role. Depending on the mineral and mining region, major environmental, social, and geopolitical challenges can be associated with extraction. For example, the working and environmental conditions during Co mining in the DRC or the use of water and chemicals in Li extraction are repeatedly the subject of criticism [23, 24].

### Raw material demand for storage capacity

Although the particular challenges depend heavily on the respective cell chemistry, Li is always required for LIBs. Depending on the cathode material used, the storage capacity of today's LIBs relative to the Li used is between 9 and 12 kWh/kg. The annual battery demand in the high GWh/yr and soon TWh/yr range (see section 1.1) leads to a corresponding demand of tens and soon hundreds of kilotons per year. [25]

Li is the undisputed leader among the charge carrying elements studied in this report, due to its extremely low weight and the high voltage of many cathode materials. Today, the active materials researched for sodium-ion batteries, for example, allow a storage capacity of more than 3 kWh per kg Na.<sup>1</sup> For zinc-ion batteries, the storage capacity is still about 1 kWh per kg Zn.<sup>2</sup>

1 Assuming a Prussian blue analogue with a cell voltage of 3 V and capacity of 140 mAh/g

2 Assuming a Zn-anode and cell voltage of 1.5 V (e.g., Mn-oxide-based cathode)

Although Li appears to be very efficient in this respect, there are major advantages for many of the other ions when considering the raw material situation. As listed in Table 3, the production of Li is very small compared to other possible charge-carrying elements in batteries. A large part of Li production is already used for the production of LIB materials, so that applications in other technologies do not represent a real buffer for supply. In contrast, when using alternative battery systems without Li, it would often be possible to fall back on a comparatively large existing supply structure.

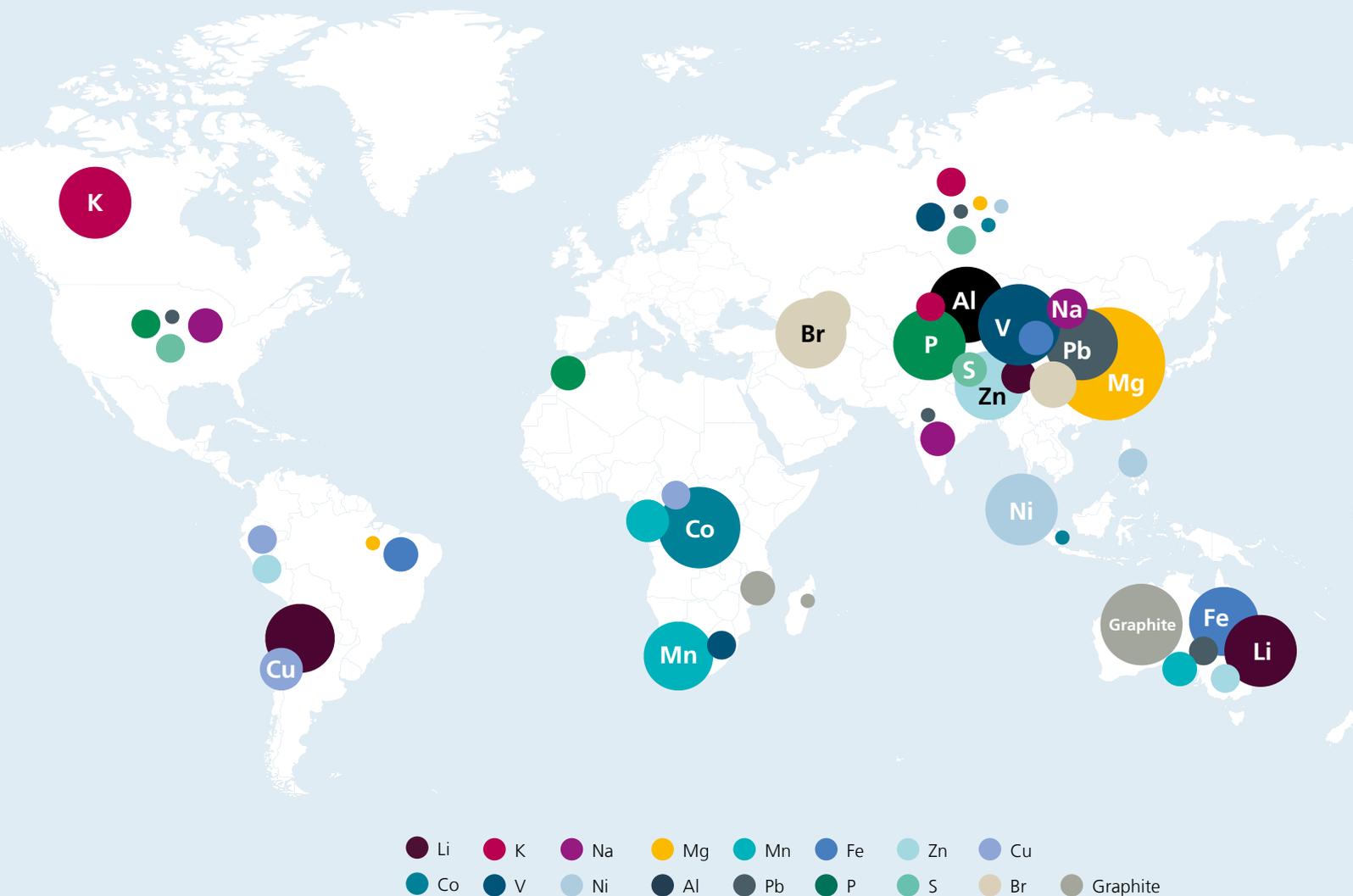
There are also large differences in raw material reserves between the metals in terms of long-term supply. The estimated reserves of 26 Mt [26] for Li correspond to about 200 TWh of storage capacity and should therefore be sufficient for LIB demand for the foreseeable future. However, exploitation could quickly become more complex and costly as known reserves start to run out. Alternatives such as Na, Al or Ca are available in almost inexhaustible quantities in the earth's crust or in seawater and can also be regarded as reliable supplies in the long term.

### Raw material production

In addition to the absolute deposits on earth, the geographical distribution of raw materials also plays a major role, especially from a European perspective. Figure 12 shows the highest production activities for the raw materials (3 biggest producing countries). Table 3 and Figure 13 show the production activities and reserves in Europe on an aggregated and country level, respectively. While European countries are not among the biggest producers for any of the materials shown, for some of them such as Na or S there are already European production activities, and existing European reserves might be used in the longer run.

The biggest producers of Li are located in Australia, Chile and China. The production in Europe is rather low, with Portugal being the biggest producer. Refinement of Li to battery grade quality is done almost exclusively in China. Other metals relevant for LIB are also distributed rather unfavorably for Europe. Co is heavily concentrated in the DRC and is produced almost exclusively outside of Europe. The situation for Ni is much more varied, but as the major mining sites are in Asia, production is also mostly outside of Europe. Mn and Fe are the least critical elements among the transition metals used in LIB. The mining of ores is globally very widely spread and access does not seem to be an issue from a European perspective. Similarly, graphite deposits can be found all over the world, including Europe.

**Figure 12: Production activities for raw materials (2022). The three biggest countries are depicted, bubble sizes illustrate shares on global production per raw material.\***



\*See footnotes [3-16] p. 42

**Table 3: Mine production and reserves of selected materials, globally and in Europe**

Material	Mine production 2022 (kt) [26]	Reserves (2022 est.) (Mt) [26]	European mine production 2022 (kt) [26]	European reserves 2022 (Mt) [26]
<b>Al</b>	70,000 <sup>3</sup>	22,000 to 29,000	2,150 <sup>3</sup>	2.3
<b>Br</b>	> 400 <sup>4</sup>	Large	Small	Small
<b>Ca</b>		Large	Small	Small
<b>Co</b>	190	8.3	Small	Small
<b>Cu</b>	26,000 <sup>5</sup>	890	1010 <sup>4</sup>	> 0.59
<b>Fe</b>	1,600,000 <sup>6</sup>	85,000 <sup>7</sup>	28,000 <sup>3</sup>	600
<b>Graphite</b>	1,300 <sup>8</sup>	330	10,75	> 0.6
<b>K</b>	40,000 <sup>9</sup>	> 3,300	3,250	218
<b>Li</b>	130 <sup>10</sup>	26	0.6	0.06
<b>Mg</b>	27,000 <sup>11</sup>	6,800	2,410	734
<b>Mn</b>	20,000	1,700	Small	Small
<b>Na</b>	> 290,000 <sup>12</sup>	Large	35,700	large
<b>Ni</b>	3,300 <sup>13</sup>	> 100	Small	Small
<b>Pb</b>	4,500 <sup>14</sup>	85	65	1.7
<b>P</b>	220,000	72,000	1,000	1,000
<b>S</b>	82,000	Large	2,310	large
<b>V</b>	100 <sup>15</sup>	26	Small	Small
<b>Zn</b>	13,000 <sup>16</sup>	210	240	4

However, not every grade is suitable for use in LIB. In addition to the extraction of natural graphite, a synthetic route is also available. The processing to anode active materials is heavily concentrated on China.

Raw material distribution looks very different for the charge-carrying elements of alternative battery technologies, but also for the materials necessary as anode and cathode hosts. For example, two European countries, Germany and the Netherlands, are among the top ten producers of common salt and therefore Na [27]. The largest Al smelters are in China

and other non-European countries, but Norway also plays an important role globally. Zn and Mg are also produced in Europe on a small to medium scale. [26]

However, overall, a similar picture emerges in terms of raw material distribution for other alternative battery technologies. For example, V is mainly extracted in China and Russia and would therefore not be directly available in Europe for possible use, e.g., in RFBs.

3 Smelter production including recycled aluminum

4 US not included

5 Including recycled copper

6 Iron content

7 Iron content of reserves

8 Plus significant amounts from synthetic processing

9 Based on data for potash

10 US not included

11 US not included

12 Based on data for NaCl and Na<sub>2</sub>CO<sub>3</sub>

13 Plus significant amounts from nickel recycling

14 Plus an additional ~ 8,000 kt from lead recycling.

15 Plus significant amounts from vanadium catalyst recycling

16 Plus significant amounts from zinc recycling

Figure 13: European reserves of raw materials in million metric tons (2022)\*

- Li   ● K   ● Na   ● Mg   ● Fe   ● Zn   ● Cu
- Al   ● Pb   ● P   ● S   ● Graphite



\*See footnotes [3-16] p. 42

## 2.4. Metal-Ion Batteries

Metal-ion (Me-ion) batteries are systems for electrochemical energy conversion and storage in which only one type of ion shuttles back and forth between the negative and positive electrodes during discharging and charging [22]. Me-ion batteries usually consist of a particular cathode material and an anode material, each deposited on a metallic current collector foil. The two electrodes are separated by a microporous separator, while ion transport is usually enabled by a liquid electrolyte. Me-ion batteries can be considered state-of-the-art in many applications, with LIBs being the best-known representative, but not the only one. Other alternative Me-ion batteries follow the same shuttle principle as LIBs, but use metals such as sodium, aluminum, zinc or magnesium instead of lithium.

Of the Me-ion batteries, LIBs are probably the best-known representative and have long been regarded as a „one-size-fits-all“ technology. Recent discussions on resource availability, CO<sub>2</sub> footprint or cost reduction have shown that alternative battery technologies are needed to meet application-specific requirements and reduce dependencies on specific materials. Thus, these alternative battery technologies do not aim to replace LIBs, but can be used as alternatives in appropriate applications according to their specific strengths. For example, sodium-ion batteries (SIBs) are, depending on their cell design, well suited for stationary applications or light electric vehicles. Aluminum-ion batteries (AIBs) can be an alternative to LTO-based LIBs or supercapacitors due to their high power densities.

SIBs are a cost-effective and sustainable alternative to LIBs. Even if their energy density is mostly still below that of lithium nickel manganese cobalt oxide (NMC) cells, in the medium term they could become an alternative to lithium iron phosphate (LFP) and PbA cells [28–31]. SIBs combine a Na-containing cathode with a carbon-based anode and – in most cases – a liquid electrolyte. Usually, intercalation or insertion materials are used at the cathode (typically layered oxides, polyanionic compounds or Prussian blue analogues), whereas the anode can consist of intercalation material, conversion material or an alloy.

Magnesium-ion batteries (MIBs) have a high theoretical capacity and are considered extremely safe due to their high temperature resistance and resistance to dendrite growth [32, 33]. Their construction is similar to SIBs and LIBs, with the difference that the anode is made of metallic Mg. Here, too, a suitable material is still being researched for the cathode and the electrolyte.

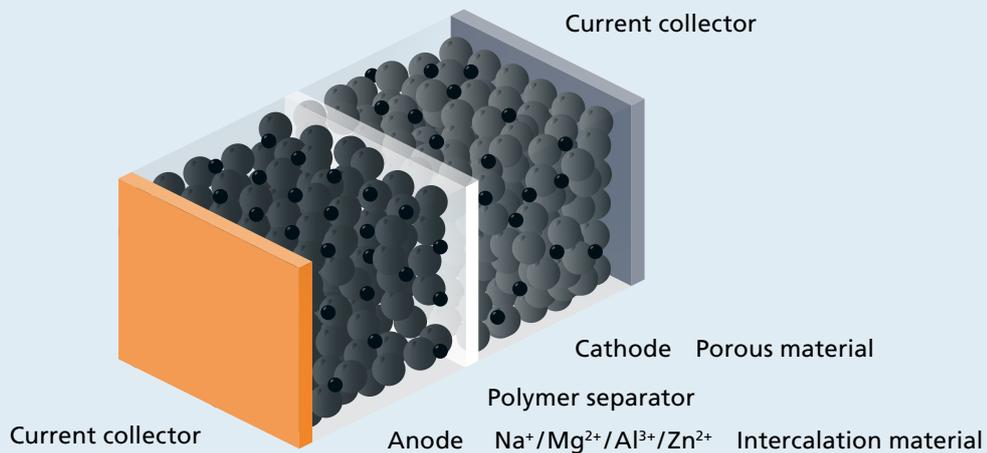
Zinc batteries (ZIBs), in particular, offer a promising solution to safety concerns regarding LIB, especially when using low-cost aqueous electrolytes, as these are non-flammable. Another advantage of ZIBs are the large deposits of Zn on earth [34]. The storage mechanism for Zn<sup>2+</sup> ions can vary greatly depending on the cathode material. However, the potential of typical cell assemblies is comparatively low and lies in the range of 1–2 V. In most cases, intercalation compounds are used at the electrodes. However, research is still being carried out into suitable material combinations.

Among the metal ions (Mg<sup>2+</sup>, Ca<sup>2+</sup>, Zn<sup>2+</sup>, Al<sup>3+</sup>), Al plays a special role due to its ability to donate three electrons that can enable a very high power density as well as high charge rates and a high cycle life depending on the cell design [35, 36]. Aluminum-ion batteries (AIBs) therefore are an interesting alternative for the transition from conventional LIBs (especially LTO-based LIBs) to supercaps. AIBs contain Al metal in the anode. Research is still being carried out into different variants for the cathode side. [35]

Due to the relevance outlined above, we focus on the aforementioned technologies in the following, even though there are other promising approaches. In recent years, for example, there has been increasing interest in fully organic Me-ion batteries such as organic LIBs or SIBs [37–39]. They promise high resource availability, low costs and a good environmental footprint. Aside from the advantages, there are two major challenges here: the low electronic conductivity and the high solubility of the organic electrode material in the electrolyte. For these reasons, the TRL of organic batteries is still very low and we are not dedicating a separate chapter to them. [37]

Figure 14: Typical structure of Me-ion batteries; Top: Liquid electrolyte; Bottom: Solid metal

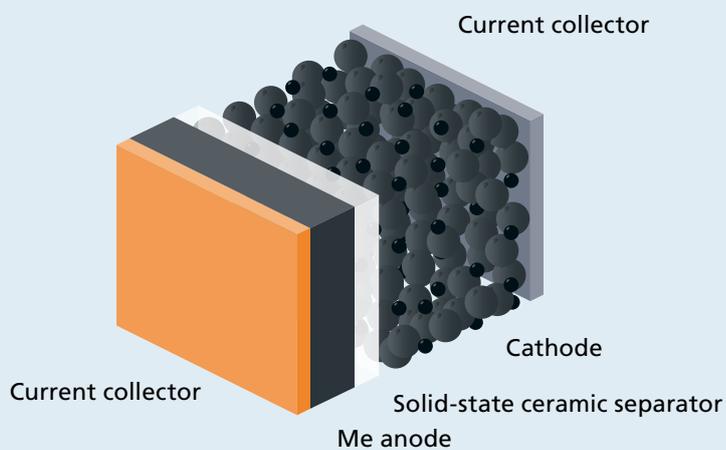
Liquid electrolyte



Ionic radii

$\text{Li}^+$	76 Å
$\text{Na}^+$	102 Å
$\text{Mg}^{2+}$	72 Å
$\text{Al}^{3+}$	54
$\text{Zn}^{2+}$	74

Solid metal



## 2.4.1. Sodium-ion Batteries

### Technology

Research on sodium-ion batteries (SIBs) dates back to the middle of the last century and much progress has been made since then. In recent years, various companies and start-ups including Faradion (Reliance), Tiamat, Natron Energy, BYD and CATL have claimed to be close to commercialization or, in the case of HiNa, have already started mass production [40, 41]. For this reason, the TRL level of SIBs can be set at 8 or 9.

Since Na<sup>+</sup> has a larger ionic radius (102 vs. 76 pm) and a higher atomic weight (22.98 vs. 6.94 g/mol) than Li<sup>+</sup> [42] and the cell voltages of SIBs are mostly lower compared to LIBs, slightly lower gravimetric and volumetric energy density are expected. Present practical gravimetric energy densities, as in the case of CATL for example, are in a range of 140–160 Wh/kg, but are expected to exceed 200 Wh/kg in future cell generations. Cycle life is typically in the range of 100–1,000 cycles [43, 44]. However, these values are highly dependent on the cell chemistry

and can also reach over 4,000 cycles at 1C and up to 80 % of the initial capacity, which is comparable with the current state-of-the-art LIB. In addition, SIBs have Coulomb efficiencies similar to LIBs and their round-trip efficiencies, with values above 90 %, are comparable to lithium iron phosphate (LFP) (97 %) and lithium nickel manganese cobalt oxide (NMC) (95 %) cells [30]. Compared to LIBs, the low temperature resistance of the cell can be an advantage: even at –20°C, capacity retention is still 90 %, compared to 60–70 % for LIBs [30]. However, as for LIBs, the temperature window also strongly depends on the cell chemistry.

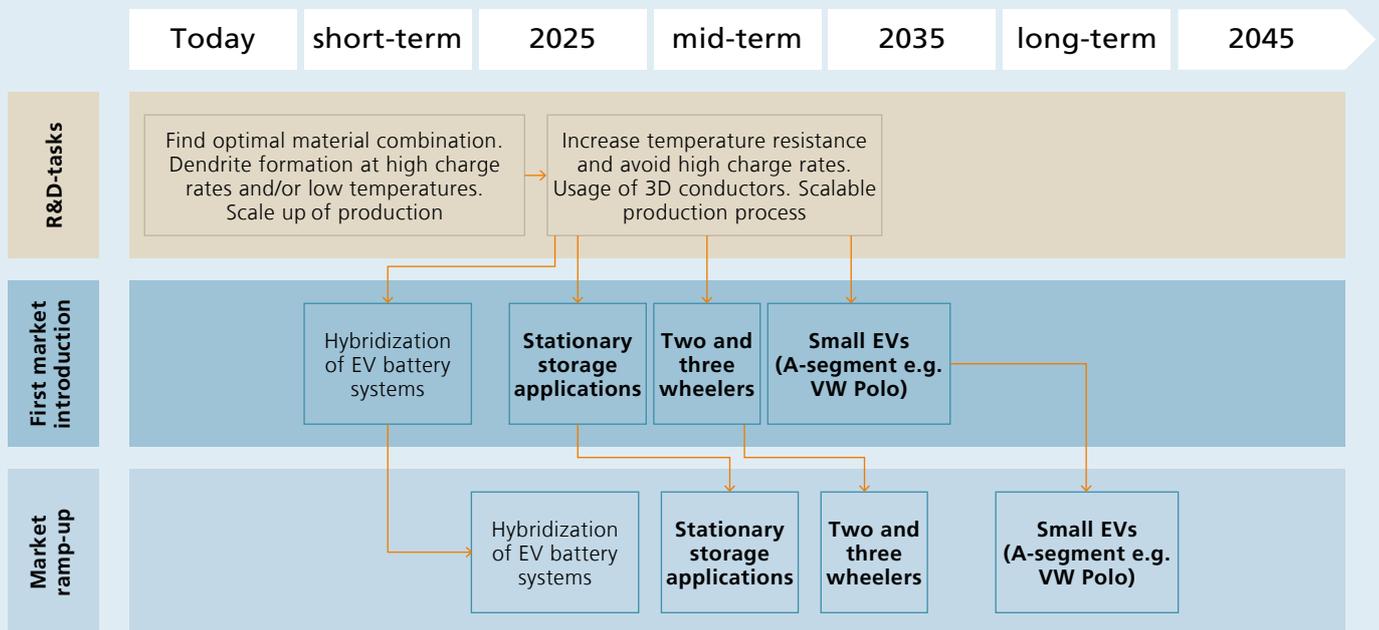
For SIBs, predominantly layered oxides, polyanionic compounds or Berliner blue analogues (or Prussian blue) are used as cathode materials. The Na-layered oxides offer high volumetric energy density. They can achieve an average cell voltage of 3.1 V over several hundred cycles and a gravimetric energy density of 500 Wh/kg. However, a frequent limitation

**Table 4: Estimated KPIs of SIBs today and in the long-term future**

KPI*	Value (today)	Value (longterm)
<b>Cell-level KPI</b>	140–160 Wh/kg	> 200 Wh/kg
<b>Vol. energy density</b>	200–300 Wh/l	> 300 Wh/l
<b>Power density</b>	100–300 W/kg	> 300 W/kg
<b>Cycle life</b>	100–1,000 cycles	500–4,000 cycles
<b>Calendar life</b>	15 years	> 15 years
<b>C-Rate</b>	~ up to 4 C	> 4 C
<b>Energy efficiency</b>	> 90 %	> 95 %
<b>Safety aspects</b>	Thermally more stable than LIB 0 V cell discharge	

\* Strongly depending on cell chemistry

Figure 15: R&amp;D and commercialization roadmap for SIBs



of many layered oxides is that their capacity fades over time. In contrast, the ability for long-term energy storage is one of the great strengths of the polyanionic compounds. In tests, these were still able to exhibit 80 % of the initial capacity after 4,000 cycles. In addition, some of the polyanionic compounds allow energy densities of 400–500 Wh/kg. The main disadvantage of the polyanionic compounds is the use of highly toxic vanadium. For Prussian blue analogues, alkali metals are used in combination with non-toxic and sustainable transition metals that can conduct, absorb and store salts or alkali metal ions (such as Na-ions) effectively. The advantage of this cathode material is its wide availability and consequently its low-cost production. The disadvantage is the low volumetric energy density compared to Na-layered oxides. [45]

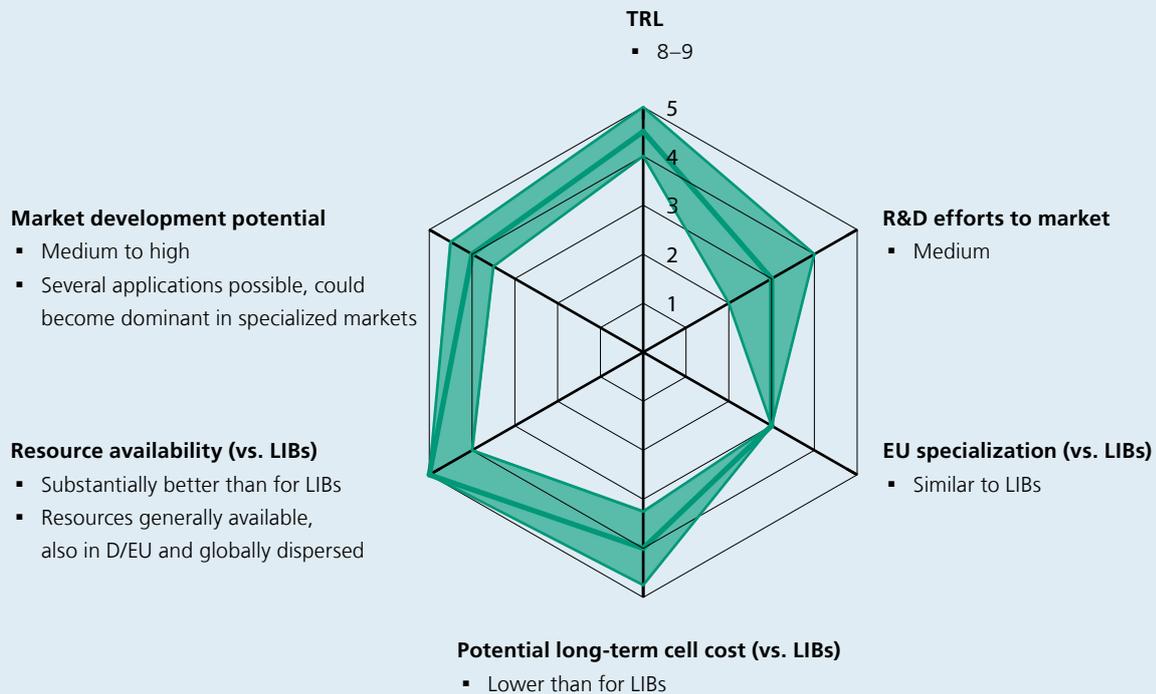
The anode usually consists of hard carbon (HC) instead of crystalline graphite, which has only a low storage capacity for Na-ions unless special solvents are used. At low temperatures or increased charging rates, however, dendrite formation can occur [46]. With regard to the electrodes, it proves

advantageous that Na does not alloy electrochemically with Al at room temperature, so that the Cu current collector can be replaced by cheaper Al [47]. At the same time, this allows a 0 V cell discharge which could be an important safety advantage over LIBs.

Due to the large variety of possible material combinations, the greatest need for research in SIBs is to design better electrode materials and to understand their interplay when used in combination. There is also a need for research into the suppression of dendrite deposition on the HC anode and the need for a high-performance electrolyte to increase the service life. [48]

#### Applications and market relevance

Depending on the design of the cathode and the residual cell, SIBs can be used in various applications: The relatively high energy capacity achieved with layered oxides makes it possible to use them in (light) EVs, among other things, while the polyanionic cathode enables good long-term storage applications. The Prussian white cathode shows good power capability,

**Figure 16: Radar chart of relevant dimensions of SIBs\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

which is why this type is also well suited for forklifts, electric tools, 12 V/48 V starting, lighting, and ignition batteries for vehicles, for example [41]. Thus, looking at the potential fields of application for SIBs, it becomes clear that they are likely to compete with LFP or PbA batteries in particular. In a corresponding comparison, SIBs perform similarly or even better in terms of energy density, power density, low-temperature behavior, fast-charging capability and total cost.

Recently, the Chinese manufacturer HiNa also presented the prototype of a small EV with a 25 kWh SIB that could be charged at up to 4C [49]. Another promising route is to combine LIB and SIB cells together in one system to generate synergies. In this case, the SIB could start and heat up the LIB, interrupting a possible chain reaction during a thermal run-away and implying that less cooling would be required during fast charging [30].

### Cost, resources, production and supply chain

The Na content in the earth's crust and water is 28,400 mg/kg and 11,000 mg/L, respectively, compared to 20 mg/kg and 0.18 mg/L for Li. Therefore, the availability of this output material is substantially higher, especially since it is not concentrated in only a few countries [50]. SIBs also have lower material costs compared to LIBs. Especially on the cathode side, considerable cost advantages can be achieved by eliminating expensive raw materials (e.g., Co or possibly Ni). In addition, the use of Al instead of Co for the anode current collector is more economical [51, 52]. However, the use of HC, which is currently more expensive than graphite, has a disadvantageous effect on the price. In addition, owing to the lower specific density of HC and the higher irreversible capacity, a thicker coating and thus more active material is required [52]. In total, the material costs of a SIB cell are estimated at approximately 40–60 % of those of a LIB cell [53]. It should be noted that the costs are heavily dependent on the material pairing and the actual cost reduction still needs to be proven in practice.

Due to the lower energy density and cell voltage, more cells per kWh have to be produced, which increases the production costs. These are estimated to be 15 % higher than LIBs [54]. Because they are so similar to LIBs, SIBs can be considered a drop-in technology [47].

The total cost of CATL's first generation of cells is estimated at ~80 USD/kWh. Once higher scales are reached, this price may drop further to ~40 USD/kWh. [55]

### Sustainability

The recycling of SIBs is technically possible without major problems due to their similarity to LIBs. However, there could be challenges from an economic point of view, as SIBs contain low-value and low-cost materials. Most SIB types do not use expensive or toxic raw materials – with the possible exception of Co, Ni or vanadium in the cathode. Nevertheless, recycling should be implemented, especially with regard to the energy-intensive Al in the current collector and cell casing, or the HC in the anode, the production of which generates high amounts of sulfur dioxide.

For the future development of a recycling strategy, it is important to first define the technical aspects, such as the materials, before concrete recycling structures can be defined.

The CO<sub>2</sub> footprint of SIB production depends on the respective material composition and energy used for production. However, the GWP stated in a range of 50 to 90 kg CO<sub>2eq</sub>/kWh is comparable to that of most LIBs. The slightly higher CO<sub>2</sub> footprint of some SIBs is due to the lower energy density of some types, which therefore require more material for the same storage capacity [30]. However, due to the substitution of the copper foil and a change in cathode materials (Co and Ni), the resource depletion of SIBs is significantly lower than that of LIBs.

### Advantages and Potential for Europe

Compared to LIBs, SIBs have advantages in terms of material costs and CO<sub>2</sub> footprint, especially due to the absence of expensive and critical materials such as Co, Ni, and Cu. In addition, Na is available in much larger quantities. In terms of technical KPIs, LIBs generally perform better, even though SIBs could be an alternative in some areas and thus could be an attractive alternative to LFP or PbA cells.

Despite the great similarity to LIBs, research is still needed, especially regarding the resulting effects and optimization of different material combinations. Finding and commercializing this optimal material combination could give Europe a competitive advantage, but would still require the global scale-up of this technology.

In the UK, Faradion (now owned by Reliance) published prismatic SIB cells with Ni – Mn – Fe layered oxide as a cathode and HC as an anode. The Chinese company HiNa Battery developed a SIB with a Cu – Fe – Mn layered oxide cathode and a disordered carbon anode. The French startup Tiamat presented a 18650 cylindrical cell with a Na<sub>3</sub>V<sub>2</sub>(PO<sub>4</sub>)<sub>3</sub> cathode and also a HC anode. Natron Energy uses Prussian blue electrodes in combination with a water-based electrolyte, while CATL uses a Prussian white cathode in combination with a HC anode [41]. If all these efforts succeed, SIBs will be a cost-effective and sustainable alternative to LIB and especially to those based on LFP.

## 2.4.2. Sodium-Ion Saltwater Batteries

### Technology

The saltwater battery (SIB Salt) is a subtype of sodium-ion batteries. While the first commercial primary saltwater batteries were developed as early as 1943, research into secondary batteries has only been increasing over the last decade. The first battery systems, such as those from Aquion or BlueSky Energy, have already been launched on the market [56–59]. Hence, the TRL level can be classified as TRL 9. However, some systems are not economically competitive yet, so further research is needed into their economic viability.

In principle, there are two types of saltwater batteries: Those with a closed system as produced by Aquion and seawater batteries with a partly open system. Seawater batteries usually consist of a closed side with an organic electrolyte and a largely open side with an aqueous electrolyte. Both sides are separated from each other by a solid Na diffusion membrane, for example [58]. In both cases, the cathode side contains

a current collector, usually a hydrophilic, net-textured carbon paper that provides a large surface area for the saltwater used as the Na<sup>+</sup> source. The anode side contains mostly Na-metal or Na insertion materials such as HC. While seawater batteries often contain one side with organic electrolyte and one side with aqueous electrolyte [58, 60], saltwater batteries often only use one common aqueous electrolyte.

For seawater batteries, the gravimetric energy density is typically < 150 Wh/kg, which is comparatively low. The reasons for this lie in the limitations with regard to the choice of anode and cathode materials and the resulting low operating voltage [56], [58]. Saltwater batteries also have a lower voltage than LIB (with approx. max. 1.3–1.7 V), because at higher voltages the water molecules can decompose into hydrogen and oxygen. However, efforts are being made to increase the voltage up to 2.6 V by using Na bis(fluorosulfonyl)imide and dosing the salt content in the electrolyte so high that there is

**Table 5: Estimated KPIs of saltwater\* SIBs today and in the long-term future**

KPI	Value (today)	Value (longterm)
<b>Cell-level KPI</b>	< 150 Wh/kg	> 400 Wh/kg
<b>Vol. energy density</b>	12–24 Wh/l	100 Wh/l
<b>Cycle life</b>	> 3,000 cycles	> 10,000 cycles
<b>Calendar life</b>	10 years	> 10 years
<b>C-Rate</b>	~ 0.25C (0.1–1C)	> 1C
<b>Energy efficiency</b>	75–98 %	> 98 %
<b>Safety aspects</b>	Water based, thus lower risk of thermal runaway	
	*Saltwater battery, KPIs on battery level	

virtually no excess water left [61]. However, the low voltage level means it requires more cells to achieve the same battery performance as a LIB, which increases weight and volume. These requirements also limit its potential applications to those that do not place high demands on weight restrictions or the installation space available. The volumetric energy density of seawater batteries is usually around 12–24 Wh/l. Experimental investigations showed a wide range of capacities from 10 mAh/g (in the case of a  $\beta$ "-Al<sub>2</sub>O<sub>3</sub> membrane and HC anode) to 900 mAh/g (for a NASICON membrane and red phosphorus anode), dependent on the electrode material used and the current applied [56]. The lifetime of seawater batteries is usually between 20 and 100 cycles, while the Coulomb efficiency is between 76 and 98%. [59, 62–65]

For saltwater batteries, both volumetric and gravimetric energy densities are comparable to seawater batteries. For example, the battery from Aquion Energy (Aspen 48S–2.2) reached a volumetric energy density of around 25 Wh/l. By increasing the salt concentration up to a „water-in-salt“ concept, the voltage and thus the energy density could be substantially increased. The lifetime of the Aquion battery was given as > 3,000 cycles (at 70% SOH) [66]. Furthermore, a deep discharge of 100%, i.e., down to a voltage of zero, is possible without causing irreparable damage. The aqueous electrolyte buffers the thermal fluctuations of the battery, and the electrolyte is not flammable or toxic. [67] The saltwater battery cell can therefore be considered very safe.

For seawater batteries, the biggest technical challenge is to increase the anode and cathode lifetime. In particular, optimizing the cathode materials to increase stability in the aqueous medium and resistance to side reactions remain challenging. In addition, there is limited membrane stability in aqueous salt water, which leads to low electrochemical performance and low coulombic efficiency. Finally, the constant supply of fresh seawater as a catalyst at the cathode must be ensured; otherwise, cell efficiency will drop substantially. [56, 58, 65]

The main challenge facing saltwater batteries could be a further increase in cell voltage to enhance energy density.

### Applications and market relevance

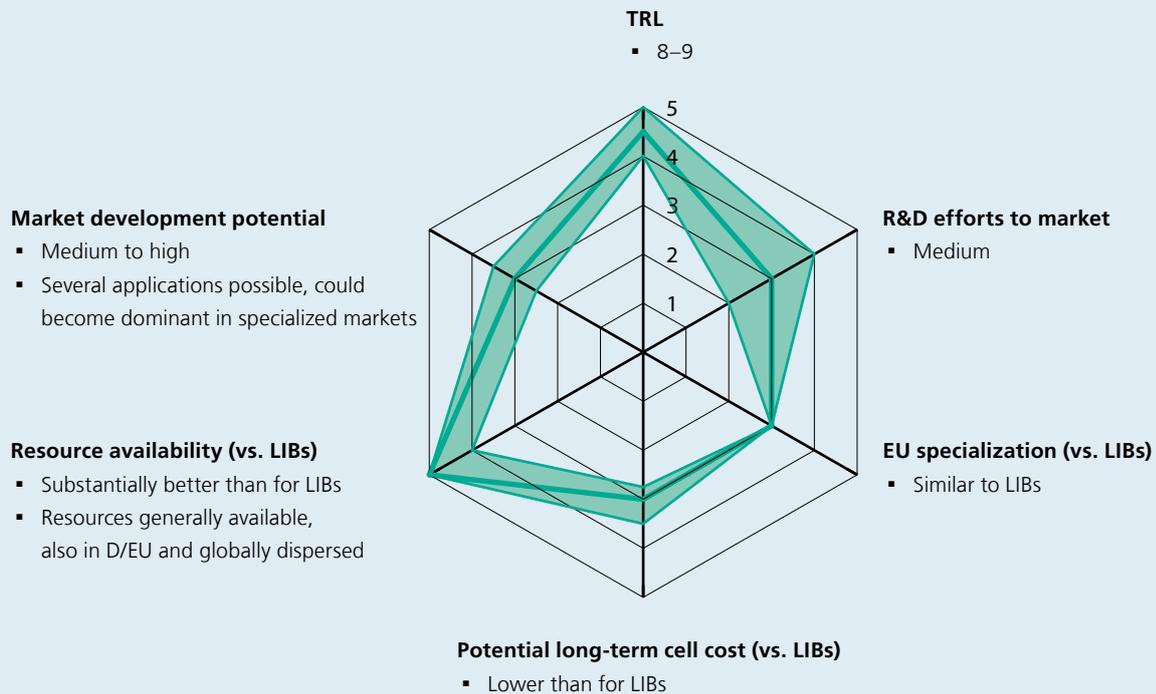
Despite their market maturity to date, saltwater batteries can still be considered a niche product. Due to their relatively low energy density and the space required as a result, they are particularly suitable for stationary applications such as large stationary ESS, grid storage or intermediate storage for electricity from (private) PV and wind power. Due to their high intrinsic safety, saltwater batteries could also be considered in facilities such as schools or hospitals. The nature of seawater batteries means they are suitable for primary public marine facilities such as light buoys and water quality monitoring stations. [56, 61, 68]

The use of seawater batteries, however, is limited to coastal locations (without further design adaptations to provide the saltwater). [56, 60, 67, 69]

### Cost, resources, production and supply chain

Saltwater batteries consist of relatively inexpensive raw materials. Due to the large impact that raw material costs have on the total costs, there is great potential for realizing low battery cost. However, the low energy density affects the cost per kWh of storage capacity, as a larger number of cells are needed. In addition, the cells are not yet being produced in large series, so significant economies of scale are missing. The reported cost of Aquion's saltwater battery was estimated at 880 USD/kWh in 2016. The price (not cost) of the batteries marketed by BlueSky under the Greenrock brand is just over 1,000 USD/kWh. However, assuming large-scale production, lower costs of ~200 USD/kWh could be achieved in the future [60].

In addition to the benefits on the material side, the saltwater battery also has low requirements regarding clean room conditions and no special treatment is required because of harmful or critical materials. This also leads to a lower energy demand in energy-intensive drying processes.

**Figure 17: Radar chart of relevant dimensions of saltwater SIBs\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

### Sustainability

Na salts are already available in large quantities and so is the raw material. Seawater, which covers about two-thirds of our planet and has a Na concentration of about 11 g/l, is a quasi-abundant resource for Na-ions. [56]

Both the saltwater and the seawater battery can be considered highly sustainable because of the absence of critical or toxic raw materials. Only the possible use of N-methyl-2-pyrrolidone (NMP) for electrode precipitation is critical from a sustainability point of view. Since the structure of the saltwater cell can be compared with that of an aqueous ZIB cell, the CO<sub>2</sub> footprint should also be in the range of 30–50 CO<sub>2eq</sub>/kWh. [70]

With regarding to recycling, no detailed studies are available yet, but no major problems are expected with regard to the materials used. The only potential obstacle is the lack of cost-intensive materials (with the exception of the ceramic membrane) which make recycling economically lucrative. [56]

### Advantages and Potential for Europe

The advantage of salt- and seawater batteries is that the resource availability is very good. In addition, the (partial) use of saltwater as an electrolyte is an environmentally-friendly and safe alternative to conventional electrolytes. The fact that they do not get damaged, even if they are 100 % discharged, makes them particularly attractive for stationary applications. Their high weight and the high volume requirement resulting from the relatively low cell voltage are likely to prevent their use in many other applications, e.g., mobile ones.

The saltwater battery should have a low CO<sub>2</sub> footprint owing to the materials used and it also offers a significant cost reduction potential by dispensing with expensive cathode and electrode materials. However, its low energy density counters these advantages and the cell costs are still a hurdle for a commercially viable market entry. Two suppliers that had already launched saltwater batteries on the market have since filed for bankruptcy due to cost, quality, and delivery problems. However, if costs can be reduced, saltwater batteries could become a sustainable and resource-saving alternative for stationary storage applications in the future, especially near the sea.

## 2.4.3. Magnesium-Ion Batteries

### Technology

Magnesium-ion batteries (MIBs) are a promising alternative to LIBs owing to their high theoretical capacity (2,205 mAh/g and 3,833 mAh/cm<sup>3</sup> [32] on the material-level), relatively low negative electrochemical potential ( $\text{Mg}/\text{Mg}^{2+} = -2.37$  V vs. SEH), high intrinsic safety, and earth abundance [33]. However, MIBs are currently still the subject of fundamental research (TRL ~3), primarily to define the right cathode-electrolyte configuration.

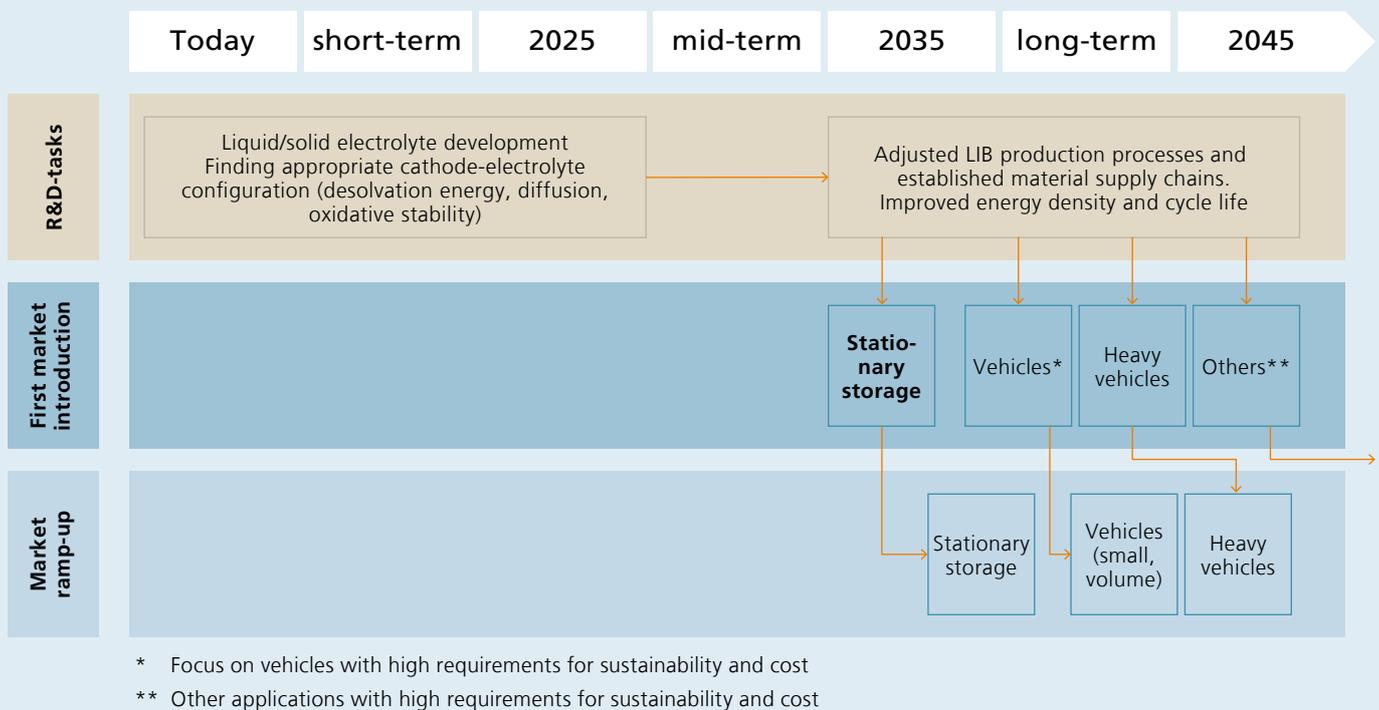
The divalent nature of Mg allows for high theoretical volumetric capacity, nearly twice as high as LIBs, and implies an increased potential to reach higher practical values than LIB cells (around 200 mAh/cm<sup>3</sup>). Even though Mg is heavier than Li (molar mass 24.31 vs. 6.94 g/mol), the energy density which is practically achievable at cell level is expected to be at least comparable to LIBs (around 150 mAh/g). Early-stage experimental MIBs surpassed this level and reached up to around 1,000 mAh/g [33]. Note the high deviation between theoretical

and practical energy densities, also found in the literature [71]. At cell level, the achievable energy densities depend on the chosen cathode-electrolyte-anode configuration. Chalcogenides (such as Chevrel phase compounds, primarily sulfur-based,  $\text{Mg}_x\text{Mo}_6\text{S}_8$ ), Molybdenum oxides, Vanadium compounds (such as  $\text{V}_2\text{O}_5$ ), spinel-type oxides ( $\text{MgA}_2\text{O}_4$  with A=Cr, Mn, or Fe) and phosphates are most relevant for cathodes. Metallic Mg, alloy-based, and carbon-based materials are most relevant for anodes. Metal oxide cathodes partnered with a metallic Mg anode are projected to achieve energy densities well above 650 Wh/kg and 750 Wh/l [72], reaching around 2.4 to 3.9 V [73]. Both solid-state and liquid electrolytes may be possible, with the latter being favored. Cycle life is expected to be almost comparable to LIBs, i.e., well above 700–1,000 cycles even under high C-rates [74, 75]. This is, among others, because MIBs do not appear to promote dendrite growth, allowing for high charging rates and indicating substantially longer lifetimes. In addition, Mg metal is thermally

**Table 6: Estimated KPIs of MIBs today and in the long-term future**

KPI	Value (today)	Value (longterm)
<b>Cell-level KPI</b>	50–150 Wh/kg	300–600 Wh/kg
<b>Vol. energy density</b>	150–300 Wh/l	400–750 Wh/l
<b>Power density</b>	~ LIB	> LIB
<b>Power per electrode area</b>	~ LIB	> LIB
<b>Cycle life</b>	150–750 cycles	>> 1,000 cycles
<b>Calendar life</b>	LIB level	LIB level
<b>C-Rate</b>	LIB level	LIB level
<b>Energy efficiency</b>	unknown	unknown
<b>Safety aspects</b>	unknown	unknown

Figure 18: R&amp;D and commercialization roadmap for MIBs



stable (e.g., auto-ignition temperature is 473 °C versus 179 °C for Li [32]) and less reactive to the air due to its self-passivating behavior [32]. Therefore, MIBs are expected to be safer than LIBs [33], which should also enhance cell-to-pack integration and thus facilitate higher useable energy densities. While the Coulombic efficiency for MIBs is comparable to LIBs, the concept of Faradaic efficiency cannot be discarded [71].

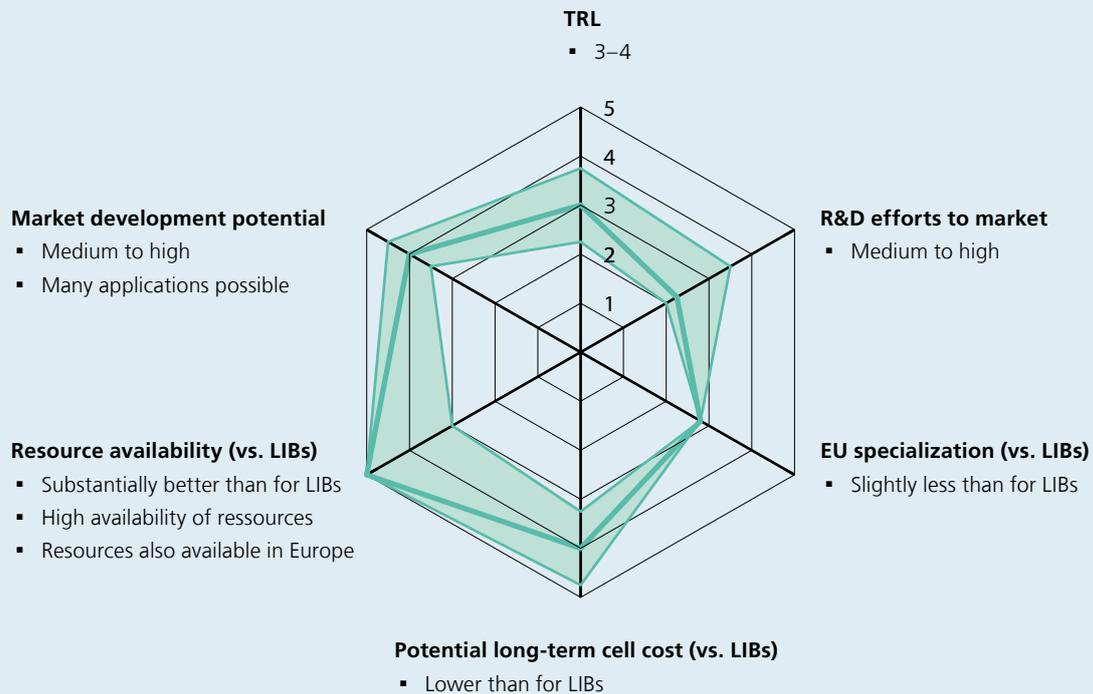
Further research should focus on optimizing the electrode-electrolyte configuration [33]. First, reasonable cathode structures need to be designed that reduce polarization and speed up ion diffusion kinetics. Second, anode modifications are required to eliminate passivation film formation. Third, a non-corrosive and compatible electrolyte must be developed to solve the current electrochemical compatibility issues and to facilitate reversible  $Mg^{2+}$  plating/stripping and high-voltage operations at around ambient temperatures [32]. In this case, solid-state electrolytes are expected to outperform liquid ones.

### Applications and market relevance

The high intrinsic safety characteristics and low-cost properties of MIBs favor stationary applications, and their increased energy capacities make MIBs attractive for mobile applications such as cars, buses, and trucks. In addition, they may be of particular interest for the aviation sector, because specific energy and safety are crucial here. While the first MIBs prototype was presented in 2000 [72] terminating large-scale commercial availability is difficult. Series production is not expected until after 2035, starting with small stationary storages and then extending to vehicles in the low-cost and volume segment, covering developing and industrialized countries.

### Cost, resources, production and supply chain

The earth's crust contains about 1000 times more Mg (23,000–29,000 ppm) than Li (20 ppm) [33, 72], while Mg is the 3<sup>rd</sup> most-used metal in industry [33]. Plus, suitable materials for high-voltage cathodes are abundant. This eliminates any depletion risk and fosters the build-up of robust supply chains for the future battery industry. Hence, the cost of Mg is roughly a third of that of Li, and this cost difference is expected to increase further with the growing rarity of Li [32]. Thus, MIBs' raw material cost may be lower than for state-of-the-art LIBs.

**Figure 19: Radar chart of relevant dimensions of MIBs\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

In addition, MIBs are seen as a drop-in technology regarding cell design and assembly to LIBs, both with liquid and solid electrolyte. This means that many existing manufacturing technologies can be used without substantial plant redesign – except for different processing environments [72]. Overall, MIB cell manufacturing is generally expected to be less energy-intensive and less toxic than the equivalent processes for LIBs [32], allowing for substantially cheaper cells, potentially around 30–40 EUR/kWh.

### Sustainability

Mg is less reactive than Li and does not form toxic compounds during the manufacturing process. Moreover, it can be recycled more easily in less energy-intensive processes and without any degradation of its physical properties [76]. This requires a corresponding ramp-up, but process technologies do already exist. Furthermore, the manufacturing processes for MIBs are expected to be less energy intensive than those for LIBs. Overall, MIBs if designed with a sustainable electrolyte, show clear advantages over LIBs in terms of toxicity, energy intensity, recyclability [76], and CO<sub>2</sub> footprint. The latter could be halved in comparison to state-of-the-art LIBs, ranging between 50 to 90 kg CO<sub>2eq</sub>/kWh.

### Advantages and Potential for Europe

Once suitable cathode-electrolyte configurations are designed, MIBs have the potential to outperform LIBs. MIBs benefit from abundant reserves in the earth's crust, low-cost potential, non-toxicity, high intrinsic cell safety, high capacities, and adequate potential. In addition, MIBs are expected to be similar in design and assembly to LIBs, meaning that many present-day findings and expenditures could be transferred. These characteristics make MIBs attractive for different applications, from stationary storages to mobility solutions. In addition, lower depletion risks and accessibility contribute to technology sovereignty. Thus, finding and optimizing an appropriate electrode-electrolyte configuration may provide Europe with a competitive advantage. However, exhaustive fundamental research is needed (TRL ~ 3) and many theoretical and feasible benefits still have to be proven in practice and for mass production.

## 2.4.4. Zinc-Ion Batteries

Zn has long been used in Zn-carbon and alkaline primary batteries and, in recent years, as Zn-air primary battery. The technology was commercialized already decades ago and is characterized by a comparably simple cell design and low-cost materials. Due to material-related problems such as dendrite growth of Zn, low  $\text{MnO}_2$  stability and conductivity, rechargeable types of Zinc-ion batteries (ZIBs) have not yet been commercialized. The TRL of ZIBs is currently at level 3–4.

### Technology

The development of rechargeable ZIBs is of high interest, owing to the abundance of Zn, which is about ten times higher than that of Li, an established Zn recycling process, and the good stability of Zn in water, which allows the use of aqueous electrolytes. Compared to organic electrolytes used in LIB, aqueous electrolytes are safer, cheaper, easier to handle and less environmentally harmful. However, so far, no suitable cathode material / electrolyte combinations have been found

that would allow commercial use of ZIBs. Several materials are under investigation, such as manganese oxides, vanadium compounds, Prussian blue analogues, polyanion compounds [77], organic cathode materials and conversion type cathodes [78]. The storage mechanism for  $\text{Zn}^{2+}$ -ions depends on the cathode and electrolyte material. The potential of typical cell setups is in the range of 1–2 V and thus lower than that of LIBs.

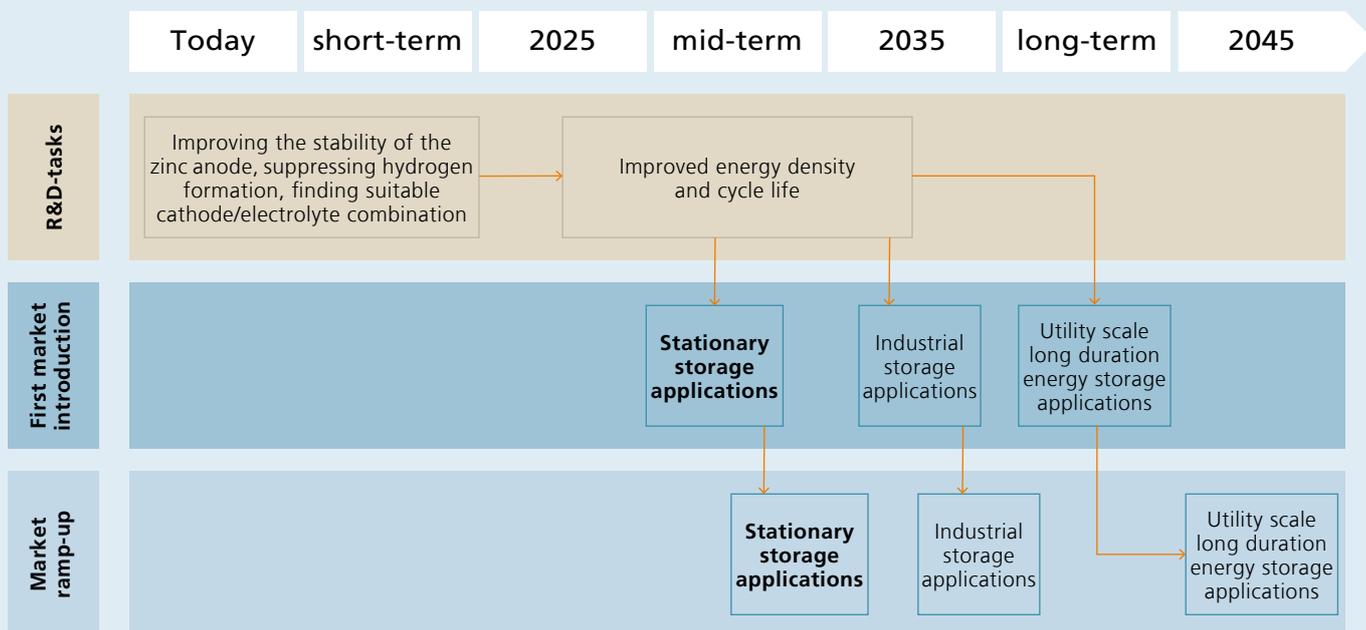
Commercially available primary Zn-air batteries (button cells) offer an energy density of  $> 400 \text{ Wh/kg}$  and  $> 1,200 \text{ Wh/l}$  [79], close to the theoretical energy density of Zn (820 mAh/g). While in the case of Zn-air batteries, the cell capacity is limited by the Zn anode mass, that of ZIBs is usually limited by the cathode material ( $\text{MnO}_2$ : 308 & 616 mAh/g for one ( $\text{Mn}^{3+}/\text{MnO}_2$ ) and two-electron ( $\text{Mn}^{2+}/\text{MnO}_2$ ) reaction, respectively). Hence, energy densities on the cell level for the rechargeable ZIB will most likely be lower. In fact, energy

**Table 7: Estimated KPIs for ZIBs today and in the long-term future**

KPI	Value (today) on lab-scale (coin cell)*	Value (longterm) on, e.g., pouch/prismatic/round cell*
<b>Cell-level KPI</b>	30–60 Wh/kg	50–120 Wh/kg
<b>Vol. energy density</b>	40–100 Wh/l	80–200 Wh/l
<b>Power density</b>	10–100 W/kg	30–150 W/kg
<b>Power per electrode area</b>	2–35 W/m <sup>2</sup>	15–100 W/m <sup>2</sup>
<b>Cycle life</b>	600–800 cycles	300–3,000 cycles
<b>Calendar life</b>		
<b>C-Rate</b>	0.05–1C	0.2–5C
<b>Energy efficiency</b>	$> 80\%$ [80–82]	80–90%
<b>Safety aspects</b>	High safety due to water-based electrolyte (non-flammable)	High safety due to water-based electrolyte (non-flammable)

\* based on Mn-based CAM

Figure 20: R&amp;D and commercialization roadmap for ZIBs



densities of 50–120 Wh/kg on the cell level are expected as long-term goals, but the values reached today (typically normalized to cathode material mass only) are substantially lower. ZIBs are considered very safe, because of the water-based, non-flammable electrolyte. Charging and discharging rates depend strongly on the cathode active material used and the amount of carbon additives; for Mn-based CAM, they are in the range of 0.1–1C (this can be significantly higher for vanadium-based and Prussian blue analogues CAM).

Technical challenges include the (long-term) stability of the CAM (dissolution, phase change) and the AAM (dendrites, passivation) during cycling. Furthermore, the electrolyte voltage stability is limited, leading to unwanted hydrogen development at the anode that reduces the overall efficiency and leads to irreversible Zn-ion loss [83]. Suppressing this side reaction is a key challenge. Another challenge is the currently incomplete understanding of the intercalation reaction at the cathode. [77]

#### Applications and market relevance

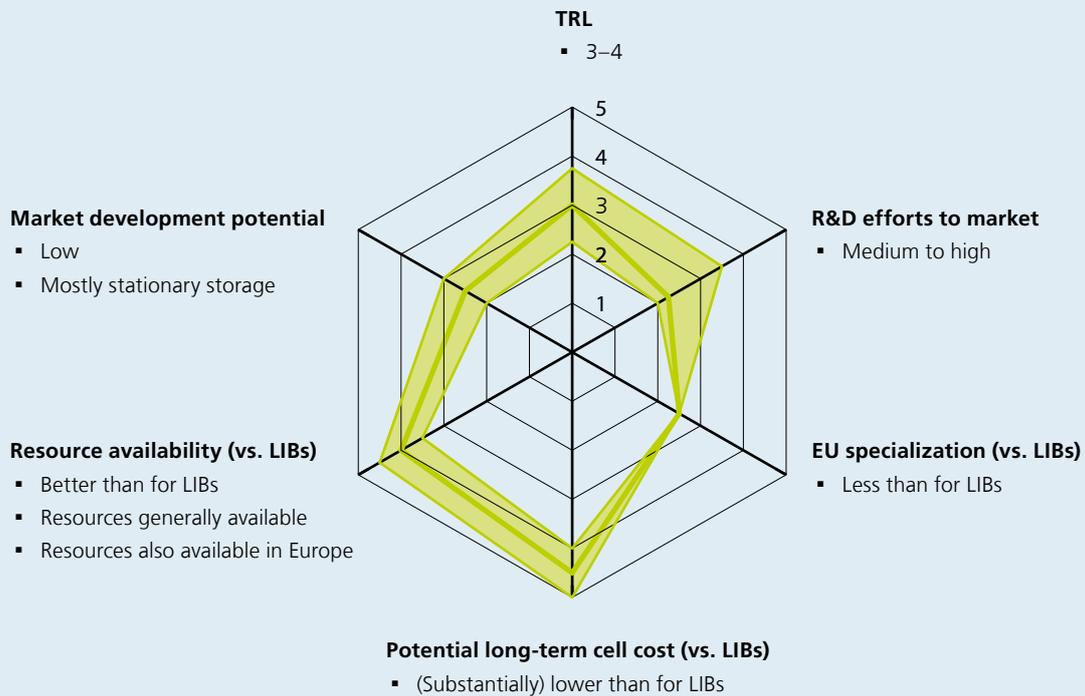
Even though no ZIB demonstrator on the module level exists yet, future commercial applications of ZIBs are considered most likely for stationary storage and consumer storage. Due to the relatively low energy density compared to LIB, mobile applications are not the focus of ZIBs and are limited (if at all useful) to short-range applications, or ships where energy density is

not too critical. Potentially low costs, high safety, no requirement for rare and critical raw materials, as well as potentially high cycle stability could make ZIBs an attractive candidate for stationary storage, e.g., as a replacement for lead-acid batteries. In the medium term, industrial storage applications might also become relevant, and in the long-term, utility-scale long-duration energy storage applications.

#### Cost, resources, production and supply chain

Due to its high availability, the cost of Zn is only a few EUR/kg [84] (Li is currently 200–300 EUR/kg). Similarly, Mn as part of potential Mn-oxide cathode materials, costs less than 2 EUR/kg. Other potential cathode materials, on the basis of V or Co, for example, are more expensive. Other components, such as the aqueous electrolyte, are available at a substantially lower cost compared to the organic LIB equivalents. The tendency toward the lowering of costs is also continuing in cell production. Advantages exist due to the elimination of NMP as the solvent for electrode fabrication and dry rooms. Experts expect costs of 80 EUR/kWh by 2025 and 40–50 EUR/kWh by 2030. In the long term, costs below 40 EUR/kWh could be achieved.

Supply chains are already established for aqueous Zn-based primary batteries. There is a conditional transferability for rechargeable batteries. However, this transferability depends heavily on the cathode materials used. No large-scale

**Figure 21: Radar chart of relevant dimensions of ZIBs\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

production processes or supply chains have yet been established for most of the materials under investigation. Similarly, no cell manufacturing processes have been established. In the medium term, production could become less complex compared to LIBs due to the lower requirements concerning an anhydrous ambient atmosphere.

### Sustainability

A recent study [70] presents LCAs of ZIBs based on different cathode materials. The calculated global warming potential of 20–100 kg CO<sub>2eq</sub>/kWh energy storage is significantly lower than the results for LIBs and SIBs in other studies. The most important factors for the ecological impact are the Zn-metal anode, the cathode material and the separator. The aqueous electrolyte has little impact.

Aside from the materials, ZIBs can also show advantages in manufacturing. The materials including the anode are mostly stable under ambient conditions. Compared to LIBs, this can lead to significantly lower energy demand since no dry room is required.

Recycling of primary zinc-carbon and alkaline batteries is well established [85]. So far, there is little work on potential recycling routes for ZIBs, but only small modifications to current recycling processes of primary Zn-batteries are expected to be necessary. In principle, metallic Zn can be recycled with high efficiency by a controlled oxidation approach. The glass fiber and Nafion separators often used in ZIBs are probably more difficult to recycle. The effort required for recycling, especially for aqueous systems is likely to be lower than for LIBs.

### Advantages and Potential for Europe

The key advantages of ZIBs, especially aqueous ZIBs with manganese-based CAM, are that no rare materials are required, there are high resource availability and low costs of the required materials, and a low ecological footprint of battery production. All of the above make ZIBs an interesting technology for the next generation of stationary storage applications. ZIBs are currently at a low TRL and consequently there are no established players on the market. This opens up the opportunity for European players to be at the forefront of the development of an industry for this technology. However, the pace of development is rapid, so that efforts must be made to industrialize this technology in the near future. If the expectations of technical improvements are met, ZIBs could play a significant role in the stationary sector in the future.

## 2.4.5. Aluminum-Ion Batteries

### Technology

Research on Al-ion batteries (AIBs) has intensified in the past years, especially since the publication of Lin and colleagues in 2015 [36]. So far, there are only a few institutes and companies that are researching this technology and are already producing first prototypes on a laboratory scale. The technology is seen in the future as a link between LIBs and (hybrid-ion-)capacitors, because it has a higher power density than a battery and a higher energy density than a capacitor. Currently, AIBs are still undergoing electrochemical development and a proof of concept is being sought (TRL 3–4).

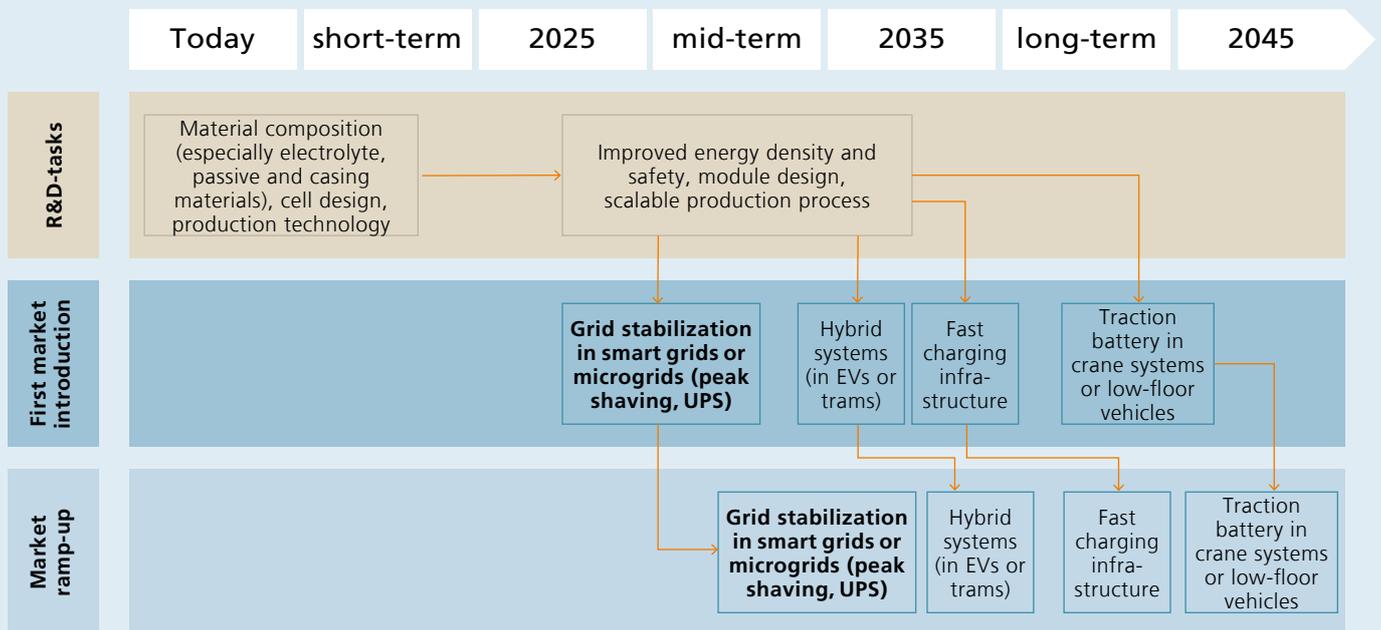
Typically, AIBs consist of an anode of Al foil, a cathode of graphite and an electrolyte of ionic liquids. Furthermore, fiberglass fleece is used for the separator and Mo for the current collector on the cathode side, and the Al foil can also be used for the current collector on the anode side. While Al or Al alloys can be used on the anode side, research is being

carried out especially on different variants of carbon for the cathode side [86]. The following illustrative figures refer to an Al-graphite-dual-ion battery with an ionic liquid-based electrolyte. On the one hand, the gravimetric energy density of 30–35 Wh/kg per cell is substantially lower than that of LIBs. On the other hand, the power density (9,000 W/kg), cycle life (> 20,000 cycles) and C-rate (180C) are much higher than for LIBs, possibly enabled by the low diffusion barrier of the intercalated  $\text{AlCl}_4^-$  in expanded graphene layers. In the short to medium term, these latter performance parameters are expected to more than double. A technical and safety-critical bottleneck is the highly corrosive electrolyte consisting of an ionic liquid. Corrosion-stable casing materials or less corrosive electrolytes (e.g., aqueous electrolytes) are possible solutions to this problem and are currently being researched. In addition, low-cost and corrosion-resistant current collectors are being actively sought.

**Table 8: Estimated KPIs for AIBs today and in the long-term future**

KPI	Value (today)	Value (long term)
<b>Cell-level KPI</b>	135–200 Wh/kg <sub>Carbon</sub>	240–280 Wh/kg <sub>Carbon</sub>
	30–35 Wh/kg <sub>Cell</sub>	45–50 Wh/kg <sub>Cell</sub>
	297–440 kWh/l <sub>Carbon</sub>	528–616 kWh/l <sub>Carbon</sub>
<b>Vol. energy density</b> <sup>[6]</sup>	35–50 Wh/l <sub>Cell</sub>	45–80 Wh/l <sub>Cell</sub>
<b>Power density</b>	9,000 W/kg <sub>Carbon</sub>	> 10,000 W/kg <sub>Carbon</sub>
<b>Power per electrode area</b>	40 mW/cm <sup>2</sup>	120 mW/cm <sup>2</sup>
<b>Cycle life</b>	> 20,000 cycles	> 50,000 cycles
<b>Calendar life</b>	several months	several months
<b>C-Rate</b>	180C	250C
	85 % @0.05 A/g <sub>Carbon</sub>	85–90 % @0.05 A/g <sub>Carbon</sub>
<b>Energy efficiency</b>	68 % @2.5 A/g <sub>Carbon</sub>	70–80 % @2.5 A/g <sub>Carbon</sub>
	Single safety critical aspect: highly corrosive electrolyte, no flammable or explosive substances, works well at room temperature	Single safety critical aspect: highly corrosive electrolyte, no flammable or explosive substances, works well at room temperature
<b>Safety aspects</b>		

Figure 22: R&D and commercialization roadmap for AIBs



**Applications and market relevance**

Due to their technical properties, applications are envisaged wherever rapidly changing energy and power requirements are necessary. Potential market entry (between 2025 and 2035) could lead to applications in both the stationary and mobile sectors. Among the first applications entering the market are highly dynamic applications for grid stabilization in smart grids or microgrids. AIBs could also be used in hybrid systems with LIBs in EVs or in trams (start-stop function). During the market ramp-up, applications include peak shaving, uninterruptible power supply, fast charging infrastructure, and crane systems or low-floor vehicles.

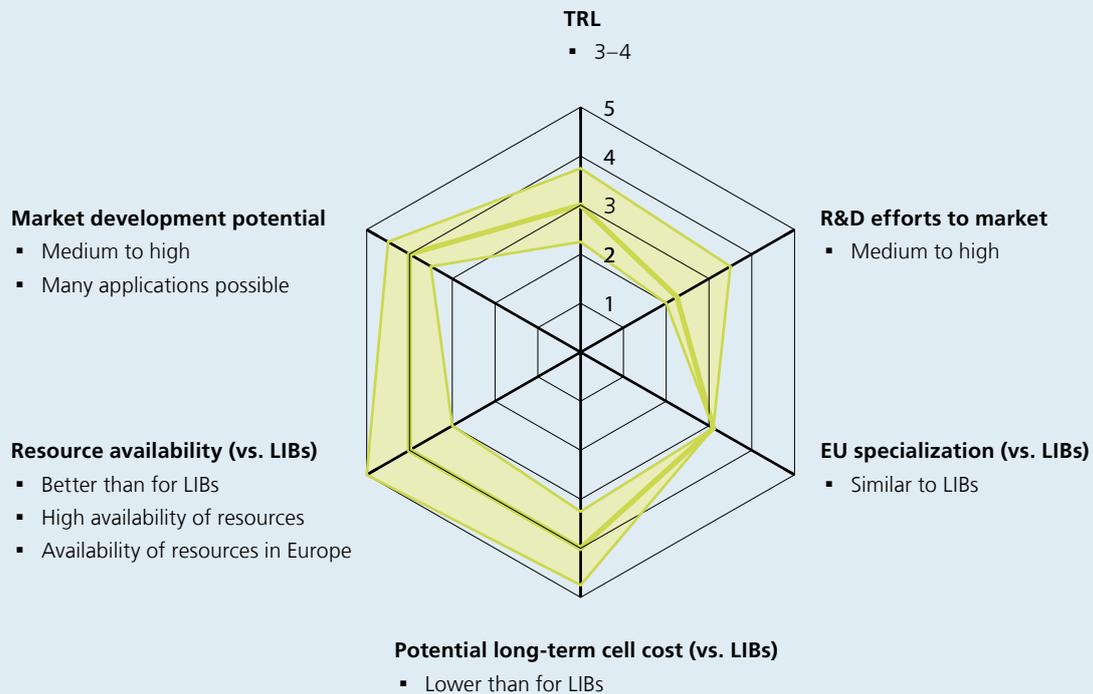
**Cost, resources, production and supply chain**

In the medium to long term, fully developed AIBs can be expected to deliver cost savings of around 10–20% in comparison with conventional LIBs. Compared to LTO-LIBs, the cost advantage will probably be even greater due to the use of cheaper materials, and the elimination of manufacturing steps (e.g., no coating processes on the anode side are necessary).

Nevertheless, AIBs can probably be produced on LIB production lines. However, avoiding humidity during production (using, for example, inert gas or dry rooms) is just as important as it is for LIBs. Due to the need for graphite as cathode material, existing LIB supply chains can be used. If Mo is used as the current collector on the cathode side, a cost-effective large-scale manufacturing technology cannot be implemented. There are projects planned to assess the substitution of the Mo current collector, so that concepts for a suitable roll-to-roll process could be developed in the coming years. Al, which is used as the anode material and current collector at the same time, is available in Europe, which is why there are already anode and electrolyte manufacturers in Germany. In general, both the availability of raw materials and the supply chains for AIBs in Europe are considered to be more favorable than for LIBs.

**Sustainability**

Considering all the materials of AIBs, the processing of Al has the highest environmental impact due to its energy-intensive

**Figure 23: Radar chart of relevant dimensions of AIBs\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

production. The production of approximately 1 kg of aluminum generates 5–40 kg of CO<sub>2</sub> emissions. Nevertheless, less soil has to be moved during its mining compared to Li mining, due to the higher deposits on earth. Moreover, the electrical energy to provide the same theoretical gravimetric or volumetric capacity of a metal anode is about 3–5 times less for Al than for Li. Furthermore, the energy consumption of the entire Al production process can be reduced by 95 % through recycling, which is why about 35 % of Al demand in 2018 was satisfied by recycled, secondary Al. A mature recycling infrastructure already exists for Al [87]. Apart from the necessary substitution of Mo as a current collector, no other critical materials or even toxic transition metals are used in AIBs apart from Al. Due to the low TRL, design for recycling can be consistently considered and implemented.

### Advantages and Potential for Europe

The main advantage of AIBs is the good resource availability of Al (the most abundant metal in the earth's crust), which can potentially result in lower costs compared to LIBs (10–20 % in

terms of EUR/kWh [87]). The metal is available in large primary and secondary, i.e., recycled, quantities in Germany and Europe. Further advantages are the exceptional performance parameters, such as higher power density than LIBs, higher energy density than capacitors, as well as high cycle life and C-rate. These KPIs create other possible applications beyond those that already exist for LIBs, such as grid stabilization in smart or microgrids. Globally, only limited R&D activities have so far been observed, which is why there could be a high potential for Germany and Europe with regard to this technology and technology sovereignty.

## 2.5. Metal-Sulfur Batteries

Metal-sulfur (Me-S) batteries are being studied and developed because of the high availability, low price, and low weight of S as CAM [88]. Many different metals are studied in combination with a S cathode, such as monovalent Li, Na, K and multivalent Mg, Ca and Al [89]. Among these systems, Li-S is the most advanced one for room temperature (RT) operation. The aforementioned metals are, however, much more abundant than Li and therefore also of high interest for Me-S batteries.

Me-S batteries aim at utilizing the high specific capacity of sulfur, which theoretically has 1,672 mAh/g in a full two-electron reaction. This value is far higher than for any cathode material currently applied in LIBs. The challenges of these cell concepts are the low electronic conductivity of sulfur and metal-sulfides, requiring the use of a conductive matrix or conductive agents in the cathode. The properties also depend on the crystal structure of S, for which several (meta-) stable phases exist.

At the anode side, the cell concepts utilize a metallic layer or reservoir. The RT concepts mostly require a liquid electrolyte, though there is some research on solid-state electrolyte setups. The alkali metals (Li, Na, K) function rather similarly in this context. Mg, Ca and Al require non-standard electrolytes, based on solvents and salts, which so far have not been used in LIBs. In contrast to RT concepts, high-temperature (HT) concepts operating at temperatures above 300°C, in particular for sodium, make use of molten Na and S and a solid ceramic electrolyte. These HT concepts are already applied commercially (TRL 9) for stationary energy storage on a GWh-scale [90]. Due to the high temperatures and large molten mass in HT concepts, it is likely that RT concepts will permit a wider range of applications.

So far, most RT cells still have a low cycle life caused by the large volume expansion during the  $S \rightarrow Me_xS$  ( $x = 2$  for Li, Na, K;  $x = 1$  for Mg, Ca; and  $x = 2/3$  for Al) conversion, general stability issues of the solid electrolyte interfaces at the anode and the cathode and the so-called “shuttle effect”. The latter is based

on the solubility of the reaction products of the metal used and S (often polysulfides) in the polar solvents, which typically act as electrolytes. The shuttle effect leads to the self-discharge of cells and loss of active materials.

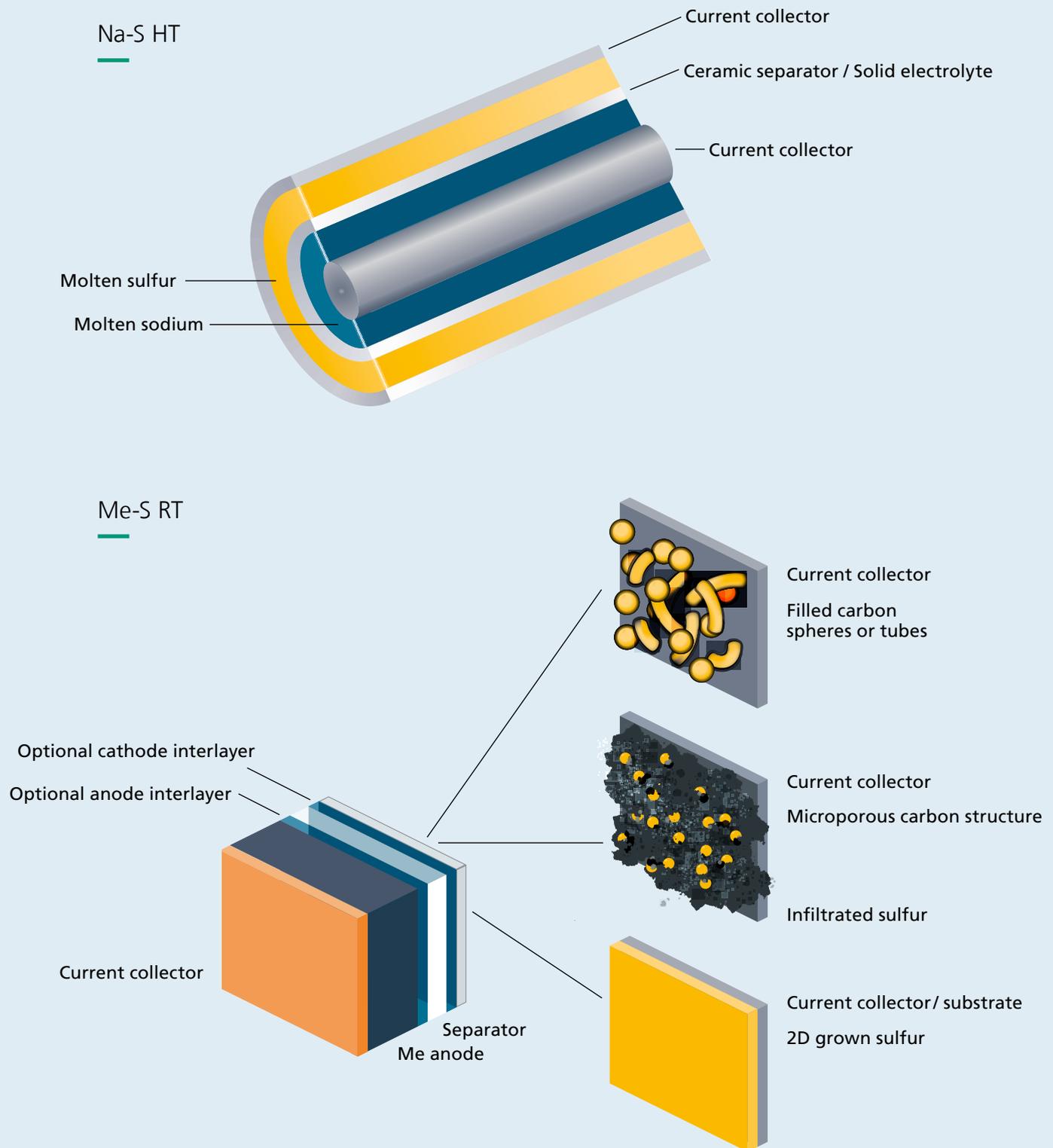
At RT and combined with a liquid electrolyte, there are high requirements for the cathode as well as for the metallic anode. As CAM, S can either be functionalized by mixing it with carbon, infiltrating it into carbon structures or in 2D-approaches, e.g., directly grown on a substrate, allowing for a highly dense and uniform cathode architecture.

A porous 3D carbon structure can serve several purposes: As a host structure for S, as a conductive network for the non-conductive S domains, and as a highly reactive surface to prevent the polysulfides from leaving the cathode. The pore structure of the 3D carbon determines the overall conductivity of the cathode as well as the degree of S loading, both of which should ideally be very high. Besides the pore structure, the chemical surface properties of the 3D carbon determine the ability of this host material to bind polysulfides and hence prevent dissolution and shuttling.

The metallic anode needs to be thin and processable. This is particularly challenging due to the high reactivity of the alkali metals. Furthermore, there has to be a homogeneous current distribution on the anode surface in order to prevent dendrite growth. This can be achieved by special intra-layers, which, for example, can improve the transport properties along the anode surface or mechanically prevent dendrite growth. The physical or chemical prevention of polysulfide shuttling is also a desired property. Besides a typical separator, Me-S cells might therefore include additional organic or inorganic blocking layers or membranes.

The selection of suitable electrolytes can be key to the stability of the systems and the reaction kinetics and hence power and energy density.

**Figure 24: Typical structure of Me-S batteries; Top: Structure of molten Na-S HT battery; Bottom: Structure of Me-S RT battery with Me-anode, optional interlayers and different cathode concepts based on filled carbon particles, carbon matrix or 2D sulfur**



## 2.5.1. Lithium-Sulfur Batteries

Among the Me-S room temperature (RT) battery systems, lithium-sulfur (Li-S) batteries are the most advanced in terms of technological maturity. Today, liquid electrolyte-based systems are at a TRL of 5–7, solid electrolyte-based systems at a TRL of 3–4. Various start-ups are currently working on the development of prototypes, but production-ready sample cells have not yet been presented to the public.

### Technology

Li-S features a discharge voltage between 2.4 and 2.0 V [88]. Utilizing the high specific S and Li capacity, energy densities of 300 to 400 Wh/kg have been demonstrated in prototype cells. It is not yet clear how cell energy will translate to the system level, since, compared to LIBs, a higher number of cells will be necessary to reach the required system voltage. Furthermore, Li-S cells might require higher external pressure. Cycling stability also often lags behind state-of-the-art LIBs and necessitates, e.g., a large electrolyte surplus. The R&D target is therefore

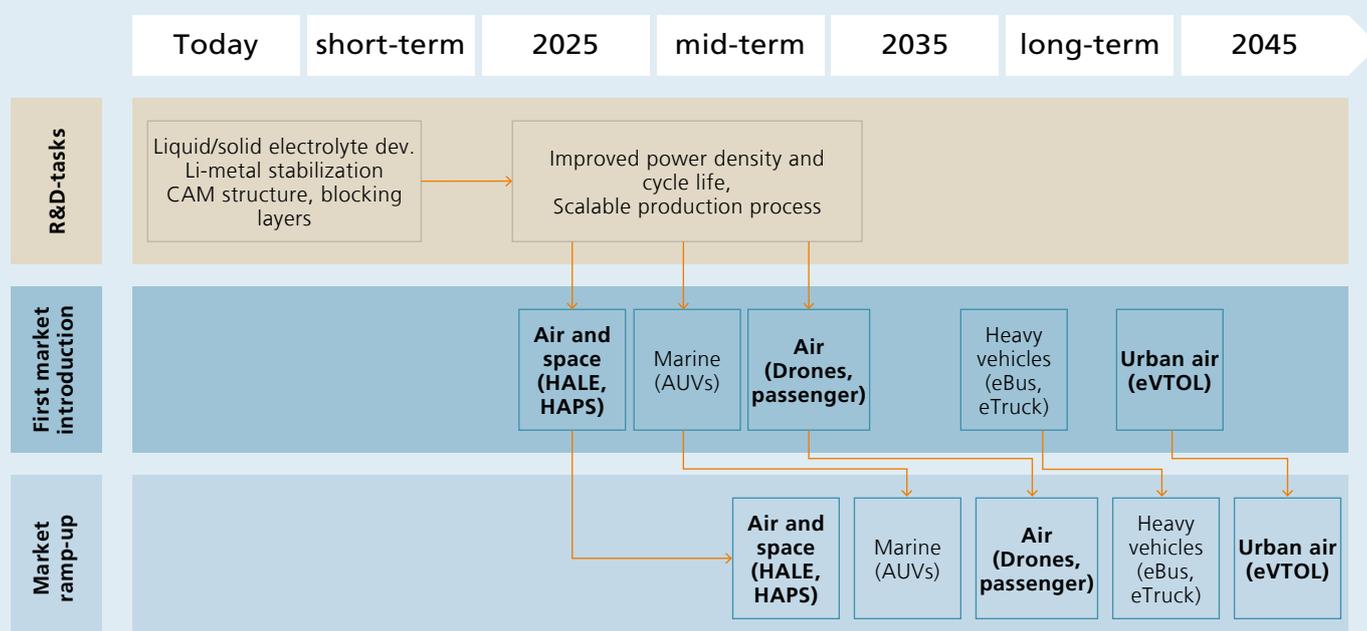
to design large format cells with both high energy density and a cycling stability of more than a few 100 cycles. Due to the kinetic properties of S and metallic Li, most systems are designed for charging and discharging rates below 1C. As with LIBs, hazards for this cell system are the flammability of the electrolyte and the reactivity of the metallic Li.

All major cell components still have to overcome R&D challenges. On the cathode side, S loading, reaction kinetics, conductivity and completeness of S utilization need to be improved. Approaches here consist in particular in selecting suitable carbon scaffold structures. The shuttle effect for Li-polysulfides can be reduced by introducing organic or inorganic interlayers. With the right chemical functionalization, the interlayer surface can adsorb or block polysulfides or accelerate their conversion into solid Li-sulfides. [6]

**Table 9: Estimated KPIs for lithium-sulfur batteries today and in the long-term future**

KPI	Value (today) [91]	Value (long term)
<b>Cell-level KPI</b>	> 300 Wh/kg	550 Wh/kg
<b>Vol. energy density</b>	300–450 Wh/l	700 Wh/l
<b>Power density</b>	< 500 W/kg	< 500 W/kg
<b>Power per electrode area</b>	≤ 20 mW/cm <sup>2</sup>	> 20 mW/cm <sup>2</sup>
<b>Cycle life</b>	50–300 (prototype cells)	> 500
<b>Calendar life</b>	unknown	
<b>C-Rate</b>	< 1C	1C
<b>Energy efficiency</b>	unknown	85 %
<b>Safety aspects</b>	Highly reactive Li-anode. Flammable electrolyte.	Improvements through use of solid electrolytes.

Figure 25: R&amp;D and commercialization roadmap for Li-S batteries



On the anode side, the production and handling of thin Li foils are still major challenges. Foils with a few  $\mu\text{m}$  Li layer thickness are not commercially available today. There are also still major challenges regarding the long-term operability of the Li anode. The development of new electrolytes could contribute to solving these problems. Finally, the required cell KPIs need to be demonstrated in larger size formats and with multi-layer cell designs.

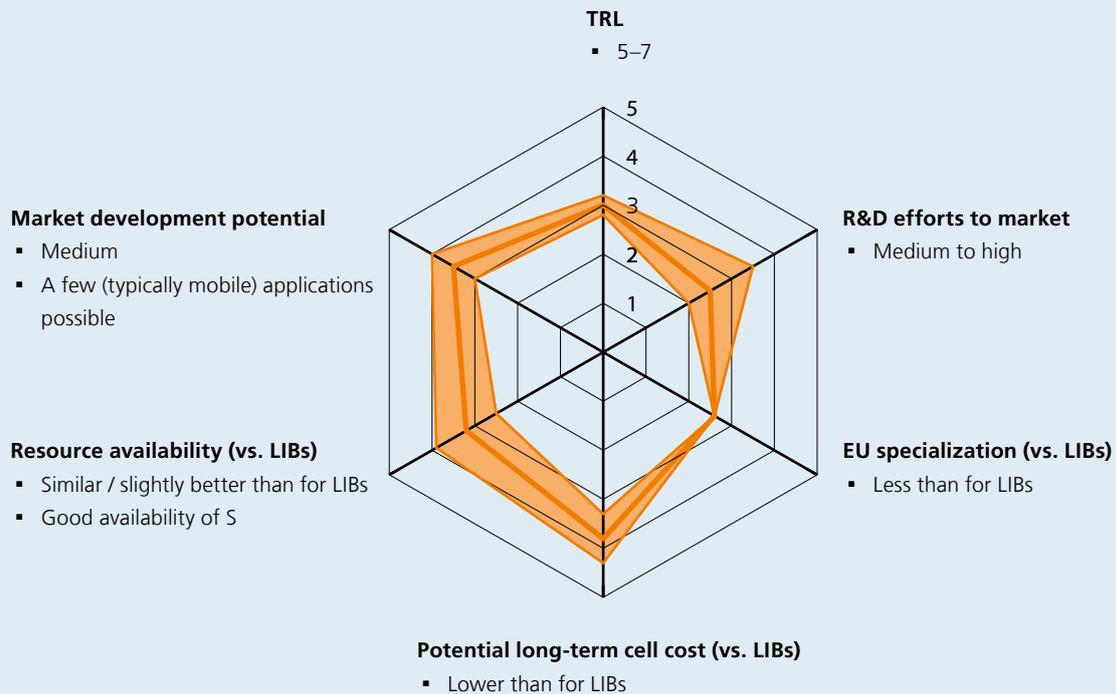
### Applications and market relevance

Li-S batteries could target applications that require particularly high gravimetric energy densities as well as potential applications with high cost sensitivity. Competitive gravimetric energy densities to LIBs have already been demonstrated with Li-S batteries. Because of the potentially very high energy densities, the technology could play a role in the field of flight

applications. However, depending on the application, high power densities may also be required, which are not offered by current Li-S batteries. The cycle life also tends to limit the use to applications with a low frequency of use or readiness for frequent battery replacements. Since the cost-competitiveness with LIBs has not yet been demonstrated in practice, the relevance, e.g., for stationary applications, is still unclear.

A further scale-up of production will require the development of the whole process chain to industrial scale. A production of 10 GWh/yr of Li-S batteries, for example, would require an input of several kilotons of CAM per year, including a 3D-carbon host material or a 2D carbon substrate and several tens of millions  $\text{m}^2$  per year of Li-metal anode<sup>17</sup>.

<sup>17</sup> Assuming a loading of  $> 5 \text{ mAh/cm}^2$  and an average cell voltage of 2.15 V. For the S cathode, a specific capacity of 1300 mAh/g (half the theoretical capacity of S) was assumed.

**Figure 26: Radar chart of relevant dimensions of Li-S batteries\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

### Cost, resources, production and supply chain

From a raw materials cost perspective, Li-S batteries can be cheaper than LIBs due to the low cost of S. However, this requires overcoming several challenges: The development and up-scaling of a cost-efficient process for thin Li-metal anodes, the reduction of the amount of electrolyte per Ah, and the increase of S loading in the cathode in combination with a low-cost carbon matrix. Experts expect cost parity between Li-S batteries and LIBs around the year 2025. In the long term and depending on the development of the Li-price, cell costs of 50 EUR/kWh might be possible for Li-S, assuming that energy-efficient processing methods like dry coating are available.

The Li-S technology can be considered a completely new one, since it makes use of new materials and concepts in all cell components. This involves both the S cathode and the Li-metal anode. Currently, there are no concepts for the large-scale production of thin Li-metal electrodes (< 30 μm). Several techniques such as extrusion and calendaring for foil production, but also liquid or gas phase deposition are available, but none

of them has been scaled up so far to multi-GWh production capacity.

Currently, CAMs and additives are mixed prior to electrode production in a solvent-based process, which is not suitable for the S filling of carbon structures. Therefore, production of S-infiltrated 3D-carbons might make fabricating the cathode material more complex. The same holds for the direct fabrication of S cathodes on substrates, which requires fundamentally different process equipment. It would be convenient if materials and formulations were compatible with conventional electrode coating processing techniques.

The concept of interlayers is also new compared to typical LIB designs. So far, LIBs only have a separator, which is sometimes coated with an inorganic protective material.

Due to the good availability of S, critical points in the supply chain are more likely to concern the availability or scarcity of Li and material production in general. Compared to LIBs, the

potential shortage of Li can be considered even more critical, as Li-S batteries require more Li per kWh battery capacity.

### **Sustainability**

From the perspective of materials and material value, recycling the Li-anode would be very interesting. In a discharged cell, Li would be in the S cathode and recycling would therefore have to process both electrodes, even though S is of low value. An advantage is that thermal treatment can largely remove S from the battery.

Several studies [92, 93] suggest significantly lower emissions for Li-S battery manufacturing, use and recycling than for LIBs, mainly due to the lower use of metals such as Ni, Co, Mn, and Cu.

### **Advantages and Potential for Europe**

From a performance perspective, the high gravimetric energy density of Li-S batteries is particularly interesting. This could lead to different applications if the challenges of cycle stability and power density can be overcome. While a conclusive cost comparison to LIBs is not possible, there are evident resource availability and cost advantages. The technology is strongly dependent on the availability of Li, which – although in low concentration – is found in various deposits around the world. S is widely available and the other key components such as electrolyte and carbon could also be established regardless of the localization of previous LIB supply chains. The enabling element for Li-S batteries is the technology rather than access to raw materials. Europe could certainly take a key position by developing competencies in material and electrode architecture as well as electrolytes. This field is not yet too heavily protected by patents, so there is scope for development.

## 2.5.2. Sodium-Sulfur Room Temperature Batteries

Even if the technological maturity of sodium-sulfur room temperature (Na-S RT) batteries (TRL 4) is still substantially behind that of Li-S batteries, they represent a very interesting alternative due to the substitution of the resource-critical Li with Na. Overall, this promises a storage solution that is almost completely free of problematic raw materials and can potentially be produced very cost-effectively. While Na-S HT batteries have already experienced some commercial breakthrough, the RT technology is still in the research phase and there are no known commercial activities so far.

### Technology

Na-S has a discharge voltage of 2.3 to 1.7 V [94]. In the short term, a gravimetric energy density of 300 Wh/kg is possible. Theoretically, the energy density could reach a value of over 1,200 Wh/kg, roughly half the theoretical value of Li-S. So far, results for lab concepts have only shown cycles at low C-rates < 1C.

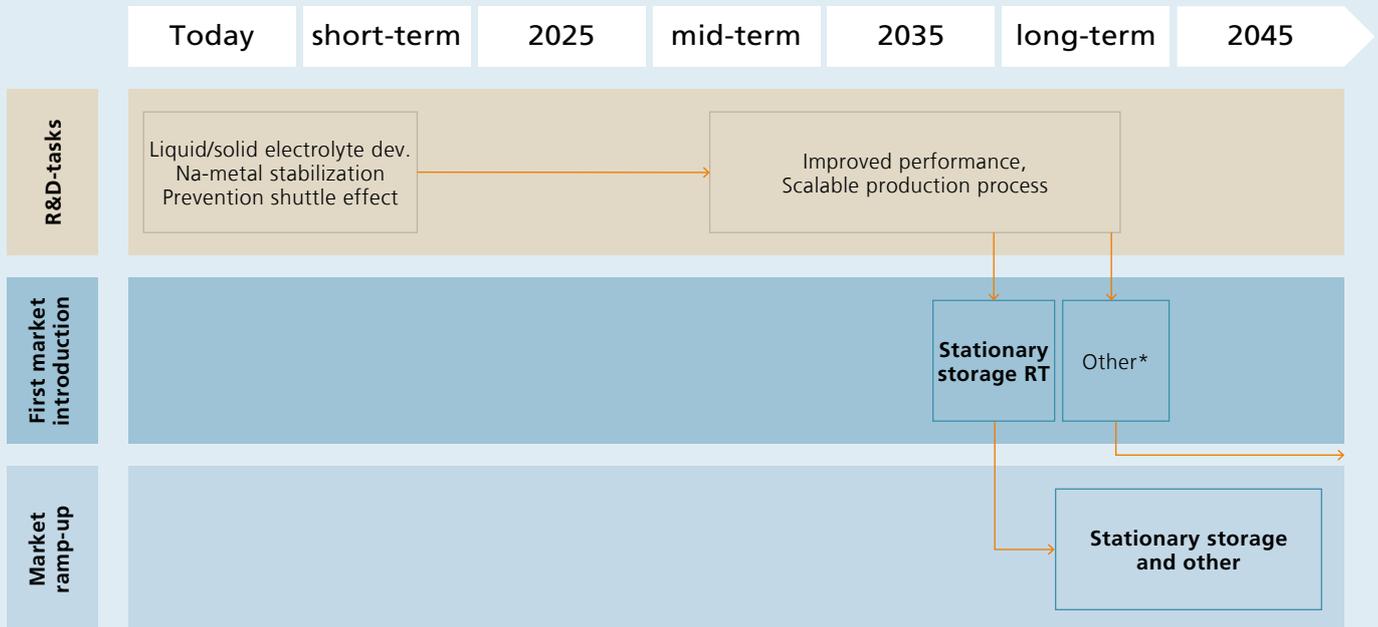
The main setup and working principle of Li-S and Na-S batteries are comparable. Nevertheless, there are significant differences due to the higher reactivity of Na, leading to a less stable protective solid electrolyte interface in typical electrolytes and to a lower electrochemical conversion efficiency, i.e., the sluggish reaction between Na and S leads to incomplete S utilization during discharge. In addition, the undesired shuttle effect seems to be more pronounced for Na-polysulfides than for Li-polysulfides. The properties of the anode also differ, and the occurrence of dendrite growth appears to be an even greater problem with Na deposition. In total, the list of challenges is even longer compared to the Li-S analogue and requires new solutions on almost all levels of the battery cell.

Many approaches address the development of new electrolytes, e.g., through the use of ionic liquids [95]. Similar to Li-S batteries, work is being done on the use of microporous carbon structures, which can trap polysulfides or prevent the formation of

**Table 10: Estimated KPIs for Na-S RT batteries today and in the long-term future**

KPI	Value (today)	Value (long term)
<b>Cell-level KPI</b>	300 Wh/kg	> 350 Wh/kg
<b>Vol. energy density</b>	unknown	unknown
<b>Power density</b>	unknown	unknown
<b>Power per electrode area</b>	low	unknown
<b>Cycle life</b>	several 100 cycles (lab cells) [98]	> 500 cycles
<b>Calendar life</b>	unknown	
<b>C-Rate</b>	≤ 1C	unknown
<b>Energy efficiency</b>	70 %	> 70 %
<b>Safety aspects</b>	Highly reactive Na-anode. Flammable electrolyte.	

Figure 27: R&amp;D and commercialization roadmap for Na-S RT batteries



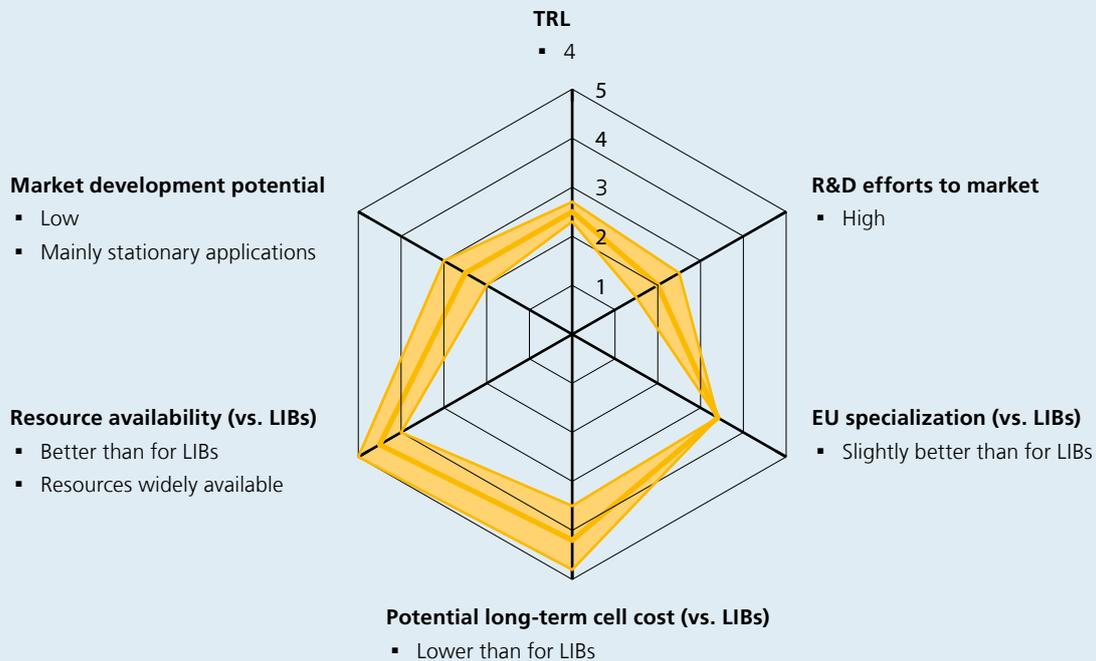
\* Other applications with high requirements for sustainability and cost

polysulfides in the first place. Often, chemical modification, doping of carbons or a combination with metal nanoparticles is necessary to achieve this [96]. However, many of the published approaches use highly tailored structures, such as filled carbon nanotubes (CNTs), or hollow carbon spheres, or graphenes. These materials are often not yet available on a large scale, or their production is associated with high costs. Scaling up could lead to additional delays in the commercialization of Na-S batteries. Interlayers are also discussed. Among other things, an approach could be implemented that is also used for Na-S HT cells: the use of ceramic solid electrolytes. However, these would need to be sufficiently ionically conductive, even at RT [97]. By and large, experts rate the associated R&D-challenges as high. From a safety perspective, the high reactivity of Na and the flammability of organic electrolytes are a concern.

### Applications and market relevance

Applications of Na-S RT batteries are seen as similar to those of Na-S HT batteries in the field of stationary storage. The heating and safety features of Na-S HT batteries seem suitable for medium- to large-scale deployment, e.g., in MWh storage. However, with the availability of RT batteries, Na-S batteries could be deployed on a smaller scale and with less complexity in the future.

The theoretical energy density of Na-S batteries also sounds interesting for mobile applications. In terms of volumetric energy density, Na-S batteries do not yet reach the benchmark of Li-S or LIBs. As Na-S batteries are not yet technologically mature, market entry cannot be specified although experts expect possible commercialization after 2035.

**Figure 28: Radar chart of relevant dimensions of Na-S RT batteries\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

### Cost, resources, production and supply chain

So far, there is no supply chain for Na-S batteries. Metallic Na is not available as foil and can only be purchased in rod form. For cell production, a transferability of Li-S batteries is assumed.

Since metallic Li is the main driver of cell costs for Li-S batteries, the raw material value is almost completely eliminated by substituting Li with Na. Likewise, when Na is used, Al can also be used as a current conductor on the anode side, which would further reduce costs compared to Cu.

### Sustainability

The technology is considered highly sustainable because the materials used are considered unproblematic. Studies [99, 100] suggest that the production of Na-S cells is significantly less harmful than LIB technology.

So far recycling has not been in the focus of research on Na-S batteries. In principle, however, the question arises as to whether the materials of Na-S batteries can be efficiently recovered in their original quality. The material value is extremely low, but metallic components could be separated mechanically.

### Advantages and Potential for Europe

The technology is highly interesting due to the readily available core raw materials: S, Na and possibly Al and steel for cell components. The potential costs of a commercialized technology are almost exclusively due to the processing involved. Unlike Li-based technologies, a supplier's commercial success is likely to be based on technological know-how and not dependent on access to global raw material flows. The technology is therefore extremely interesting for Europe.

## 2.5.3. Sodium-Sulfur High Temperature Batteries

First described by Weber and Kummer at the Ford Motor Company in the 1960s [101], Na-S HT batteries have already experienced commercial breakthrough as stationary energy storage systems. Due to its high operating temperature, this battery system is also called a thermal battery or molten Na battery and should not be confused with Na-S RT batteries, which are operated at room temperature.

### Technology

The main components of the Na-S HT cell are a solid electrolyte consisting of ceramic  $\beta$ -alumina and electrodes of Na and S in a liquid state. The electrolyte is only permeable for Na-ions and is used as a cylindrical tube in which the liquid Na is placed as the anode. The cells are electrically and mechanically interconnected and are housed in a thermal enclosure that maintains a temperature in the range of 300–350 °C to keep the electrodes liquid. A separate thermal management system provides initial heating and dissipation of waste heat

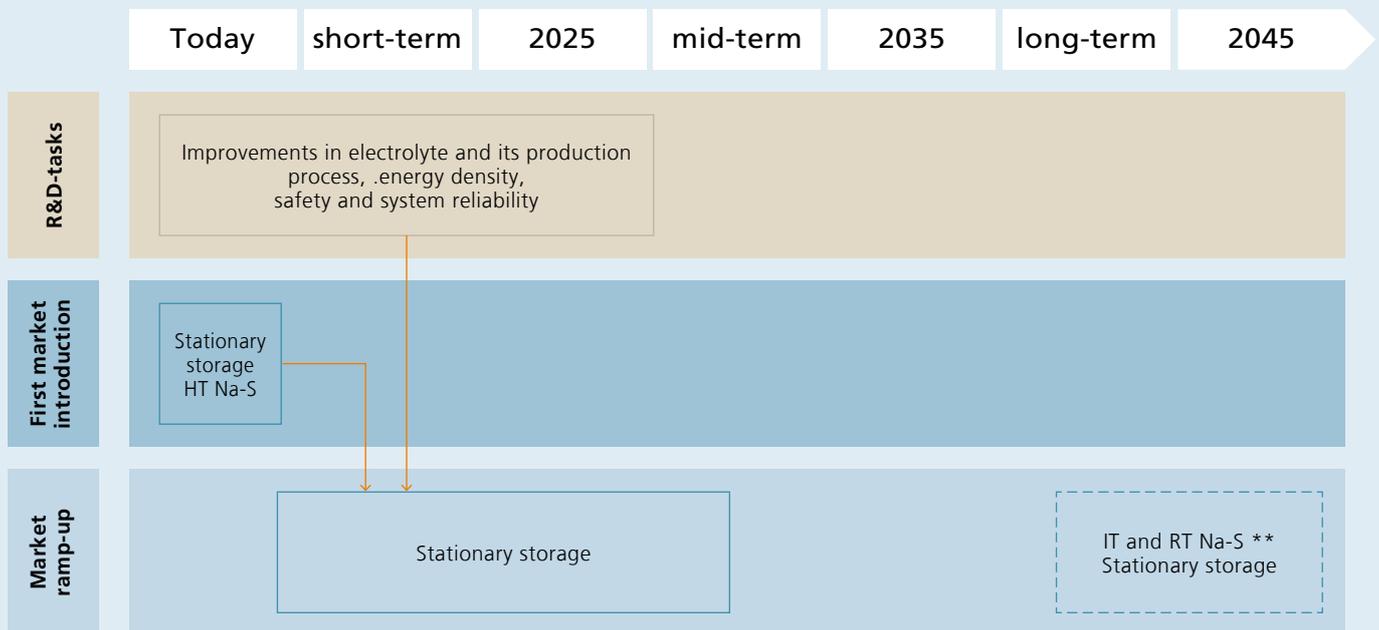
from the battery during operation [94], as the maximum temperature range should not exceed 360 °C [102] due to safety issues.

During discharge, the positive Na-ions diffuse through the ceramic solid electrolyte to the molten S – Na is oxidized and S is reduced – and are converted into sodium polysulfides  $\text{Na}_2\text{S}_x$ . The discharge voltage is approximately 2 to 1.7 V [94]. On the cell level, the high theoretical energy density is limited to approximately 760 Wh/kg by the utilization rate of the S cathode [94]. For today's commercialized Na-S HT batteries, the practical energy density is in a range of 300–414 Wh/l with an expected operational lifetime of 15 years or 4,000–4,500 cycles [102, 103]. Typically, the tubular Na-S HT cells are connected to form a battery module, and several modules are subsequently packed together in a container [103]. The spaces between the cells are filled with sand in order to prevent greater damage in the case of thermal propagation of a cell.

**Table 11: Estimated KPIs for Na-S HT batteries today and in the long-term future**

KPI	Value (today)	Value (long term)
<b>Cell-level KPI</b>	180–268 Wh/kg [102, 104, 105]	pot. 300 Wh/kg
<b>Vol. energy density</b>	300–414 Wh/l ty [102, 104]	pot. 440 Wh/l
<b>Power density</b>	36 W/kg [104]	
<b>Power per electrode area</b>		
<b>Cycle life</b>	4,500 cycles [102, 103]	> 7,000 cycles
<b>Calendar life</b>	15+ years [102]	15–20 years
<b>C-Rate</b>	1/6C for 4–6h systems [102]	
<b>Energy efficiency</b>	70–80 % RTE [102, 104, 105]	> 80 %
<b>Safety aspects</b>	Toxic gas formation and flammability if separator breaks (due to corrosion and degradation, but considered to be under control)	Under control; optimized cell interconnection

Figure 29: R&amp;D and commercialization roadmap for Na-S HT batteries



\* Since the Na-S HT storage technology is already mature in Japan and also the USA, the ramp-up refers specifically to Europe.

\*\* It is still unclear whether intermediate-temperature Na-S or room-temperature Na-S technology will compete with Na-S HT or whether the technologies will coexist in a long-term perspective

The chemical reactivity of Na and S is hazardous as it is flammable and releases toxic  $\text{SO}_2$  gas. As the  $\beta$ -alumina is essential for the safety and performance of the battery, degradation of the ceramic electrolyte as well as corrosion of the housing can also have hazardous effects. However, the technology is considered to be well controlled, although it has been on the market for more than 20 years, only one major accident during operation has been reported so far; it happened in 2011. [104]

Besides Na-S HT batteries, Na-NiCl<sub>2</sub> batteries (also called ZEBRA battery) are also commercially available thermal batteries. Their design differs primarily in the use of liquid NaNiCl<sub>2</sub> as an electrode instead of S, and a slightly lower operational temperature of approximately 270°C. The design also uses  $\beta$ -alumina as a ceramic electrolyte and shares the positive characteristics of Na-S HT batteries, such as a long cycle and calendar life, good recyclability and attractive system costs. These are slightly higher than for Na-S HT batteries due to the use of nickel [106, 107]. The ZEBRA battery is considered to be relevant for grid-scale energy storage in the future. Due to the focus on

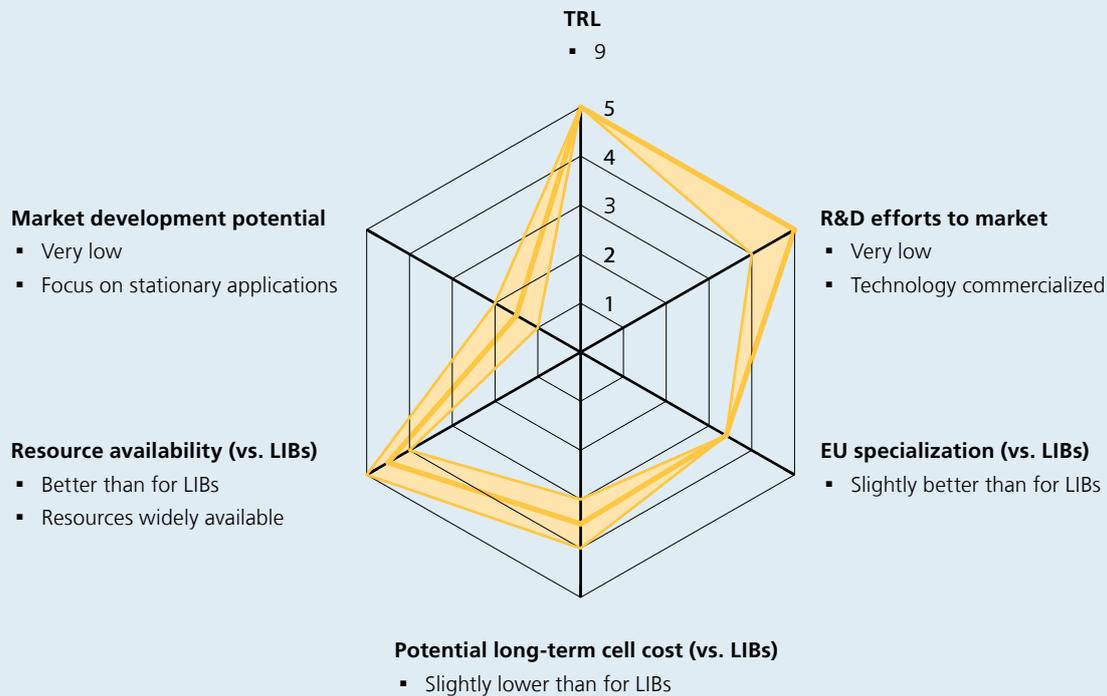
Me-S batteries in this roadmap, the Na-NiCl<sub>2</sub>-technology is not discussed in further detail.

### Applications and market relevance

Na-S HT batteries have been commercially available for decades. While most Na-S HT batteries have been commissioned in Japan and the USA, the technology is increasingly discussed and used in Europe. With a rapid response time and typical discharge durations of 6–7 hours or 1/6C, the containerized systems are scalable to tens or hundreds of MWh and therefore predestined for large-scale battery storage projects and grid-scale services [105]. One of the largest battery storage systems in the world has been deployed in the UAE with a total capacity of 648 MWh [108]. With more than 200 Na-S HT battery projects commissioned, the deployed storage volume is already > 4.2 GWh worldwide [102, 104].

### Cost, resources, production and supply chain

There is already an established production process for Na-S HT systems. Na and S are abundant raw materials and

**Figure 30: Radar chart of relevant dimensions Na-S HT batteries\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

the integration of the cells into modules or storage systems is fully automated. The production of ceramic components in the form of ceramic solid electrolytes has already been well researched and developed. The system-level costs of Na-S HT batteries are in the range of approximately 300–450 EUR/kWh [104, 105]. Therefore, high-volume and low-cost production could be beneficial for further deployment, as there are no major barriers to production and supply [94, 109]. Recycling Na-S HT batteries is considered relatively easy [110].

Research in the Na-S battery field currently focuses on improvements to the electrolyte and to its energy-intensive production, increasing the cells' energy density and fostering the systems' reliability [104, 109].

### Sustainability

If the Na-S HT battery is regularly cycled, the heat produced during operation is sufficient to maintain the high operating temperature [94, 109] and has to be handled by a thermal management system. However, external energy is needed to maintain the electrodes' liquid state if the system is not in use

for a longer period of time, which has an impact on its environmental friendliness, unless renewable energy is used. However, during the use phase, Na-S HT batteries perform differently (i.e., slower in discharge) than LIBs, at least in the heated HT version, and are therefore better suited to e.g., long-term renewable energy storage. Overall, the technology is considered to be environmentally-friendly, produces no emissions during operation (e.g., gases if properly sealed), has reasonable round-trip energy efficiency and can be largely recycled [104, 109].

### Advantages and Potential for Europe

The Na-S HT batteries are a mature, environmentally-friendly and cost-competitive technology for stationary storage systems and therefore interesting for renewable energy storage and the deployment of sustainable batteries in terms of raw materials discussions in Europe [104]. However, to increase system efficiency, reduce operating costs and improve safety, intermediate-temperature (IT) or RT Na-S are being discussed prominently and have been the subject of research as a further development of Na-S HT batteries.

## 2.6. Metal-Air Batteries

While primary metal-air (Me-air) batteries are already widely used (e.g., Zn-air batteries are typically used in hearing aids), secondary Me-air batteries are the subject of current research endeavors. In Me-air batteries, the energy results from a chemical reaction between metal and  $O_2$  [111], which is – in contrast to other battery types – not kept as an active material within the cell. This means that cell capacity is determined by the anode capacity, allowing for theoretically high discharge capacities.  $O_2$  is either captured from the surrounding air (open system) or fed in via a connected oxygen tank (closed system). However, both systems come with specific challenges. While capturing  $O_2$  from the surrounding air means that the air has to be compressed as well as cleaned of other components such as  $CO_2$  (carbonate formation in alkaline electrolyte) to prevent negative consequences for battery life and other characteristics, a connected  $O_2$  tank requires sufficient space [112] and additional aggregates. The water management in aqueous Me-air cells is also quite complex, especially if there is extreme humidity fluctuation in the ambient air.

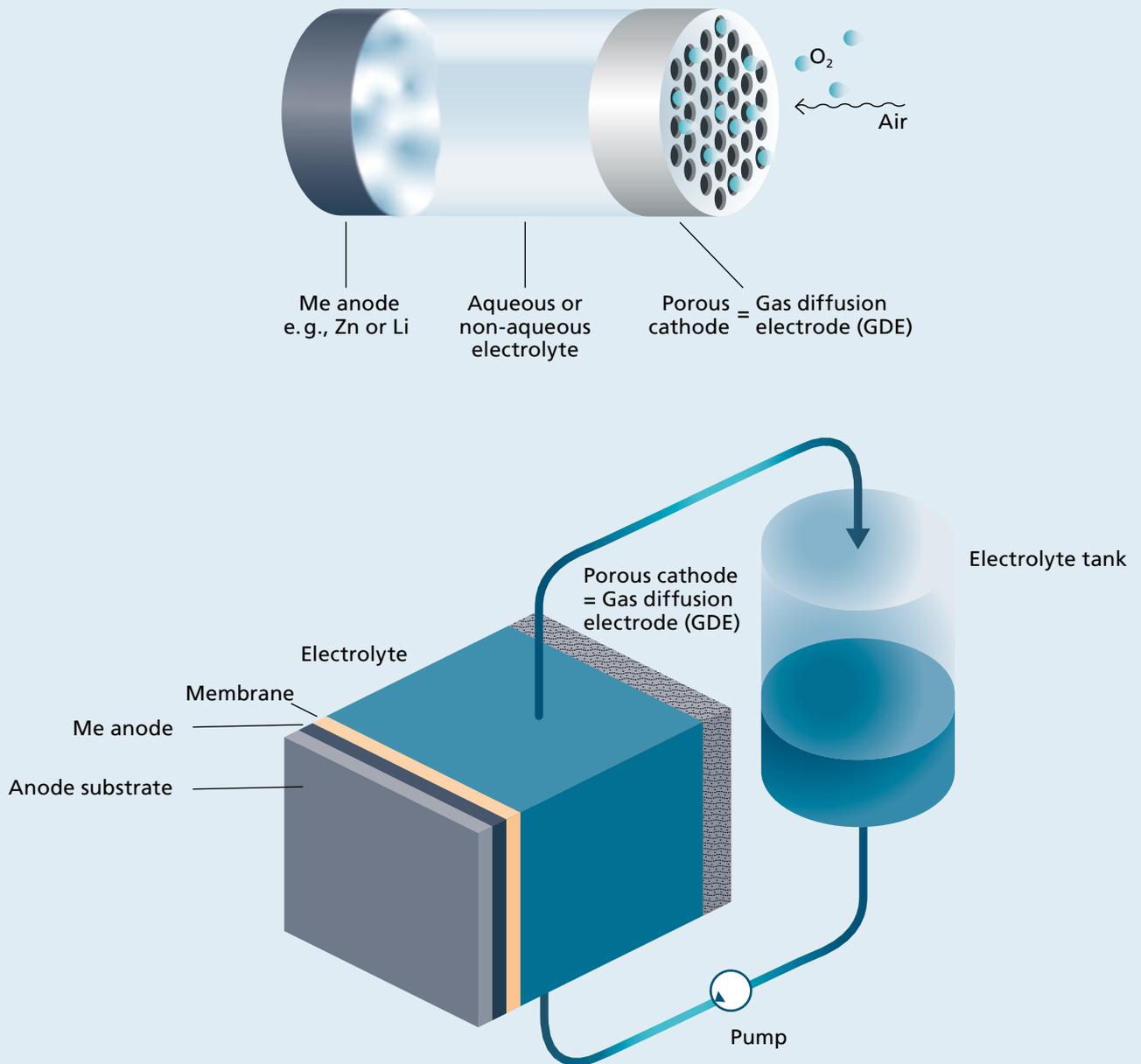
The classic structure of a rechargeable Me-air battery consists of a metal anode (e.g., Zn or Li), an electrolyte (aqueous, non-aqueous, hybrid, solid) and the gas diffusion electrode (GDE) as the positive air cathode, which enables the supply of the active  $O_2$  component. The electrochemical performance of Me-air batteries depends on the activity of oxygen reduction/evolution reactions (ORR/OER) in the GDE during discharging/charging [113, 114]. Moreover, the formation of the so-called three-phase boundary (TPB) in the GDE is essential for yielding high current densities. In organic and water-free ionic liquid (IL) electrolytes with low surface tension, however, the

formation of the TPB is an issue and only low current densities are achieved [115]. As both oxygen reactions are kinetically sluggish, the search for efficient and stable catalysts is one key challenge. Doped-carbon composite catalysts have been researched as one type of modified electrode to improve stability and bi-functionality for ORR and OER [116, 117] as well as hybrid cell designs with anolyte and catholyte [118] to stabilize the overall system.

The main advantage of Me-air batteries over LIBs is the theoretical high energy density and the potential low cost [117, 119]. Costs can be relatively low due to the batteries' high energy density, material savings and cheaper materials at the cathode side, while non-aqueous Me-air batteries are more expensive than aqueous ones due to higher electrolyte costs. Other remaining challenges are related to poor cycling capability and low energy efficiency. Nonetheless, Me-air technology is considered to be environmentally-friendly, inherently safe in aqueous designs and primarily a competing technology for stationary storage systems [114].

Besides Ca, Na, Al, Mg, Fe and K, very prominent materials for Me-air batteries are Li and Zn, which receive the most attention in R&D. As Li metal is highly reactive with water but has a very high theoretical energy density, Li-air batteries are appropriate for non-aqueous electrolyte systems. Zn-air batteries are appropriate for an aqueous electrolyte system as Zn has a number of advantages compared to other metals such as Ca, Al, Fe, Cd. [113]. In addition, R&D investigates further options such as seawater electrolyte-based Me-air batteries [120], which might be combined with offshore wind systems.

**Figure 31: Exemplary structures of Me-air batteries; Top: Open cell design; Bottom: Flow battery design**



## 2.6.1. Lithium-Air Batteries

### Technology

Li-air batteries are considered promising due to their high theoretical energy densities. While the technology has been increasingly investigated and substantial improvements have been made during the past decades, basic research is still needed (TRL 2–3) and only a few prototypes have been developed.

Most R&D efforts have been spent on non-aqueous (organic) systems because of their high theoretical energy densities [121] and the relatively simple battery design [122]. Specific energies vary depending on the  $\text{LiO}_2$  formed and are  $\sim 3,500$  Wh/kg for  $\text{Li}_2\text{O}_2$  assuming a voltage of  $\sim 3\text{V}$  [114, 123]. In prototypes, relatively high energy densities are currently only possible with low cycles (e.g., 500 Wh/kg for 10 cycles [124] and vice versa [125]). The highly reactive Li-metal anode shows persistent formation of dendrites, resulting in safety issues [126]. While aqueous and solid Li-air batteries have fewer critical issues than

non-aqueous ones [121], their specific energies are also lower ( $\sim 2,170$  Wh/kg), making them less attractive.

The main technical challenges are: to increase the cells' practical capacity while keeping/increasing cycling stability, to improve energy efficiency, to solve safety issues [122, 123, 126], to purify and compress ambient air to prevent parasitic side-reactions and allow efficient  $\text{O}_2$  transfer. Residual moisture and nitrogen from the air as well as the formation of the TPB in the GDE are additional major problems, which need to be overcome. R&D addresses these challenges by searching for suitable materials, e.g., electrolytes, and by developing application-oriented cell concepts.

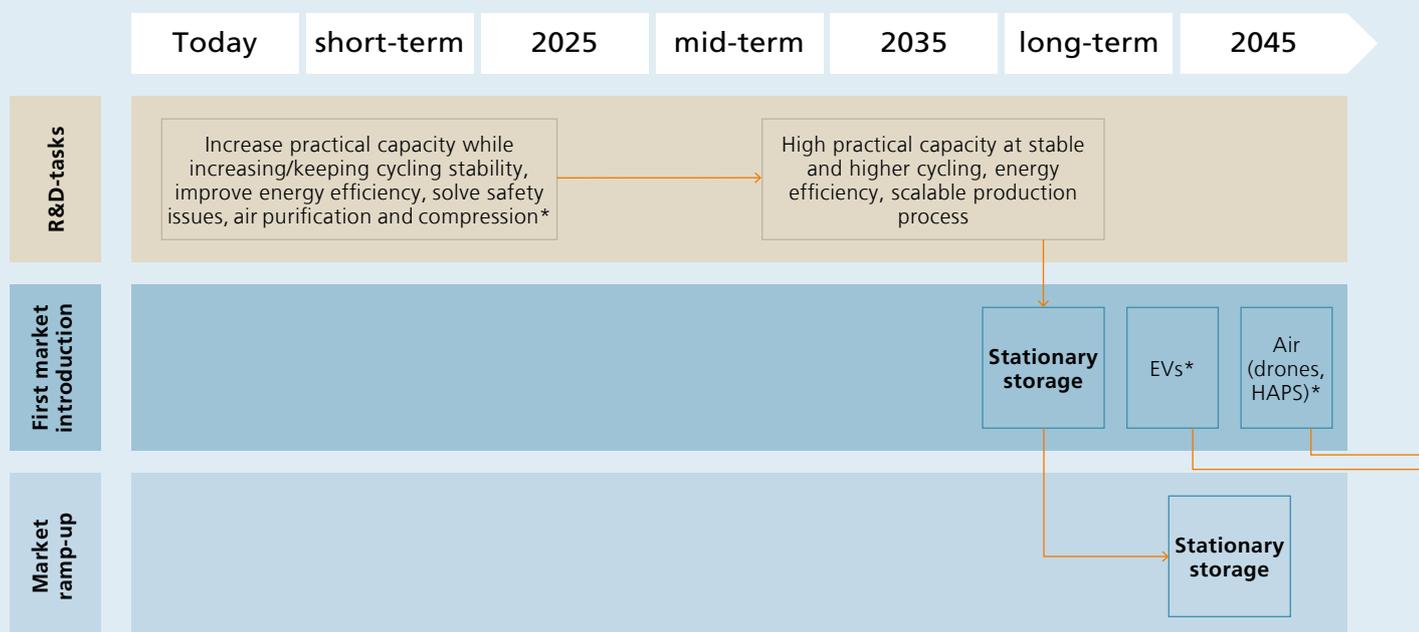
### Applications and market relevance

It is most likely that electrochemically rechargeable Li-air batteries will be used in stationary storage applications [114]. Potential market shares are estimated at around 5% for these

**Table 12: Estimated KPIs for Li-air batteries today and in the long-term future**

KPI	Value (today)	Value (longterm)
<b>Cell-level KPI</b>		Theoretical: $\text{Li}_2\text{O}_2$ : $\sim 3,500$ Wh/Kg
<b>Vol. energy density</b>	$\leq 500$ Wh/kg	Practical: 1,230 Wh/kg [47]
<b>Power density</b>	< LIB	Practical: 880 Wh/l [47]
<b>Power per electrode area</b>	< LIB	< LIB
<b>Cycle life</b>	1–550 cycles	< LIB
<b>Calendar life</b>	unknown	unknown
<b>C-Rate</b>	unknown	unknown
<b>Energy efficiency</b>	40/60–80% due to high hysteresis [47], [121]	unknown
<b>Safety aspects</b>	Fire/explosions: Dendrite formation due to highly reactive Li-metal anode	

Figure 32: R&amp;D and commercialization roadmap for Li-air batteries



\* R&D mainly focuses on the search for new materials.

\*\* EVs and further applications are considered very unlikely.

applications. Further applications might be EVs [123, 125] or even drones or high-altitude pseudo-satellites (HAPS). However, all of these come with further challenges, and they are, therefore, subject to debate. Commercial applications are not expected within the next 10–15 years.

### Cost, resources, production and supply chain

Li-air battery cell costs are expected to be lower than those of LIBs due to material savings and the use of less expensive materials (typically carbon modifications for the GDE vs. graphite). However, they still require Li, which is one of the most expensive components. Because of the low TRL, cost estimates for Li-air batteries are very uncertain; potential pack prices are estimated between 70 and 200 EUR/kWh [112].

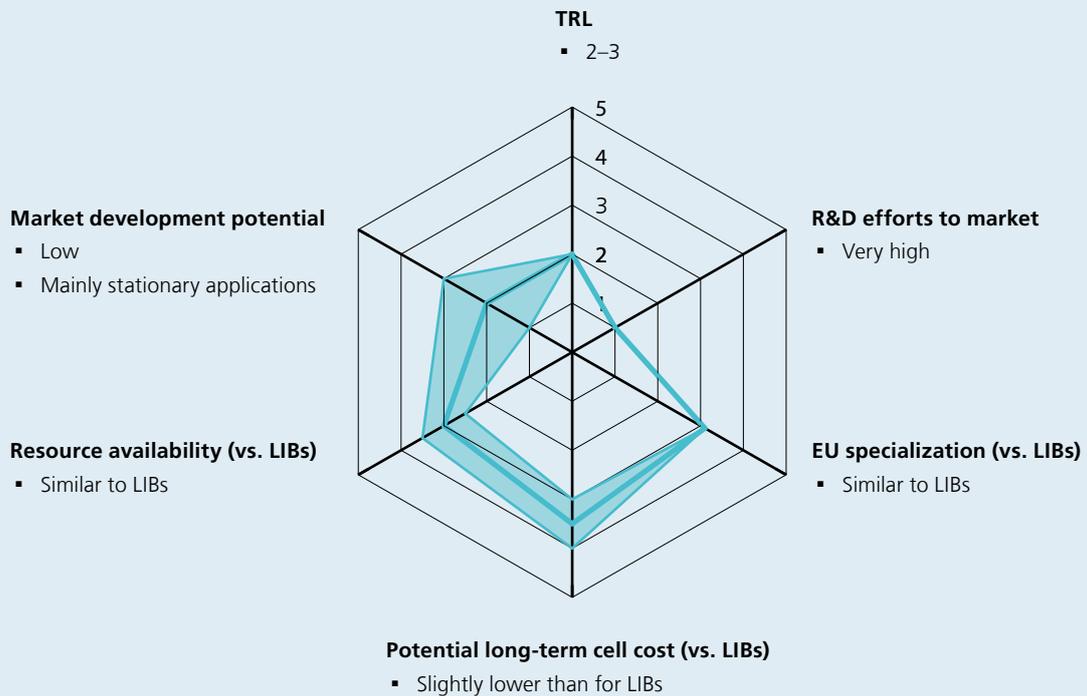
In terms of resources, Li-air batteries are independent from materials such as Co and Ni and use less material than LIBs, especially at the cathode side. Current research efforts aim to extract Li from seawater, which can also be beneficial for

recycling, and to identify national Li sources. Due to similarities in materials, existing LIB value chains might be (partly) used for Li-air batteries.

The production process for Li-air batteries has not been established as the cell design has not been finalized. While the production of the GDE at the cathode side might require new manufacturing equipment, which could be based on established production processes for primary batteries or fuel cells, changes in material and structure at the anode require new process steps – in addition to modifications in stacking, contacting, and enclosing [47].

### Sustainability

As for LIBs, recycling can play a crucial role to reduce resource dependencies for Li and might result in a reduction of 10–30% of the environmental impact of Li-air batteries [127]. Once established for LIBs, recycling processes might also serve as a basis for Li-air battery recycling.

**Figure 33: Radar chart of relevant dimensions of Li-air batteries\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

For non-aqueous Li-air cells, the expected GHG emissions are on average around 56 kgCO<sub>2,eq</sub>/kWh (ReCiPe 2016 method) [70]. The biggest contributors are the Li-foil and the electrolyte [126, 128].

### Advantages and Potential for Europe

While their extremely high theoretical energy densities and potentially low cost make Li-air batteries seem a promising alternative, fundamental issues have to be resolved first. Due to their dependence on Li, the opportunities are limited for a substantial reduction of raw material dependencies, the development of new value chains, and, hence, the establishment of European technology sovereignty. However, basic R&D can still help to develop processes that might be beneficial for other technologies as well (e.g., metal anode production).

## 2.6.2. Zinc-Air Batteries

### Technology

Although primary Zinc-air (Zn-air) batteries have been commercially available for several years, there is still a lack of rechargeable Zn-air batteries with good overall performance. The zinc oxide occurring after the ORR cannot be recovered and therefore inhibits the capacity of rechargeable batteries immensely by absorbing the anode during discharge [129]. One simple way to make the battery rechargeable is therefore to mechanically replace the used Zn anode or to replace the electrolyte within a flow system. More complex methods are necessary to recharge the batteries electrochemically.

Work on rechargeable Zn-air batteries and concepts has been ongoing for several years, e.g., on electrochemically rechargeable closed cell systems, flow batteries (anolyte or electrolyte cycling) or mechanically exchangeable materials (battery active material swapping) [130]. Despite many announcements and a few prototype systems, rechargeable batteries have not yet

been commercialized. Basic technology research is still needed, as the TRL of 2–4 reveals, in terms of rapid capacity fade and overall system stability.

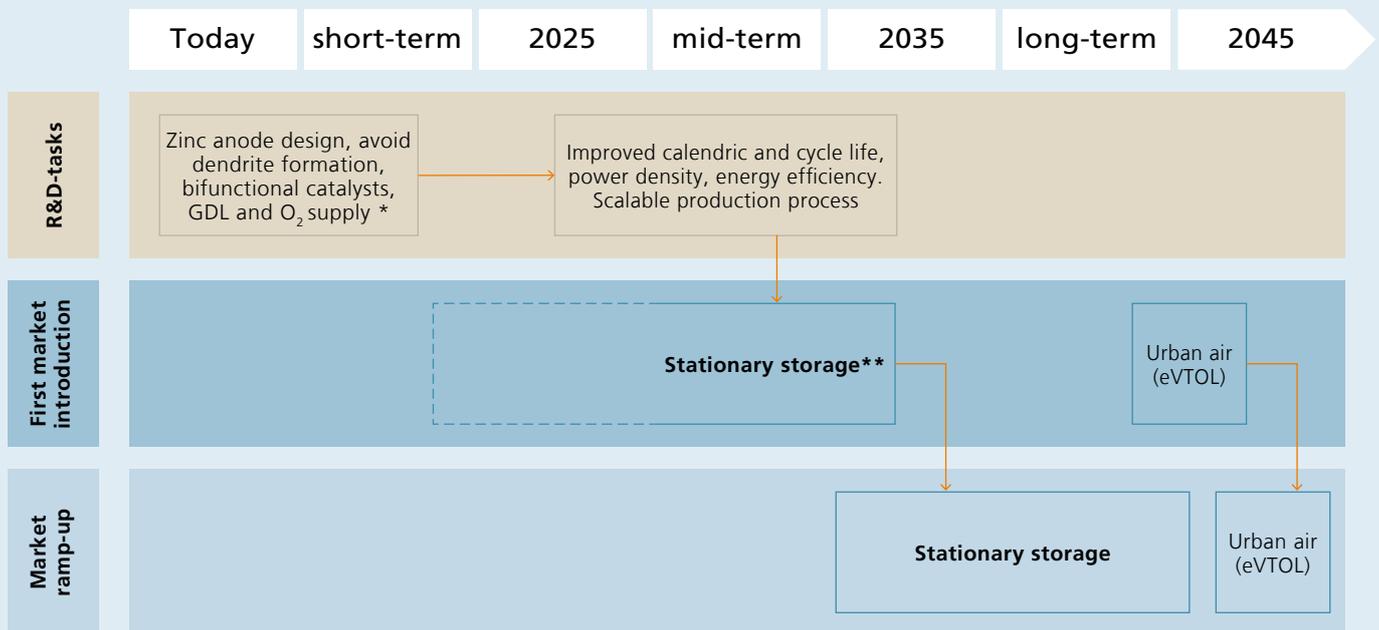
Rechargeable Zn-air batteries have a high theoretical energy density of 1,353 Wh/kg (excluding O<sub>2</sub>) or 1,086 Wh/kg (including O<sub>2</sub>) but on the downside lower power and round-trip efficiency and a poor lifetime (still with low depth of discharge, DOD) compared to LIBs [131–133]. As cycle lifetime can be optimized to more than 9,000 cycles by cathode replacements in Zn-air flow batteries [134], the lifetime in current R&D prototypes is in a range of 200 up to 320 cycles, i.e., for a ZnO<sub>2</sub> chemistry [135]. Some reports indicate more optimistic performance indicators for certain cell designs [136]. The open-circuit voltage of 1.65V highlights the rather weak power capability [114].

Major challenges are the dendrite-free redeposition of Zn and the sluggish kinetics of ORR and OER reactions. Future R&D

**Table 13: Estimated KPIs for Zn-air batteries today and in the long-term future**

KPI	Value (today)	Value (longterm)
Cell-level KPI	150–200 Wh/kg [139] 300 Wh/kg [136]	Theoretical: 1,086 Wh/kg [133] Practical: 100–300 Wh/kg [140]
Vol. energy density	100–200 Wh/l [139]	
Power density	low	< LIB
Power per electrode area	10–435 mW/cm <sup>2</sup> depending on Zn-electrode type used [141]	< LIB
Cycle life	Zn-air: up to few 100 [136] Zn-air: low	Zn-air: 100–2000 Zn-air flow: 10,000–14,000 Zn-air: low
Calendar life	Zn-air flow: 25	Zn-air flow: 25
C-Rate (C)	unknown	unknown
Energy efficiency	Zn-air: 55–65 % [133] Zn-air flow: 59–64 % [134]	Zn-air: < 69 % Zn-air flow: < 69 %
Safety aspects	high safety and environmental friendliness; non-flammable aqueous electrolyte	high safety and environmental friendliness; non-flammable aqueous electrolyte

Figure 34: R&amp;D and commercialization roadmap for Zn-air batteries



\* R&D tasks focusing electrochemically rechargeable cell design.

\*\* There have been repeated announcements of zinc-air flow batteries over the years, but market introduction has not yet taken off.

efforts must address these, e.g., special alloy properties and also additives for the Zn anode design, high Zn utilization, the improvement of bi-functional catalysts for ORR/OER [129, 137] and properly designed membranes to minimize dendrite formation [135, 138].

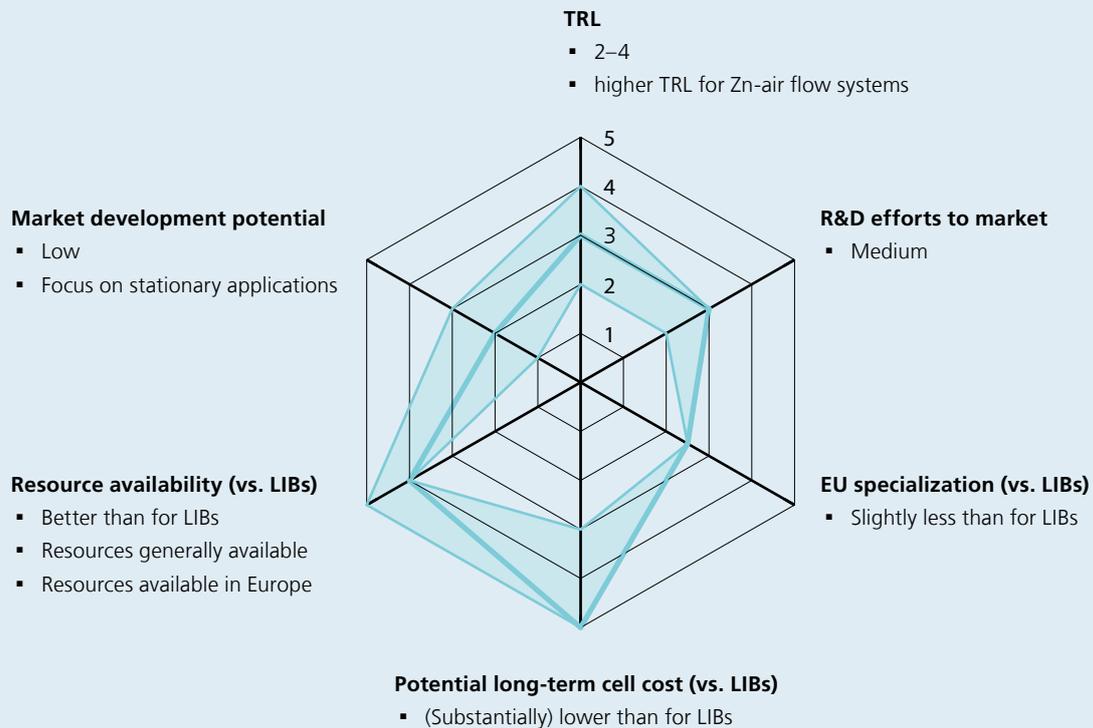
### Applications and market relevance

Due to their theoretically high energy density at low cost, the technology is primarily discussed for stationary storage [114, 134, 138]. The low power density makes these systems appear attractive for large-scale buffer storage, even if the service life still poses challenges. Zn-air flow batteries appear to be most promising for storage systems, as corrosion is still a major problem for battery electric vehicles with mechanically replaceable systems. Due to these problems, Zn-air batteries are not expected to play a major role in the automotive sector in the medium-term future, although first mechanically rechargeable prototypes show that they are basically suitable and the technology maturity of these Zn-air systems is higher than that of Li-air batteries. In the long term, Zn-air batteries might be interesting for urban air mobility applications.

### Cost, resources, production and supply chain

Commodity prices for Zn are substantially lower than those for lithium carbonate, with 1.5 to 4 USD/kg vs. 12 to > 70 USD/kg between 2017 and 2022. As Zn is the only active material, the chemical cost of storage is approximately 6 USD<sub>2022</sub>/kWh, which is seven times lower than that for Li-air systems [114]. Manufacturing costs for Zn-air batteries are not yet known as the technology still has to improve its TRL to mass production, but estimations below 150–100 USD<sub>2022</sub>/kWh [114, 142] can be made based on energy storage efforts in the U.S. The costs might decrease to below 10 USD<sub>2022</sub>/kWh in the future [133].

Rechargeable Zn-air batteries are considered easy to manufacture, but still require optimized methods, e.g., for large-scale and cost-effective electrocatalyst production [133]. The raw material Zn is already present in a European and global circular supply chain – the end-of-life recycling input is already 45 % globally. In 2020, the International Zinc Association (IZA) launched the Zinc Battery Initiative (ZBI) to facilitate cooperation between Zn producers and Zn battery manufacturers [143].

**Figure 35: Radar chart of relevant dimensions of Zn-air batteries\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

### Sustainability

Existing recycling routes for Zn could be adopted and further used for this technology, which could exploit synergy effects and retain Zn in a European value chain. Nevertheless, it can be generally assumed that it is economically uninteresting for recyclers because of the low value of the raw materials used in Zn-air batteries [144]. The aqueous electrolyte (commonly a KOH solution) is non-toxic and non-flammable, and the required O<sub>2</sub> is conducted from the ambient air [145]. In addition to these benefits, the expected GHG emissions for alkaline Zn-air battery types are in the range of 22.1–95.2 kgCO<sub>2,eq</sub>/kWh [70] according to the ReCiPe 2016 method, which is significantly lower than today's LIBs.

### Advantages and Potential for Europe

Zn-air batteries do not require any critical raw materials [145]. The main advantages of Zn-air systems are the large quantities of Zn available (in Europe and globally), their good recyclability and existing circular value chains, low cost, as well as good safety and environmental friendliness [146]. This battery

technology is the most technologically mature metal-air battery (primary and secondary) [114]. Europe already has a circular Zn industry and manufacturing capacity for primary Zn-air batteries. This offers the opportunity to develop rechargeable Zn-air batteries in parallel and across the value chain, which would reduce global raw materials and manufacturing dependencies and help to establish European technology sovereignty. However, challenges exist at all levels, from material to system design, which is why a broad market introduction of Zn-air batteries in Europe is not likely until after 2030.

## 2.7. Redox Flow Batteries

### Fundamentals

Redox flow batteries (RFBs) are a different type of battery compared to the other battery technologies discussed in this report. RFBs consist of two electrolyte tanks in which redox couples are stored, a battery cell for energy conversion that contains the electrodes and separating membrane, and pumps for circulating the electrolytes through the battery cell [147]. The electrical energy is stored in the electrolytes that contain the redox couples, a solvent (typically water) and additives that, e.g., enhance the solubility of the redox-active species.

In RFBs, energy and power can be scaled separately by scaling the electrolytes tanks (energy) and the electrode area in the battery cell (power). They can therefore be adjusted to the specific system requirements of the corresponding application. High cycle stability as well as good recyclable electrolyte materials are advantages of this technology. [148]

Different chemical redox systems exist for redox flow batteries, such as vanadium/vanadium, zinc/bromine (Zn/Br), iron/iron (Fe/Fe), iron/air, or organic electroactive molecules [149–151]. The most mature electrochemical system is the vanadium redox flow chemistry. Due to high costs of vanadium and limited supply sources, there is much interest in alternative chemistries, which are intensively researched.

### Technology

Vanadium redox flow batteries (V-RFBs) are currently the most mature representative of RFBs and are already commercially available (TRL 9). Due to the different setup and application scenario, the KPIs used for LIBs do not necessarily play a major role for RFBs. Table 13 summarizes the relevant KPIs for vanadium-based RFBs (and Fe-air RFBs), although it has to be emphasized again that energy density and power density are not the most relevant for RFBs and can be scaled separately. Energy densities refer to the energy density in the liquid electrolytes.

**Table 14: Estimated KPIs of vanadium-based RFBs (if not indicated otherwise), today and in the long-term future**

KPI	Value (today)	Value (long term)
<b>Cell-level KPI (electrolyte only)</b>	22–30 Wh/kg (20 Wh/kg for Fe-air RFB)	> 35 Wh/kg (> 170 Wh/kg for Fe-air RFB)
<b>Vol. energy density (electrolyte only)</b>	30–40 Wh/l (28 Wh/l for Fe-air RFB)	> 50 Wh/l (> 290 Wh/l for Fe-air RFB)
<b>Power density</b>	Scalable	Scalable
<b>Power per electrode area</b>	100–300 mW/cm <sup>2</sup>	> 400 mW/cm <sup>2</sup>
<b>Cycle life</b>	> 10,000 cycles	(1,000 cycles for Fe-air RFB)
<b>Calendar life</b>	20 years	20 years (15 years for Fe-air RFB)
<b>C-Rate</b>	scalable	scalable
<b>Efficiency</b>	typically between 60% and 90% [147, 148, 152]	
<b>safety aspects</b>	very safe (no flammable components, no threat of explosion, no H <sub>2</sub> formation); possible H <sub>2</sub> formation in non-vanadium RFB	very safe (no flammable components, no threat of explosion, no H <sub>2</sub> formation) ; possible H <sub>2</sub> formation in non-vanadium RFB

Figure 36: Typical structure of a vanadium-based RFB

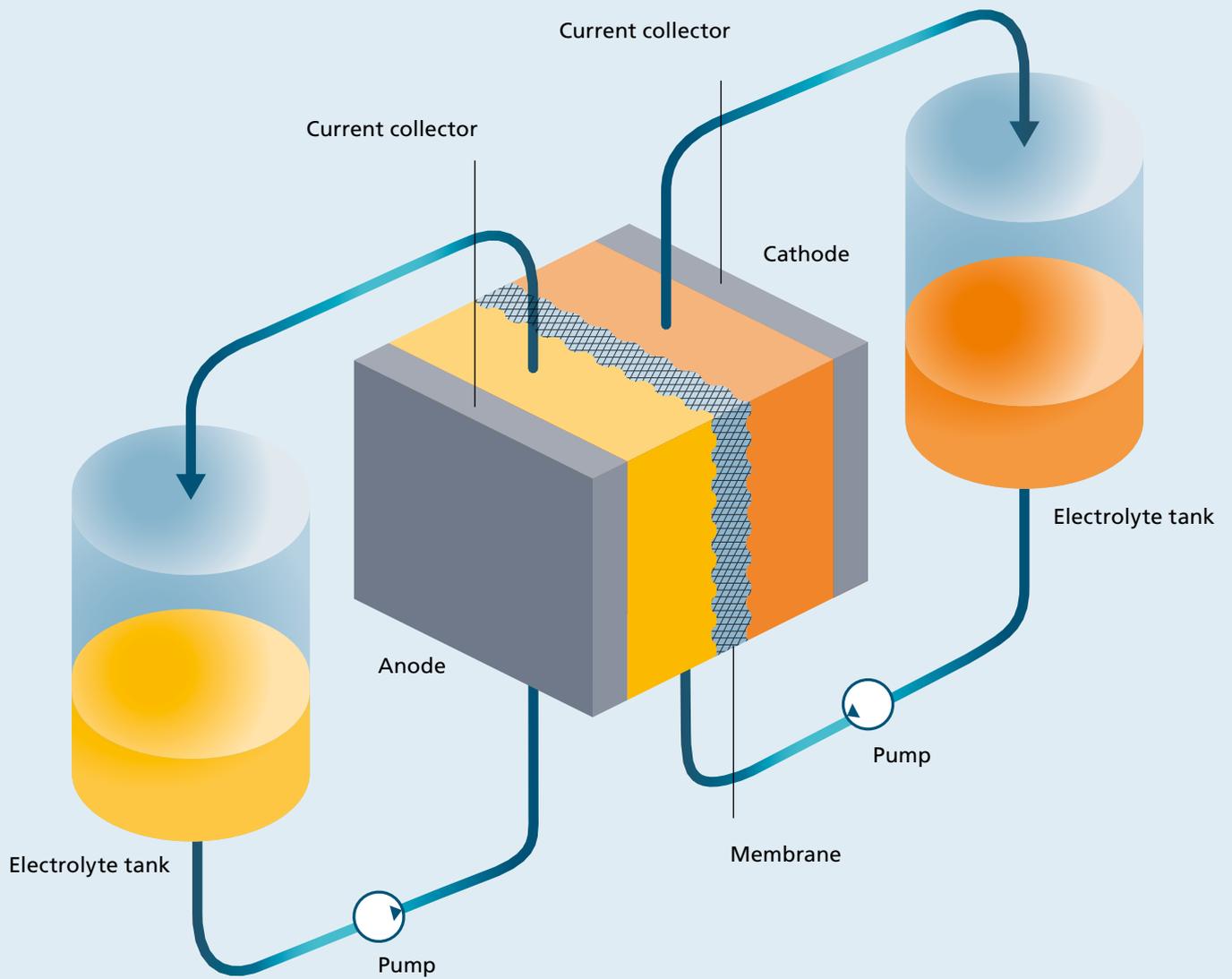
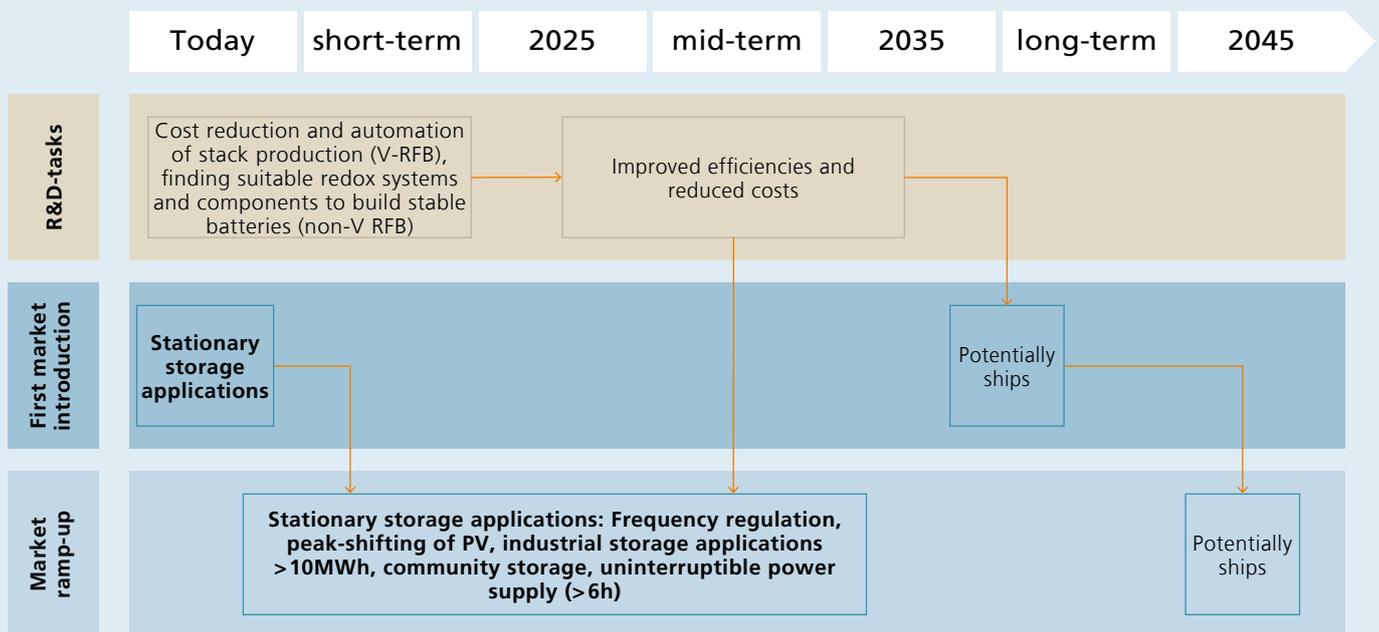


Figure 37: R&amp;D and commercialization roadmap for RFBs



Compared to LIBs, they are low, but this is typically not critical for stationary applications. Depending on the application and the duration of storage, the power to energy ratio can be adjusted. RFB systems with supply periods between 5 and 10 hours [152] are typically used for buffering renewable energies (wind and solar), i.e., they can be fully charged or discharged within this time.

RFB systems with supply periods between 5 and 10 hours [152], i.e., they can be fully charged or discharged within this time, are typically used for buffering renewable energies (wind and solar).

One bottleneck of RFBs can be the limited operating temperature range of typically 5–40°C for vanadium-based RFBs. Additives and new developments in redox couple chemistry could increase the temperature range. Another bottleneck is the lower round trip efficiency compared to LIBs [153]. Further developments in the battery cell (electrode materials, flow field designs, etc.) could improve efficiency.

### Applications and market relevance

Currently, the only application for redox flow batteries is ESS. Systems can be designed in the range of a few kWh (home storage) up to several hundred MWh (utility storage). The

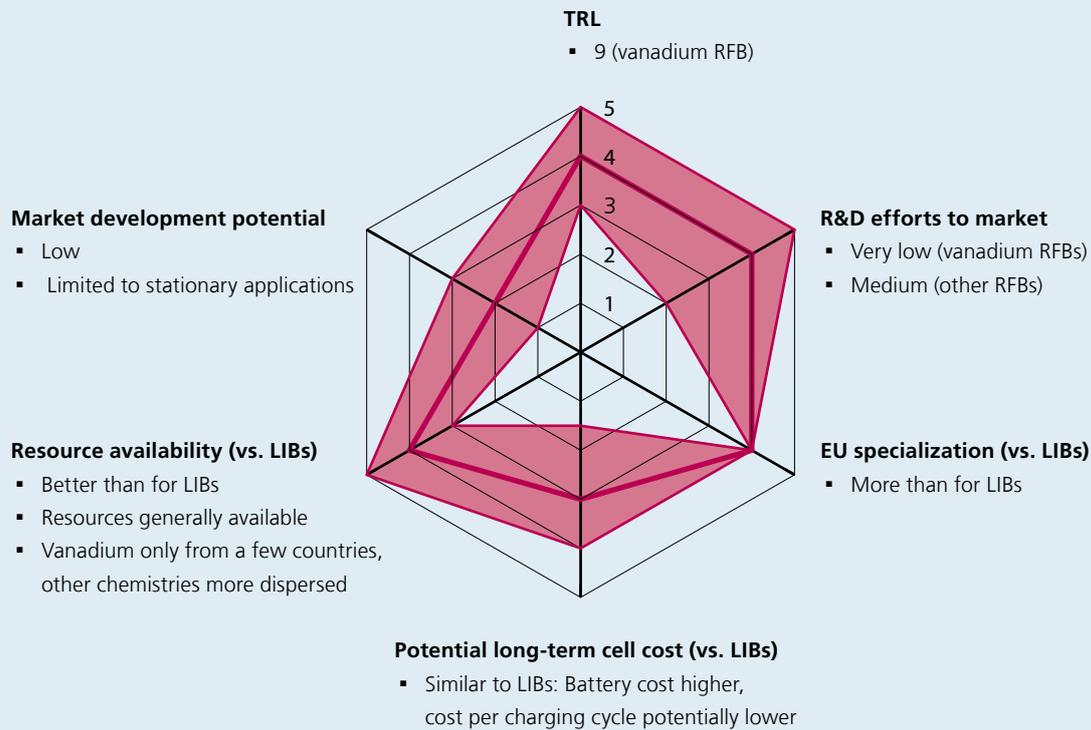
corresponding power can be scaled as needed. First large-scale projects have been successfully installed [154, 155]. The future market relevance of RFBs for ESS applications will depend mainly on the price per stored kWh. Advances in cheaper and more abundant RFB chemistries – beyond vanadium chemistry – might be decisive for large-scale utilization of this technology.

Beyond the stationary market, there are potential applications on ships in the medium- to long-term future.

### Cost, resources, production and supply chain

The materials needed for RFBs depend on the chemistry used. For V-RFBs, the main cost driver is the vanadium pentoxide with costs of 15–21 EUR/kg [156]. Vanadium is not a rare element, but it is not mined in Europe. Therefore, vanadium import will create dependencies on other countries such as China, Russia, South Africa and Brazil [157]. For this reason, other RFB chemistries such as Zn/Br, Fe/Fe and organics are being researched, as material availabilities and costs could be (significantly) lower and less critical.

A limiting factor for RFB production is the cell stack production, which is currently mostly performed manually. Automated production processes and scale-ups are necessary to reduce costs.

**Figure 38: Radar chart of relevant dimensions of RFBs\***

\* A more detailed description of the dimensions and levels can be found in the Appendix.

System-level costs of vanadium V-RFBs are currently approximately 430 EUR/kWh, 80 % of which are material costs. In the long-term future, costs of 240 EUR /kWh could be achieved by using automated production processes. For other chemistries, significantly lower costs are hoped for, e.g., long-term costs of < 25 EUR /kWh are anticipated for Fe-air RFB.

### Sustainability

How sustainable RFBs are depends strongly on the production of the batteries and component materials and thus differs for different RFB chemistries. Due to the energy-intensive production of  $V_2O_5$  [153], vanadium-based RFBs have the biggest ecological footprint (global warming potential GWP of 180 kg  $CO_{2,eq}$ /kWh compared to zinc/bromine (GWP of 160 kg  $CO_{2,eq}$ /kWh) and iron RFBs (GWP of 75 kg  $CO_{2,eq}$ /kWh)) [158].

Recycling the chemical compounds in the electrolytes of RFBs is possible [153], although the exact processes need to be developed when the first larger RFBs reach their end-of-life. Recycling the battery cell or stack is more complicated. However, as no rare or critical materials are used here, it is less relevant compared to some electrolytes. Tanks and tubes can be recycled with standard polymer and metal recycling methods.

### Advantages and Potential for Europe

RFBs allow for cost-efficient stationary energy storage in certain application scenarios, i.e., for medium to longer-term energy storage (hours to days). Further developments in non-vanadium chemistries could improve sustainability, cost and material availability aspects and make RFBs an important battery technology for stationary storage.

As the market is still small and not dominated by large companies, RFB production in Europe could become relevant and important for Europe's energy security and independence, especially as substantial industrial activities already exist in Europe (mainly in Germany).

## 3. Roadmap & Comparison

In the past, LIBs often represented a general solution for applications due to their advantageous KPIs. However, the focus is now increasingly on alternative battery systems, driven by questions of raw material availability, costs or sustainability.

While some battery technologies such as sodium-ion batteries (SIBs), sodium-sulfur high temperature (Na-S HT) and redox flow batteries (RFBs) are already available on the market, albeit not to a substantial extent in Europe, the TRL level of other technologies, e.g., lithium-air (Li-air) batteries, has not progressed much beyond basic research.

The TRL level is also reflected in the R&D efforts required. However, if the research challenges can be overcome, the costs of zinc-ion batteries (ZIBs), zinc-air (Zn-air) or sodium-sulfur room temperature (Na-S RT) batteries can be substantially reduced and may be only half those of LIBs. Likewise, aluminum-ion batteries (AIBs), magnesium-ion batteries (MIBs) and possibly lithium-sulfur (Li-S) batteries could also achieve considerable cost advantages over LIBs.

In addition to cost advantages, the resource availability of some battery technologies is an important point. This applies in particular to the Na-based battery technologies (SIBs, Na-S RT and Na-S HT batteries) and MIBs, for which there are many potential sources both in Europe and globally. Hence, compared to LIBs, the raw materials for these technologies are in very good supply and a comparatively low risk of raw material dependence can be expected. The resource availability for most other battery technologies is also relatively good.

However, while the respective battery technologies have certain advantages, they are not suitable for all applications due to their specific properties and KPIs. SIBs, AIBs and, to a lesser extent, Li-S batteries are suitable for many applications and can also play a dominant role. Many other battery technologies may be limited to one application and under certain circumstances can also play an important role there, or are used in other applications as a supplement.

### Key Performance Indicators

Figure 39 shows the key performance indicators (KPIs) of the alternative battery technologies considered in this roadmap. KPIs are used to determine the suitability of a particular battery technology for a specific application, usually based on its technical KPIs and the requirements of the corresponding application. For most applications, gravimetric or volumetric energy density or cycle life is a decisive criterion. However, a direct comparison of the KPIs with those of LIBs only makes sense with regard to a specific application. For example, the gravimetric energy density of RFBs at 140–160Wh/kg is substantially lower than that of LIBs. However, RFBs function according to a different principle and are primarily intended for stationary applications, for which weight or volume restrictions are less relevant than for mobile applications. Hence, it makes little sense to compare the KPIs of existing battery technologies without considering the targeted applications.

Today, the energy density of LIBs, which we used here as a benchmark, is around 200–300 Wh/kg (gravimetric) or 600–750 Wh/l (volumetric). It is expected that the energy density of LIBs will increase by a further 60–80 % by around 2035 through continuous improvements and that cell costs could be halved compared to today.

More and more battery technologies might find their way from research on to the market, bringing with them very specific advantages in terms of their KPIs. However, many of the battery technologies considered are still under development and partly still being tested on a laboratory scale. For these technologies, assessing the KPIs of a marketable product is only possible to a limited extent and the corresponding uncertainties must be taken into account. Furthermore, successful market entry and subsequent market differentiation are by no means predetermined for all battery technologies and there are still demanding research tasks to be mastered, as for example in the case of metal-air (Me-air) batteries.

Some metal-ion (Me-ion) batteries have already been introduced to the market and demonstrate a high TRL level. Nevertheless, there is still a need for further research in this area, as the KPIs differ depending on the materials used and there is often still a high potential for optimization. While SIBs are very similar to LIBs in terms of their structure and functional principles, they are less resource-dependent, more sustainable and less costly. ZIBs have a much lower energy density, but much better ecological properties at the same time due to the aqueous electrolyte. MIBs have the potential for high gravimetric and volumetric energy density, which could exceed that of LIBs. AIBs are a special case in the range of Me-ion batteries under consideration: They have a higher power density than LIBs, a higher energy density than capacitors as well as a high cycle life and C-rate. However, the energy density of AIBs is significantly lower than that of most other metal-ion battery technologies.

Some of the metal-sulfur (Me-S) battery technologies considered seem promising with regard to KPIs. Lithium-sulfur (Li-S) batteries offer the potential for a high gravimetric energy density compared to LIBs, while the volumetric energy density and cycle stability are likely to be lower. The resource availability of Li-S batteries can be considered good and there is the potential to realize low costs per kWh due to the high energy density and cheap sulfur. However, before these low costs are achieved, the cycle stability and power density have to be further improved.

Another battery technology from the field of Me-S batteries are Na-S HT batteries. These are rudimentarily established on the market – but not to a substantial extent in Europe. They achieve a slightly lower gravimetric energy density than LIBs, although LIBs harbor more potential for future improvements. In contrast, Na-S HT batteries have a lower CO<sub>2</sub> footprint when it comes to materials. Nevertheless, their system efficiency and the comparatively high costs are challenges. Na-S RT batteries offer noticeably more advantages in this respect. In the long term, they could also achieve a similar gravimetric energy density to LIBs.

Metal-air (Me-air) batteries, in particular Li-air batteries, have a low TRL and are therefore still far from market introduction. In theory, Li-air batteries could have an extremely high gravimetric energy density at slightly lower costs than LIBs. To achieve this, however, the problem of cycle stability must first be solved. Zinc-air (Zn-air) batteries are more developed with a higher TRL and could also achieve a relatively high energy density (comparable to LIBs). However, while their power density is relatively low, Zn-air batteries offer potentially lower costs and a low CO<sub>2</sub> footprint.

Finally, RFBs are already established on the market, but still offer potential for improvement and hence further deployment, for example, through material substitution (e.g., of vanadium), to further reduce costs and their CO<sub>2</sub> footprint.

Due to the different KPIs of the alternative batteries considered, they can be suitable for specific applications.

Figure 39: Alternative battery technology roadmap – KPIs and challenges

		Today & Short term	2025
	<b>LIB</b>	200–300 Wh/kg, 600–750 Wh/l 90–175 €/kWh	
<b>Me-ion</b>	<b>SIB</b>	140–160 Wh/kg, 250–300 Wh/l 80–120 €/kWh	
	<b>SIB–Salt</b>	< 150 Wh/kg, 10–25 Wh/l 700–1000 €/kWh*	Incre
	<b>MIB</b>	50–150 Wh/kg, 150–300 Wh/l	
	<b>ZIB</b>	30–60 Wh/kg, 40–100 Wh/l	
	<b>AIB</b>	30–35 Wh/kg, 35–50 Wh/l, but 9,000 W/kg and >20,000 cycles	
<b>Me-S</b>	<b>Li-S</b>	> 300 Wh/kg, 300–450 Wh/l	
	<b>Na-S RT</b>	> 300 Wh/kg	Multiple
	<b>Na-S HT</b>	180–268 Wh/kg, 300–414 Wh/l, long calendar and cycle lives 300–450€/kWh*	
<b>Me-air</b>	<b>Li-air</b>	<= 500 Wh/kg, but with a very low cycling stability	Safet
	<b>Zn-air</b>	100–200 Wh/kg, only flow design with pot. high cycling stability 100–150 €/kWh	No sta
	<b>V-RFB</b>	22–30 Wh/kg, > 10 000 cycles, 20 years calendar life	Improved op

\* Cost on system level

Medium-/long term	2035	Vision
Continuous improvement	320–360 Wh/kg, 800–960 Wh/l 45–90 €/kWh	
Optimizing material combinations	> 200 Wh/kg, > 400 Wh/l < 40 €/kWh	
Increasing operating voltage and reducing costs	< 200 €/kWh*	
Stable cathode-electrolyte combination	> 300 Wh/kg, > 400 Wh/l < 40 €/kWh	
Stability of electrodes and electrolyte	50–120 Wh/kg, 80–200 Wh/l	
Highly corrosive electrolyte	45–50 Wh/kg, 45–80 Wh/l, but > 10,000 W/kg and > 50,000 cycles; 10–20 % cost saving compared to LIBs	
Cycling stability and power density	550 Wh/kg, 700 Wh/l 50 €/kWh	
Challenges especially on cathode and anode side	> 350 Wh/kg	
Cost reduction and safety improvements	220–300 Wh/kg, 320–440 Wh/l, long calendar and cycle lives < 300 €/kWh*	
Energy efficiency, unhealthy side reactions	theoretical: 3500 Wh/kg practical: 1230 Wh/kg	
Stable planar cell design, low power performance	200–300 Wh/kg, 2000–14000 cycles 10–100 €/kWh	
Operational temperature and automated cell stacking	> 35 Wh/kg, > 10 000 cycles, 20 years calendar life	

## Applications

The wide range of advantages and disadvantages of the respective battery technologies makes them either only suitable for individual niche applications or able to be used across several fields of application. Figure 40 shows when and in which applications the alternative technologies considered are likely to enter the market and be deployed.

For *mobile* applications, the gravimetric or volumetric energy density is of particular importance because of limited available space or payload. Currently, none of the technologies considered is used in a mobile application to a significant extent. SIBs are likely to be the first. Depending on the cathode material, SIBs can offer different advantages in terms of energy density, cycle life or resource availability/cost, whereby each combination also comes with corresponding disadvantages. Nevertheless, they are suitable for a wide range of applications. They can be used in combination with lithium nickel manganese cobalt oxide (NMC) cells to benefit from their advantages at low temperatures, in terms of safety when used as a supplement or as a hybrid battery in cars. In the near future, SIBs will also be increasingly used in 2–3-wheeled vehicles and small cars, where they will compete with lithium iron phosphate (LFP) cells. When and whether SIBs will also be considered for larger car segments or heavy vehicles is not yet clear. In these size classes, energy density plays a particularly important role and in the long term, MIBs could become significant here. Li-S batteries have the potential to do so too, although the volumetric energy density would probably limit their use to vehicles with a substantial installation space (such as buses or trucks). On an even longer time scale, if the research challenges are solved, Li-air batteries with their exceptionally high energy density could be another interesting option in the future. This characteristic can also qualify Li-air batteries for the use in drones. However, it is questionable whether Li-air batteries can be used in mobile applications. Li-S batteries are expected to already be strongly represented when they enter the market by the middle of the coming decade. Drones are presumably more of an intermediate step for Li-S batteries. In the immediate

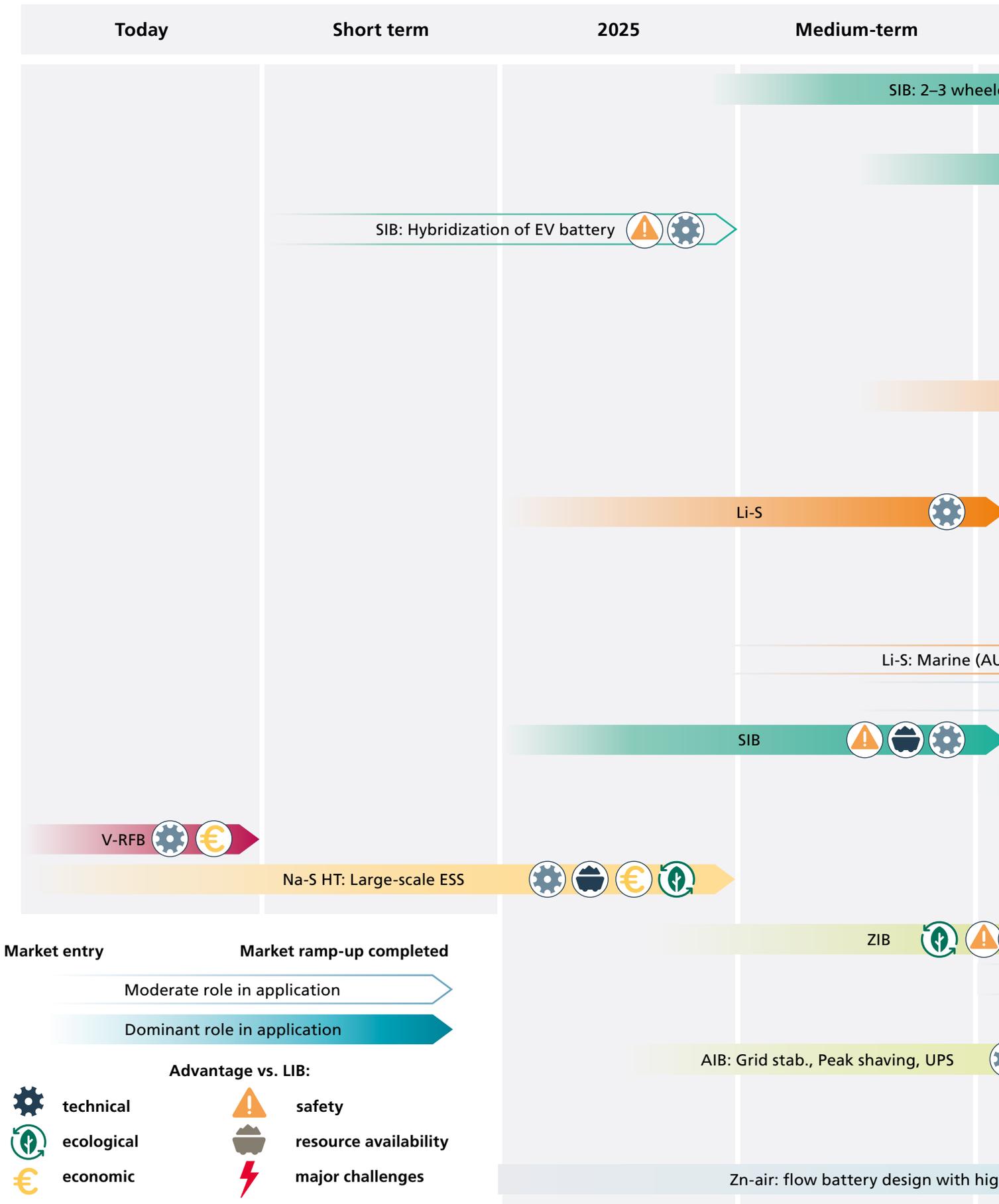
future, Li-S batteries are likely to be used in high altitude long endurance (HALE) aircrafts and high altitude pseudo-satellites (HAPS). Once they are qualified for and used in drones, they could also be a promising option for electric vertical take-off and landing (eVTOL). There, they might compete with Zn-air batteries, among others, which could have weaker characteristics in terms of KPIs, such as energy density, but advantages in terms of CO<sub>2</sub> footprint and possibly costs.

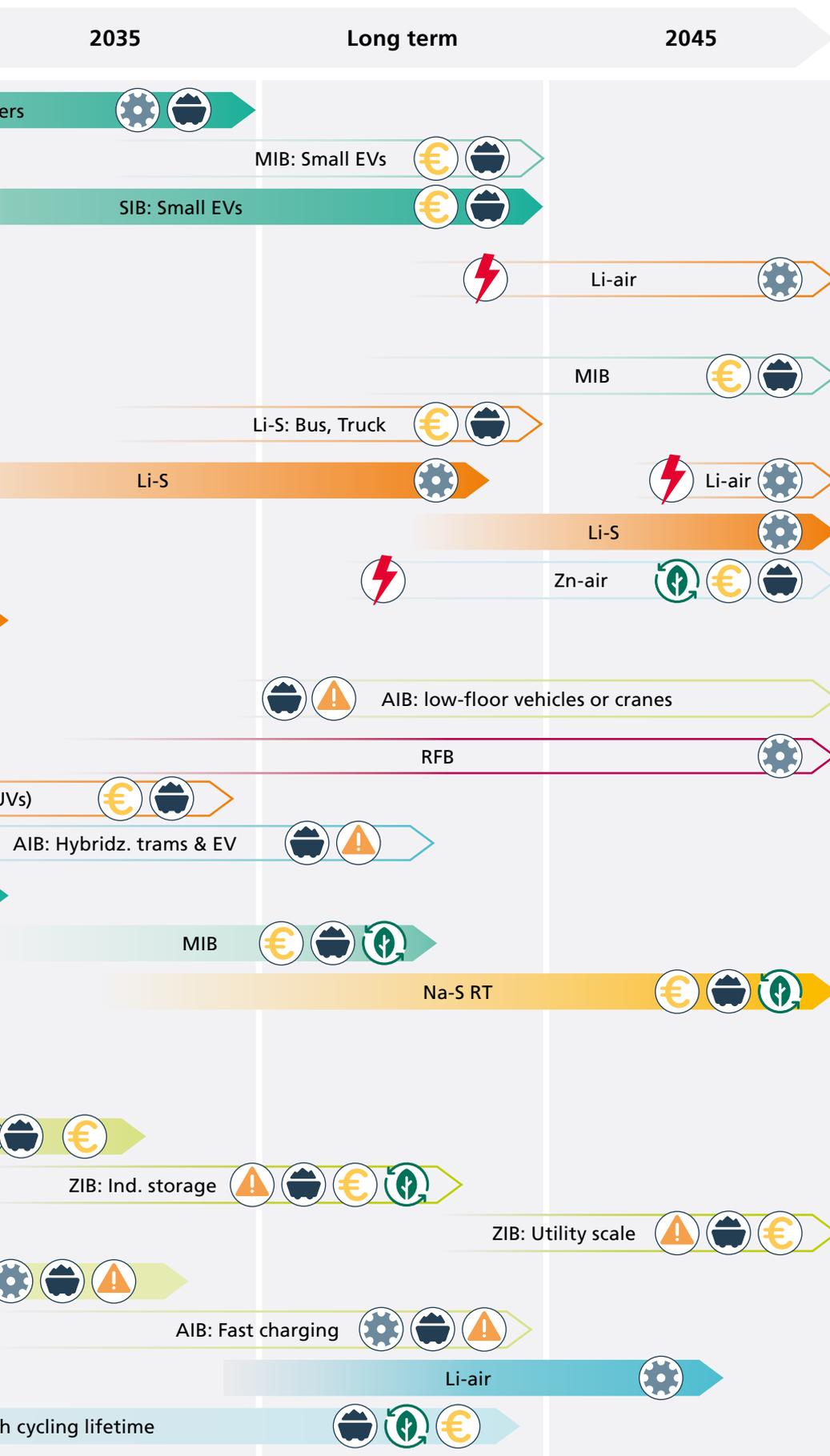
While alternative battery technologies beyond LIBs are only starting to enter the market in the mobile sector, some of them have already been introduced in *stationary* storage (ESS) applications. For example, RFBs, saltwater SIBs (SIBs Salt) or Na-S HT batteries (especially for large-scale storage) have been commercially available for many years. In the foreseeable future, classic SIBs (non-saltwater) are also likely to find their way into stationary applications. This is because of their high resource availability, safety and deep discharge capability. ZIBs may also be used in stationary applications but in the medium term. They represent a cost-effective and, due to the aqueous electrolyte, safe and environmentally-friendly solution. In addition, the low energy density is not as important for stationary applications as it is for mobile ones. Hence, ZIBs could also be considered for industrial storage in the longer term or, even more prospectively, at utility scale. Also in the longer term, MIBs could play an important role as ESS before making the leap to mobile applications. As a representative of Me-air batteries, Zn-air batteries could already be considered in the medium term for ESS, as their low power density makes them more suitable for stationary than for mobile storage. Zn-air batteries are particularly suitable for large buffer storage units, and come with further advantages such as low cost and high energy density. While the aforementioned Na-S HT batteries are only suitable for larger storage facilities due to the required infrastructure, Na-S RT batteries, which are not expected to enter the market before the middle of the next decade, can also enable the use of Na-S batteries in smaller storage facilities. In contrast to the aforementioned battery technologies, AIBs are very much aimed at highly cyclical applications with a high C-rate, as is the case for grid stabilization or peak

shaving. In the longer term, AIBs could also be used for fast charging.

This technology comparison shows that each alternative battery technology considered has its own specific advantages and disadvantages. While this means that there is no universal solution suitable for a high number of applications like LIBs, it also implies that battery technologies will be selected according to the specifications of the respective application. Due to geopolitical events, European regulations or the increased demand from end customers for sustainable products, „softer“ criteria such as resource availability or CO<sub>2</sub>-footprint will increasingly play a role in the assessment and selection of batteries.

Figure 40: Alternative battery technology roadmap – applications





2-3 wheelers	Road
Light vehicles	
Cars	
Heavy vehicles	
Drones	Air
eVTOLs	
HALE/HAPS	
Logistics	Others
Ships	
Trains	
Stationary	

## 4. Conclusions & Implications

### Conclusions

Given the current significant increase in demand for batteries and the concurrent political and geopolitical tensions, the question is whether there are potential alternative technologies to the state-of-the-art LIBs in the way they are widely produced and used today. For example, a scaled production of alternative technologies and established competitive supply chains could help to ease the tight raw material situation and reduce dependencies in the future.

The opportunities for alternative battery technologies seem to be favorable at the moment, as the range of battery applications is steadily increasing. In addition to the increasing demand in established technologies such as electric passenger cars, commercial electric vehicles (e.g. electric buses, electric trucks), ESS or consumer electronics, batteries will be needed in increasingly diverse and also new applications such as various micro mobility concepts or aviation (e.g., eVTOLs, drones). This increasing demand, combined with the current drive toward a better (European) energy and technology sovereignty could provide an unprecedented window of opportunity for alternative battery technologies to enter the market. Moreover, potential supply shortages resulting in more increasing LIB costs could further reinforce this opportunity.

Several alternative battery technologies hold promise for complementing LIBs in the medium-to-long-term. While a few of the alternative battery technologies such as SIBs, RFBs or Na-S HT batteries have started to enter certain markets, most alternative battery technologies are still at a relatively low level of technological development. In addition to the technological advancements, production capacities and supply chains would need to be established for all alternative battery technologies before widespread availability in the GWh range can be conceivably considered.

Increasing LIB cost resulting from resource scarcity and technological advances in alternative battery technologies would act as economic drivers for industry to develop and deploy

alternative battery technologies. In addition, plans to secure raw material mining also in Europe (particularly for Lithium) address the strategy of easing the dependencies along the supply chain, and alternative battery technologies could make inroads under aspects such as ecological advances or the potential European technology sovereignty that could be leveraged. However, these gains are generally not reflected in cost, so policy support may be needed to close these gaps.

The driving forces for the market entry of alternative battery technologies are still characterized by high degree of uncertainty, e.g., regarding the technological progress, the producibility and scalability, developments in other areas of the LIB value chain, such as LIB recycling volumes, as well as developments at the geopolitical level. Moreover, alternative battery technologies will compete with next-generation LIBs, including SSBs, and non-battery technologies such as supercaps and fuel cells depending on the area of application.

Nevertheless, the question is whether there will be one or more promising alternative technologies to LIB in the foreseeable future.

It is reasonable to conclude that none of the alternative battery technologies considered is suitable for the wide range of applications currently covered by LIBs. Hence, LIBs are expected to continue to play their dominant role in the future. The alternative battery technologies considered have varying characteristics, in particular their technical KPIs such as their energy or power density or cycling stability, making them suitable for specific applications. While Me-ion batteries, for example, seem to have the biggest range of applications, others such as Li-S batteries are particularly advantageous for air applications. In addition, some technologies, e.g., Zn-based batteries, have clear advantages in terms of economic or ecological aspects that could outweigh less favorable technical performances.

As a result, the battery market is expected to increasingly diversify in terms of the technologies used in the medium to

long term, and alternative battery technologies may complement LIBs in certain applications. More particularly, specialized markets (e.g., certain stationary storage applications or hybrid forms in combination with LIBs in passenger cars) or new ones (e.g., eVTOLs) seem to offer good opportunities for the entry of alternative battery technologies and the exploitation of their specific advantages.

However, for most alternative battery technologies, market entry is only possible once the step into production has been taken and developmental challenges have been solved before costs can be significantly reduced so that alternative battery technologies are also economically attractive. In the meantime, LIBs can contribute to growth of these specialized and new markets before alternative batteries can complement or even replace LIBs.

In the coming decade, and given the high level of uncertainty, alternative battery technologies are more likely to make the transition to large-scale production and deployment if they are compatible with the current LIB ecosystem in terms of production processes, standards and/or applications. However, longer-term forecasts are difficult owing to the great uncertainties surrounding technological and geopolitical developments, and even the establishment of new battery ecosystems is possible. As such, this roadmap can be considered as an initial step that reflects the current position, however, continuous monitoring and roadmapping are still required as the advancement of technologies but also the development of the market, its environment and framework conditions could lead to a new or different assessment in the future.

### Opportunities, challenges and implications for the EU and Germany

While the dependencies on LIBs and the established ecosystems are expected to remain in the future due to their broad range of applications, alternative battery technologies offer the potential for entry into specific applications and therefore for

a more resilient and technologically sovereign battery system from a German and European perspective.

Analyses of patents and publications indicate that Europe is better positioned for the technological development of some of the alternative battery technologies than it is for LIBs, e.g., RFBs, Li-air and AIBs – while Japan and China are still the leading countries in patent and publication activities, respectively.

While the potentially important role of alternative battery technologies has been recognized in Germany and at EU level, and corresponding research activities are increasingly supported at German and EU level [159], the market introduction of alternative battery technologies requires additional policy support. In particular, if an early development of a battery ecosystem is desired, local industry may need to be incentivized in this initial phase, as market development and the framework set by policymakers are still uncertain.

Thanks to intensive funding in recent years, there is a local R&D base, but due to largely low TRL, ecosystem and supply chain building has not yet started. While research and education need continuous policy support to overcome current technical challenges, funding is also required in terms of market readiness, leading to a general increase in funding costs and efforts. When it comes to these alternative technologies, European production capacities and supply chains would need to be established for alternative battery technologies, and relevant resources outside the EU need to be secured. While a few battery policy instruments already exist, such as the IPCEIs, they have so far been focused only on LIBs and are less open to alternative battery technologies.

In addition, in order to achieve a German or European market advantage and to avoid getting left behind as with LIBs requires integrated and fast action. An integrative policy approach could give promising/key technologies a boost towards market readiness and deployment. This approach should cover the entire supply chain including the continued build-up of a patent portfolio, the development and

qualification of production processes, the safeguarding of resources (i.e., commodity agreements with relevant supply countries) and the integration of an end user to test and commercialize the practical application. Yet, this funding is characterized by high cost and risk and can therefore only be applied to a limited number of technologies. Funding may be discontinued due to highly dynamic developments in other fields of technology or unsolvable challenges. In this case, pre-defined criteria for terminating funding and/or path-dependent decision making are required. Systematic and regular screening processes can help to develop criteria for selection and for terminating funding such as insufficient progress in terms of technological development or producibility at scale. Such selection criteria should consider the application(s) that can and should be addressed and could relate to market readiness and/or producibility at scale, cost or ecological advantages, or greater independence in terms of resources or supply chains. The different aspects have to be prioritized and potential trade-offs have to be considered.

This will require developing, scaling and certifying production equipment for alternative battery technologies. Well-established institutions such as Fraunhofer Research Institution for Battery Cell Production (FFB) or the UK Battery Industrialization Centre (UKBIC) provide a unique opportunity for Germany and the EU to take on this role. These institutions could also participate in emerging supply chains to help establish them. However, it is advisable for these institutions and other machinery and equipment suppliers to prioritize developments that in the medium term align with established LIB processes and standards to subsequently benefit from synergies.

Funding programs should be designed to attract different industry players. Not only big firms – that have traditionally mostly shaped battery ecosystems – but also SMEs and start-ups can play an important role. They can identify relevant specialized markets of manageable size and strive to become „hidden champions“. Moreover, high rates of funding and multistage processes could facilitate market entry, especially for smaller firms. In addition, the current rather rigid certification processes could prevent firms from entering the field and adapting new battery technologies to new areas of application. Certification should be made more flexible while

maintaining quality and safety levels. Firms should seek to achieve certification for close-to-market products for future applications early on (e.g., air applications), in addition to participating in demonstration projects.

At present, the application-pull for alternative battery technologies in Europe is not yet pronounced, but this could change in the future. While the current demand pull for alternative battery technologies tends to be outside Europe, e.g., large demand pulls for stationary storage in Australia and China, or related to small low-speed, short-range passenger cars (SIBs) in China, future changes in mobility behavior or technology developments (e.g., the availability of smart/fast charging infrastructure) could result in new markets in Europe.

## Outlook

In addition to the alternative battery technologies considered, other technologies, particularly SSBs or high energy LIBs, may develop and also serve as alternatives to state-of-the-art LIB in the future. There is still a great need for R&D and advances in new materials and cell concepts for future battery applications, even beyond the alternative battery technologies considered in this roadmap. This R&D could also allow for potential spillover effects between the different battery types. In addition, markets and supply chains may be affected by political and geopolitical tensions as well as the increasing importance assigned to environmental friendliness.

It is therefore essential to define milestones for development and market relevance, as well as to monitor and roadmap the progress of alternative battery systems accordingly. As such, this roadmap for alternative battery technologies can be considered as a more detailed successor to the Battery Roadmap 2017: High-energy batteries 2030+ and prospects for future battery technologies [19] and complementary to the SSB roadmap published by Fraunhofer ISI in 2022 [160]. In addition, Fraunhofer ISI will update the roadmap on high-energy LIBs in 2023 (to be published in 2024).

# Appendix

**Table 15: Legend of radar charts of the alternative battery technologies considered**

Scale	1	2	3	4	5
<b>Current TRL</b>	TRL 1	TRL 2–3	TRL 3–5	TRL 6–8	TRL 9
<b>Current R&amp;D efforts to market</b>	Very high	High	Normal	Low	Very low/already commercialized
<b>Current EU specialization (vs. LIBs)</b> (Specialization in relation to LIBs, $(RPA+RLA)/2$ )	Substantially less than for LIBs $((RPA+RLA)/2 = 1)$	Less than for LIBs $((RPA+RLA)/2 = 2)$	Similar to LIBs $((RPA+RLA)/2 = 3)$	More than for LIBs $((RPA+RLA)/2 = 4)$	Substantially more than for LIBs $((RPA+RLA)/2 = 5)$
<b>Potential long-term cell cost (vs. LIBs)</b>	Substantially higher than for LIB ( $> 200\%$ )	Higher than for LIBs ( $100\% - 200\%$ )	Similar to LIBs ( $\sim 100\%$ )	Lower than for LIBs ( $50\% - 100\%$ )	Substantially lower than for LIB ( $< 50\%$ )
<b>Potential resource availability (vs. LIBs)</b> (Resources generally available? Availability in DE/EU and/or globally dispersed?)	Substantially worse than for LIBs (No/No)	Worse than for LIBs (Probably not/Probably not)	Similar to LIBs	Better than for LIBs (Yes/Probably yes)	Substantially better than for LIB (Yes/Yes)
<b>Market development potential</b> (How many applications? Dominance in one or more applications?)	Very low (One/No)	Low (A few/No)	Medium (A few/Probably yes)	Medium to high (Multiple or Yes)	High (Multiple/Yes)

The radar chart consists of six dimensions, in which the technologies are classified: TRL, R&D efforts to market, EU specialization, potential long-term cell cost, resource availability, and market development potential. While the first two of these dimensions stand by themselves, i.e., are independent of LIBs, the last four categories allow for a comparison with LIBs as a reference. In addition, TRL, R&D efforts to market and EU specialization relate to the current situation, potential long-term cell cost, resource availability and market development potential relate to long-term developments, i.e., after successful commercialization.

For each of the dimensions, technologies were classified into a 5-step scale as shown in Table 15 and based on the information gained during the roadmap process (i.e., literature, interviews, workshop), as well as on discussion within the roadmap team.

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76139 Karlsruhe, Germany  
info@isi.fraunhofer.de  
www.isi.fraunhofer.de

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## **Project Executing Organization**

Projektträger Jülich (PtJ)  
Neue Materialien und Chemie  
Werkstofftechnologie für Energie und Mobilität (NMT 1)  
52425 Jülich

## **Scientific Coordination**

Dr. Annegret Stephan  
Competence Center – Energy Technology and Energy Systems  
Fraunhofer Institute for Systems and Innovation Research ISI  
Phone +49 721 6809-274  
annegret.stephan@isi.fraunhofer.de

## **Project Lead**

Dr. Axel Thielmann  
Head of Competence Center – Emerging Technologies  
Fraunhofer Institute for Systems and Innovation Research ISI  
Phone +49 721 6809-299  
axel.thielmann@isi.fraunhofer.de

## **Authors**

Dr. Annegret Stephan, Dr. Tim Hettesheimer, Dr. Christoph  
Neef, Dr. Thomas Schmaltz, Steffen Link, Maximilian Stephan,  
Jan Luca Heizmann, Dr. Axel Thielmann

## **Layout and Illustrations**

Renata Sas, Karlsruhe

## **Cover-Illustration**

Heyko Stöber, Hohenstein

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## Contact

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Dr. Annegret Stephan (Scientific Coordination)  
Competence Center – Energy Technology and Energy Systems  
Phone +49 721 6809-274  
[annegret.stephan@isi.fraunhofer.de](mailto:annegret.stephan@isi.fraunhofer.de)

Dr. Axel Thielmann (Project Lead)  
Head of Competence Center – Emerging Technologies  
Phone +49 721 6809-299  
[axel.thielmann@isi.fraunhofer.de](mailto:axel.thielmann@isi.fraunhofer.de)

Fraunhofer Institute for Systems and Innovation Research ISI  
Breslauer Str. 48  
76139 Karlsruhe, Germany  
[www.isi.fraunhofer.de](http://www.isi.fraunhofer.de)