Scheme for the classification of secondary battery types

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When categorizing more than 2,000 battery projects for the BecoSearch database – some of which deal with highly experimental new battery systems – it becomes increasingly apparent that there is no clear system for classifying the growing number of different battery types. There is no standard work that can be referred to, and there are often no clear definitions and delimitations for battery types, some of which are outdated.

For example, electrode materials are now used in lithium-ion batteries that store lithium ions via other mechanisms (insertion, conversion, alloy formation) than via classic intercalation, but these are not yet taken into account in definitions. If lithium metal anodes are used, lithium ions are no longer “intercalated” at all, but are deposited in amorphous structures. This leads to new challenges in research and development, new battery properties and new manufacturing processes, which is why it makes sense to assign such battery systems their own category. There is a trend among researchers in the field of alternative battery systems to refer to batteries as metal-ion batteries, although these use metal anodes and sometimes cathodes in which the metal ions are not stored at all. Liquids are added to solid-state batteries, but they are still often referred to as ALL-solid-state batteries.

Clear taxonomies that are as simple and future-proof as possible are necessary to make large volumes of battery-relevant data such as information and results from scientific projects, literature and patents easy to search and find. These must be as well thought out, expandable and flexible as possible in order to be able to react quickly to innovations and changes without having to make costly adjustments to systems based on them. The categorizations must not only be used today. Data categorized today should also be retrievable in the future. If this is not the case, data that is keyworded today will have to be re-categorized at some point at great expense. Such categorizations are only possible with clear definitions of the individual battery types, which in turn form an important basis for standards, legal regulations and many other areas.

With the help of scientists from various disciplines, the KLiB has therefore developed an initial proposal for a clear categorization of secondary electrochemical batteries. The aim is to create a simple standard according to which secondary electrochemical energy storage devices can be clearly categorized into meaningful groups. It should be based as closely as possible on terms and definitions that are commonly used in science and industry and, if possible, only “intervene” where there are errors, ambiguities or similar. We try to update this standard continuously and make it freely accessible on the Internet in German and English.

We would like to discuss our proposal with you and look forward to your criticism and suggestions. We are particularly interested in the following questions:

1. What do you think of the classification scheme? Is it correct and, in your opinion, applicable to all known types of secondary electrochemical batteries (not only to those systems that are already on the market, but also to all experimental approaches)? Where do you see errors in content, ambiguous or problematic definitions and categorizations? Do you agree with the chosen and partly new terms for battery types or do you have suggestions for more suitable or more common terms? Do you have any other suggestions for improvement?
2. Can you imagine integrating our proposal into your daily work/research routine? If not, why? What prevents you from doing so? How could this be changed?

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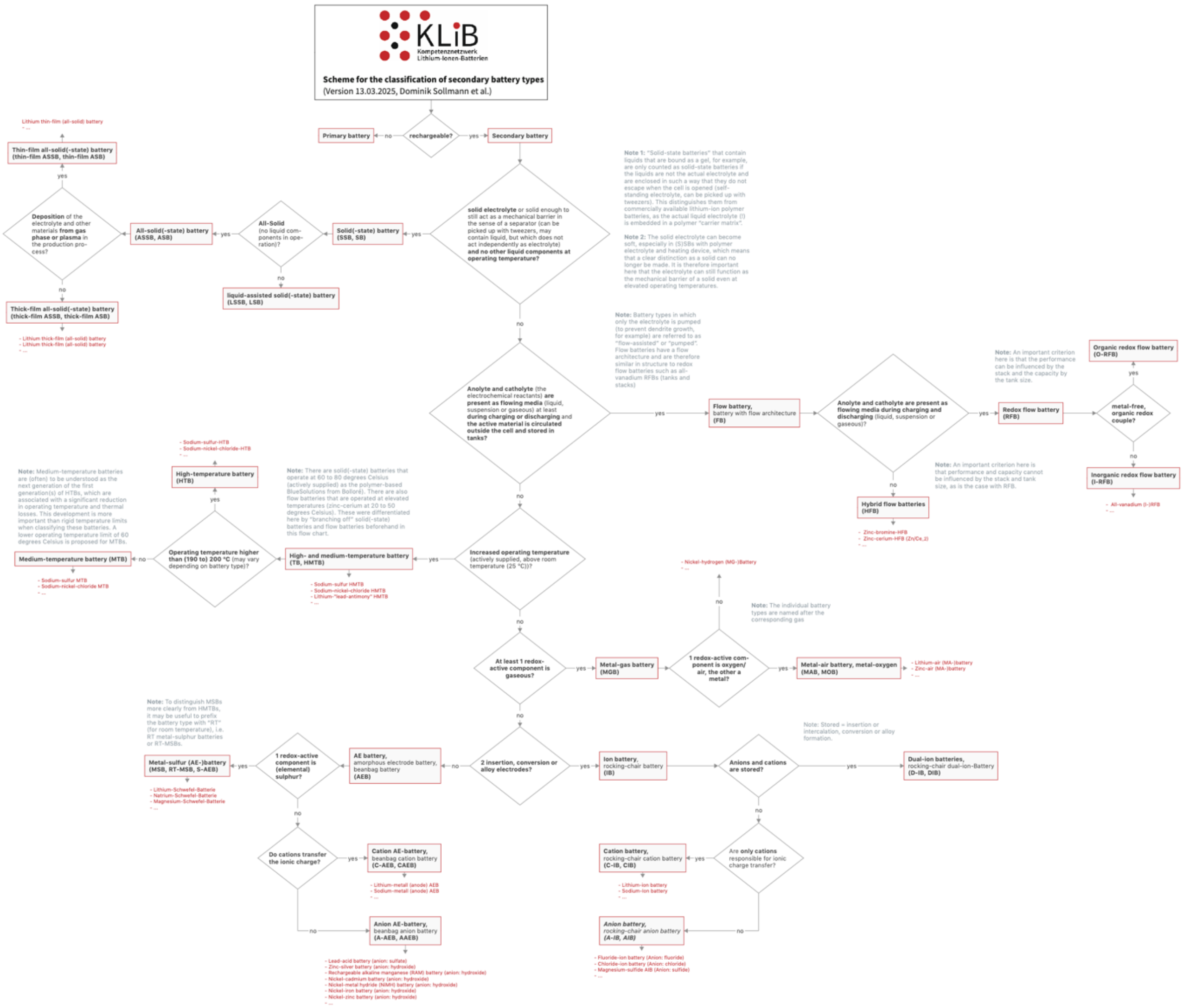
Flow chart for the classification of secondary electrochemical batteries

Please use download our flow chart as a PDF file at https://becosearch.com or https://www.batterieofrum-deutschland.de.



Notes on the classification scheme

- Each battery type may only be assigned to one category. Multiple classifications are rather problematic in the database.
- The classification scheme attempts to make a clear distinction between all known secondary battery types and at the same time intervene as minimally as possible in the subdivisions used in science and industry. For this reason, a conscious decision was made to avoid strict subdivisions based on just one parameter such as charge transfer or elements used. Instead, an approach was chosen that attempts to identify the commonalities of common subdivisions, close gaps and update and refine existing definitions and, where deemed necessary, propose new ones. This resulted in clear delineations of battery types being enabled by a flowchart, i.e. by answering predetermined questions in a clear sequence, progressively excluding different battery types preceding them in the scheme (e.g. high and medium temperature batteries = batteries with operating temperatures of >25 °C that are NOT solid-state batteries).

- The current scheme only provides for as many subdivisions of battery types as currently appear necessary for the subdivision of various works in Germany in order to keep it as lean as possible. It is so flexible that extensions can be made if this appears to make sense (re-categorization in a database may be necessary).
- The current scheme makes decisions on the categorization of certain battery types as they are currently considered appropriate (e.g. metal-sulphur (AE) batteries). However, the system is flexible enough to allow such battery types to be subordinated to other categories at a later date, should this appear to make more sense.

Definitions and explanations of the categories

Solid(-state) batteries[1] (SSB, SB)

All battery types that contain only components that are in a solid aggregate state at their operating temperature[2] are referred to as **all-solid(-state) batteries (ASSB, ASB)**.

Solid(-state) batteries that contain little liquid, such as gel, are only counted as solid(-state) batteries if the liquid does not function independently as an electrolyte and is enclosed in such a way that it does not escape when the cell is opened (self-standing electrolyte, can be picked up with tweezers). These are referred to as **liquid-assisted solid(-state) batteries (LSSB, LSB)**. This distinguishes them from commercially available lithium-ion polymer batteries, which are not classified as solid(-state) batteries because the actual liquid electrolyte (!) is embedded in a polymer carrier matrix.

All-solid(-state) batteries and liquid-assisted solid(-state) batteries are summarized under the term **solid(-state) batteries (SSB, SB)**.

Solid(-state) batteries that are operated at elevated temperatures also count as solid(-state) batteries - even if the heat is actively supplied (heating element) - as long as the components remain in a solid state even at the elevated operating temperature. The solid electrolyte may become soft (especially in the case of SSBs with polymer electrolyte and heating device), which means that it is no longer possible to clearly distinguish them as solid-state. Such batteries are classified as solid-state batteries as long as the electrolyte

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[1] Solid-state batteries have become particularly important as further developments of lithium-ion batteries with flammable, liquid electrolytes (and other metal-ion batteries). The current manufacturing processes and special properties (interfaces, safety, performance) make a clear differentiation from the “predecessors” with liquid electrolytes appear sensible. A different classification of solid-state batteries - for example as all-solid lithium-ion batteries as a sub-category of lithium-ion batteries - would lead to significantly more sub-categories when classifying such types in databases. Research on solid-state electrolytes would then have to be assigned to many different battery types without it being clear in advance in which type they are used). This would make it more difficult to find such battery types and is less in line with the intuitive search behavior of different users. It was therefore decided to “filter out” this category at the beginning of the schema.

[2] The insertion “at your operating temperature” serves to clearly distinguish them from high and medium temperature batteries, in which solid battery components liquefy when heated to operating temperature. As long as no components of the solid(-state) batteries defined here liquefy at operating temperatures higher than 25 °C (the solid(-state) electrolyte may become somewhat softer, but must be able to maintain the function of a mechanical barrier of a solid(-state) battery), they are still classified as solid(-state) batteries.

can still assume the function of the mechanical barrier of a solid even at elevated operating temperatures.[3]

Because the manufacturing processes in particular, but also the properties of **thin-film and thick-film solid(-state) batteries** differ, these types are divided into subcategories:[4] If the electrolyte and other materials are deposited from the gas phase or a plasma, the batteries are classified as thin-film solid-state batteries.

Flow batteries[5] flow-assisted battery types

In **flow batteries (FB)**[6], the electrochemical reactants (anolyte and catolyte) are present as flowing media (liquid, suspension or gaseous) at least during charging or discharging and the active material is circulated outside the cell and stored in tanks (flow architecture). Batteries in which only the electrolyte is pumped to generate a flow (to prevent dendrite growth, for example) are classified as other battery types and are given the suffix **flow-assisted** or **pumped**. Flow batteries have a flow architecture and are therefore similar in design to conventional redox flow batteries such as all-vanadium RFBs.

If the electrochemical reactants are present as flowing media (liquid, suspension or gaseous) during charging and discharging, these are called **redox flow batteries (RFB)**. An important criterion for classification as an RFB is that the performance of the battery can be influenced by the stack dimensioning and the capacity by the tank size. Depending on whether the redox pairs used to operate the battery are organic or inorganic compounds or elements, a distinction is made between **organic and inorganic RFBs (O-RFB and I-RFB)**.

Hybrid flow batteries (HFB), in which anions or cations are deposited or removed at an electrode during charging or discharging, and performance is no longer influenced solely by the stack dimensioning and the capacity by the tank size, are distinguished from RFBs.

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[3] If batteries are developed that require heating devices and contain a polymer electrolyte that becomes so soft that an additional separator is required, these are classified as HMT batteries. If the required operating temperature is less than 60 °C, it is proposed to introduce a new sub-category of HMTB (the low temperature batteries, LTB) and to classify the described battery type there.

[4] A subdivision according to the type of solid electrolyte [ceramic (sulphide, oxide, phosphate) and polymer] is also obvious here. In view of the different production lines and characteristics of the resulting battery types and a research community that already seems to have split into two "camps", the subdivision based on production and the resulting product properties was considered more appropriate.

[5] Redox flow batteries (which are combined here with other battery types to form flow batteries due to their characteristic "flow architecture") have the unique property that the performance of the battery is determined by the stack dimensioning and its capacities by the tank size, which also gives these batteries their own category in the widely used categorization. Similar to solid(-state) batteries, filtering out flow batteries later in the flow chart would result in them forming not just one category but several subcategories of battery types, making them more difficult to find, making the categorization of battery types more complicated and resulting in more data to maintain. The classification in the scheme before the metal-gas batteries is particularly important for a clear differentiation from this battery type (the flow architecture is the more decisive characteristic).

[6] or batteries with flow architecture.

High and medium temperature batteries[7,8] (HMTB)

Batteries that are operated at temperatures higher than room temperature (25 °C) and to which the heat is actively supplied (heating device or similar) are referred to as **high and medium temperature batteries (HMTB)[9]**, unless they are solid(-state) batteries or redox flow batteries.[10]

To further specify this type of battery, HMTBs are classified as **high-temperature batteries (HTB)** if the operating temperature is higher than (190 to) 200 °C (e.g. sodium-sulphur high-temperature battery or sodium-nickel-chloride HTB). For operating temperatures below (190 to) 200 °C, the term **medium temperature batteries (MTB)** is used.[3]

Medium-temperature batteries are usually to be understood as the next generation of the first generation(s) of HMTBs, which are associated with a significant reduction in operating temperature and thermal losses. This development is more important than rigid temperature limits when classifying these batteries. In particular, new developments for reducing the operating temperature of battery systems that are available on the market should be identified.

60 °C is suggested as the lower operating temperature limit for MTB.

Metall-gas batteries[11] (MGB)

Batteries that use at least one redox-active component that is gaseous and that are not solid-state, flow or HMT batteries are summarized under the term **metal-gas batteries**

[7] A key component of HMTBs that clearly sets them apart from most other battery types is the required heat supply device. This reduces the energy density of the actual battery and leads to continuous energy consumption. In order to achieve clear distinctions between solid(-state) batteries and flow batteries, a sequence was established in the scheme and definitions were specified (see. footnotes 2 and 10 as well as definitions of solid(-state) and flow batteries): 1st decision criterion: all-solid(-state)?, 2nd criterion: flow architecture?, 3rd criterion: heat supply? Some solid-state batteries are currently also operated with heating devices, but at significantly lower temperatures. Many such batteries are still being operated on a laboratory scale or have not been available on the market for a very long time, so it is not unlikely that new generations will be able to do without a heating device.

[8] According to the Duden dictionary, thermal means caused by heat, relating to heat, relating to hot springs, using hot springs (in the sense of thermal springs, "thermal bath"). It seems more appropriate to refer to the battery types as high and medium temperature batteries, HMTB for short, to avoid the association with hot water springs.

[9] Or just TB.

[10] Introduced to differentiate redox flow batteries that are operated at elevated temperatures (e.g. zinc-bromine RFBs that are operated at 20 to 50 °C, see Linden's Handbook of Batteries 4th Edition, Chapter 30.6, p. 1026 of 1457).

[11] What metal-gas batteries have in common is that, unlike other battery types, they have so far required complex and/or heavy peripherals in order to store or purify gases. In connection with the further development of lithium-ion batteries, gas batteries have become particularly interesting because, at least in theory, they promise very high energy densities by saving electrode material (and dispensing with gas tanks), which gives metal-air batteries an important unique selling point. The term metal-air batteries is already firmly established. These considerations led to the introduction of the metal-gas battery category.

(MGB). The batteries are designated using the gas used, such as lithium-air battery, lithium-oxygen battery or nickel-hydrogen battery.[12]

Ion batteries (IB)

If ions are inserted into and removed from the anode and cathode during charging and discharging by insertion, conversion or alloy formation, and if the batteries are not solid-state, flow, HMT or metal-gas batteries, the term **ion batteries (IB)**[13] is used.

If only cations are responsible for the ionic charge transfer in the battery, which are stored in and removed from a host grid or form a chemical bond with the electrode material (insertion, conversion, alloy formation), IBs are referred to as **cation batteries (C-IB)**[14], which include lithium-ion batteries. If the ionic charge transfer takes place exclusively via anions, they are referred to as **anion batteries (A-IB)**. If it takes place via anions and cations, IB are referred to as **dual-ion batteries (D-IB)**.

AE batteries[15] (AEB)

If, during charging and discharging, the ions are not deposited in and removed from two electrodes with a host grid or form a chemical compound with the electrode material (insertion, conversion, alloy formation), but instead are deposited amorphously on at least one of the electrodes, batteries that are not solid(-state) batteries, flow batteries, HMTB or metal-gas batteries are referred to as **AE batteries (AEB)**[16].

Historically, **metal-sulphur (AE) batteries (MSB, MSAEB)**[17] without active heat supply have become very important, which is why a separate category was introduced for these battery types within the AEB.

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[12] This subdivision serves to maintain common terms such as metal-air or metal-oxygen battery and nickel-hydrogen battery, is meaningful and unambiguous.
[13] also rocking-chair batteries.
[14] also rocking-chair cation batteries, CIB, C-IB.
[15] This type of battery was newly introduced because it (often still) presents different properties and challenges compared to the IBs, such as a higher volume change in the battery during charging and discharging and thus contacting and interface problems or challenges for process engineering, for example due to the handling of highly reactive metal foils (especially with regard to lithium metal anode batteries). On the other hand, such battery types promise higher energy densities if host grids or similar can be dispensed with. Another important reason for the development of this category is the very inconsistent use of the term metal-ion battery for battery types that use cations other than lithium for charge transfer. In many cases, these work with metal anodes and do not store cations in both electrodes via insertion, intercalation, conversion or alloy formation. A (desired?) analogy to lithium-ion batteries is therefore not given according to this scheme. This classification is intended to achieve clearer definitions of such battery types. As a result, a large number of battery types that have so far been referred to as metal-ion batteries (sodium, magnesium, aluminum-ion batteries, etc.) would have to be referred to as AEB, beanbag cation or metal-anode batteries (sodium-, magnesium-, aluminum-metal batteries or sodium, magnesium, aluminum AEB).
[16] also amorphous electrode batteries or beanbag batteries (as counterpart to rocking-chair batteries).
[17] also RT metal-sulfur batteries, RT-MSB, MS-AEB; RT = room temperature.

If only cations are responsible for the ionic charge transfer, AEBs are referred to as **cation AE batteries (C-AEB)**, which include lithium metal anode batteries. If the ionic charge transfer takes place exclusively via anions, they are referred to as **anion AE batteries (A-AEB)**[18].

Our questions, which we would like to discuss with you:

- Are gas batteries and flow batteries with gases as electrochemical reactants sufficiently clearly and meaningfully differentiated from each other?
- Does it make sense to assign metal-sulphur batteries their own category? Should metal-sulphur batteries be assigned to other categories - such as cation batteries - but then the question arises as to how these should best be differentiated from metal-anode batteries?
- With regard to the proposed new designations and abbreviations for batteries such as AE or Beanbag battery: Please let us know what you think of the designations and make your own suggestions.

[18] also beanbag anion batteries, AAEB, A-AEB.

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