INTERGOVERNMENTAL FORUM
on Mining, Minerals, Metals and
Sustainable Development

A BRIEF GUIDE TO BATTERIES

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1. What Are Batteries, and Why Are They Important for the Low-Carbon Transition?

A battery is a device that converts chemical energy into electric energy, thereby releasing stored energy. This process is known as electrochemistry.

FUN FACT: Did you know?

The very first battery, created about 2000 years ago, was a ceramic pot battery known as the “Baghdad Battery.” This world’s oldest “ceramic pot battery” was thought to have been used for metallic plating rather than as a battery to generate electricity. The voltage would have been about 1.5–2 volts. It is not known exactly what the electrolyte solution would have been, but it was most likely vinegar or wine.[1]

Today, batteries have become essential parts of our lives. Our portable devices, electronic appliances, and vehicles all function on batteries, and as the world embraces the low-carbon transition, battery technologies are becoming increasingly critical. While they continue to play vital roles in our electronic devices, batteries are set to become indispensable for storing energy generated from renewable sources (such as solar and wind) and to power electric vehicles, homes, and potentially industrial production sites.[2]

[1] Panasonic Energy. (n.d.). *History of batteries*. https://www.panasonic.com/global/energy/study/academy/history

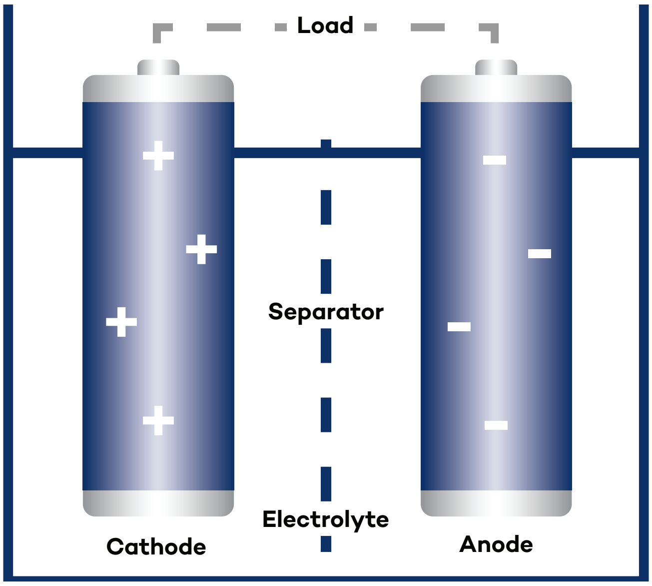
[2] Katz, C. (2020). *In boost for renewables, grid-scale battery storage is on the rise*. Yale Environment 360. https://e360.yale.edu/features/in-boost-for-renewables-grid-scale-battery-storage-is-on-the-rise

2. What Are the Main Components of Battery Cells?

The system that makes a battery function is called an electrochemical cell. The cell is the unit that is used to generate or store electric energy, created by a reaction that involves the movement of electrons from one material to another via an electric circuit.

Cells consist of two electrodes—a negative electrode called the **anode** that *releases* electrons to the external circuit and a positive electrode called the **cathode** that *acquires* electrons from the external circuit. They are separated by an **electrolyte**, which is a medium that provides the *ion* transport mechanism for the electrons between the anode and the cathode. It can be a liquid or a solid.

Figure 1. Battery cell components



The materials contained in anodes and cathodes are made of different types of minerals, metals, or other chemical compounds (see Table 1).

There is a wide range of battery types using different chemistries that are suited for different types of applications. Broadly, batteries can be classified into four types:

(i) Disposable or non-chargeable batteries, typically used in remote controls, wristwatches, cameras, etc. They account for **20% of the battery market**.[3]

(ii) Rechargeable batteries, like those used to power electric vehicles (EVs) (discussed in further detail below).

(iii) Reserve batteries, used in specific applications, such as military application systems.

(iv) Fuel cells, an energy storage facility that feeds into batteries from an outside source.

3. Why Do We Need to Understand Battery Chemistry?

By changing the composition and materials used to build anodes, cathodes, and electrolytes, we obtain different types of battery chemistry. These enable us to design different types of battery cells with varying properties that are adaptable to different applications.

Understanding battery chemistry is **crucial**, as this is what determines the key characteristics of the battery—such as its energy intensity, durability, and stability, among others—which in turn determine its applications. Rechargeable batteries have different characteristics based on their chemistry. The most widely used are:

- Lead-acid batteries
- Nickel-based batteries, in particular, nickel-cadmium batteries and nickel-metal hydride batteries

[3] Source: Petrovic, S. (2021). *Battery technology crash course*. Springer Nature Switzerland AG.

- Lithium-ion batteries (Li-ion)
- Lithium-sulphur batteries.

See Appendix B for more details on lead-acid batteries, nickel-based batteries, and lithium-sulphur batteries.

Li-ion batteries are mostly used in electronic devices, storage facilities, and EVs. Li-ion batteries have high energy density and thermal stability and are light and compact. These characteristics make them suitable for portable devices and good candidates for the battery packs currently used in EVs.

The material used in the anode is currently mostly ***graphite***. Cathodes are more complex and use a combination of many different materials. Table 1 provides a summary of the six main types of cathode chemistries used in Li-ion batteries.

Table 1: Main types of cathode chemistry used in Li-ion batteries

Cathode chemistry	Key characteristics	Applications
Lithium cobalt oxide – LCO ($LiCoO_2$)	Most commonly used. **Benefits** are high specific energy and reliability. **Drawbacks** are low specific power, short battery life, thermal instability, and relatively low cost (cobalt price).	Mobile phones, laptops, cameras
Lithium manganese oxide – LMO ($LiMn_2O_4$)	**Benefits** are thermal stability, relatively safe, rapid charging, and high specific power. **Drawbacks** are low voltage and a shorter lifetime.	Power tools, medical equipment and devices, electric motorbikes, laptops, and EVs
Lithium iron phosphate – LFP ($LiFePO_4$)	**Benefits** are good thermal stability, long battery life, cost-effectiveness, and safety. **Drawbacks** are lower specific energy density compared to LCO and a relatively high self-discharge rate.	Electric bikes and EVs (Tesla's Model 3), power tools, energy storage at power stations
Lithium nickel cobalt manganese oxide – NMC ($LiNiMnCoO_2$)**	**Benefits** are high specific energy, high charging rate, internal resistance, good stability, and safety. **Drawback** is they are thermally less stable.	EVs, E-bikes, industrial (medical devices), power tools, automobile powertrains
Lithium nickel cobalt aluminum oxide – NCA ($LiNiCoAlO_2$)	**Benefits** are high specific energy, good specific power, and a long life cycle. **Drawbacks** are thermally less stable and expensive.	Medical, industrial, EVs (Tesla grid storage)
Lithium titanate – LTO **Anode: uses lithium-titanate nanocrystals instead of carbon** **Cathode: either LMO or NMC chemistry**	**Benefits** are high safety, long lifespan, and very rapid charge time. **Drawbacks** are low energy density and very expensive.	Military or aerospace equipment, electric vehicles, wind and solar energy storage, charging stations, high-end EVs

Did you know?

The naming convention for batteries is based on the first letter of the key raw materials included in the cathode, along with their proportion. For instance, NMC batteries, which accounted for 72% of global EV batteries in 2020 (except in China), use different proportions of materials, which confer different characteristics to the batteries. Commonly used NMC chemistries are:

NMC 622, currently the dominant chemistry, is composed of 60% nickel, 20% manganese, and 20% cobalt.

NMC 523, also widely used, is composed of 50% nickel, 20% manganese, and 30% cobalt.

NMC 811, likely to overtake NMC 622 in 2025, is composed of 80% nickel, 10% manganese and 10% cobalt.

NMC 9.5.5, expected to be dominant in 2030, is composed of 90% nickel, 5% manganese, and 5% cobalt.

4. What Minerals and Metals Are Used in Batteries, and Where Do They Come From?

The key mineral in Li-ion battery anodes, mainly used in EVs, is graphite. Cathodes require a mineral mix of lithium, nickel, manganese, and cobalt.

Figure 2. Natural graphite: % share of global production, 2021

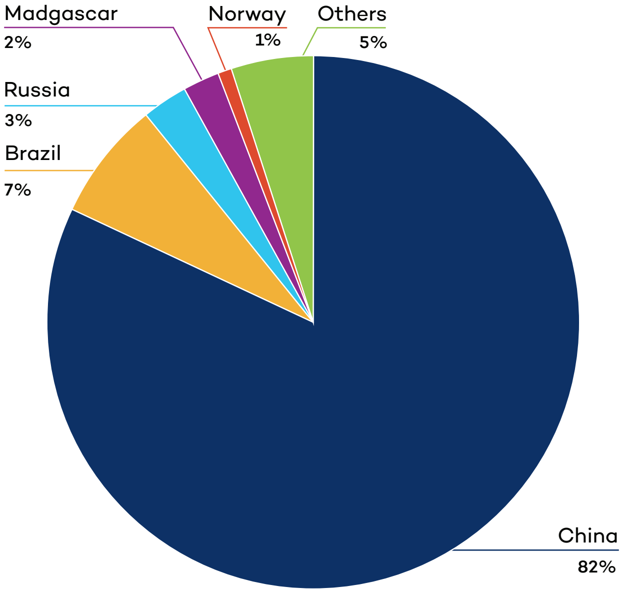
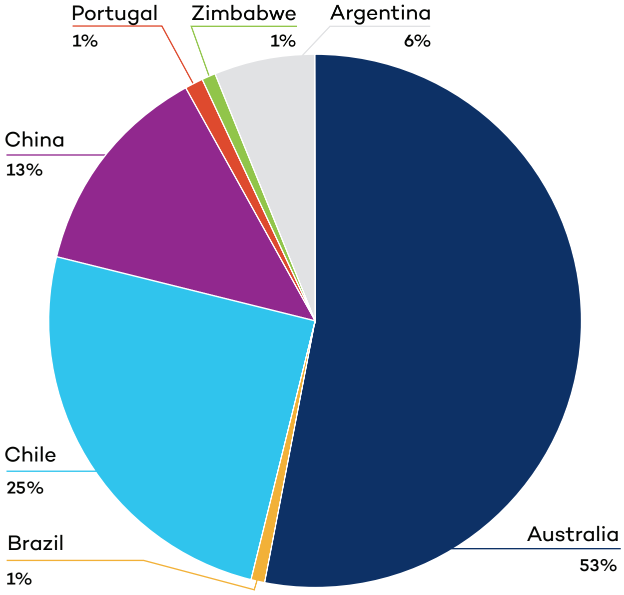


Figure 3. Lithium: % share of global production, 2021[4]



[4] Data for figures 2–6 is from the U.S. Geological Services (n.d.). *Minerals yearbook: Metals and minerals.* https://www.usgs.gov/centers/national-minerals-information-center/minerals-yearbook-metals-and-minerals

Figure 4. Cobalt: % share of global production, 2021

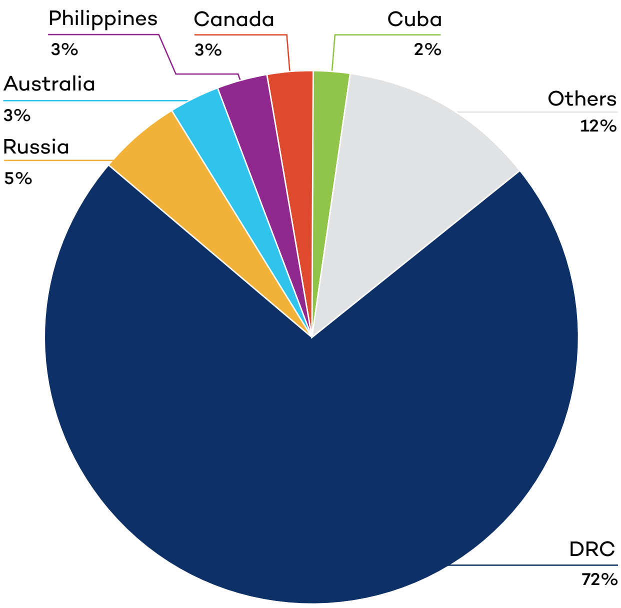


Figure 5. Nickel: % share of global production, 2021

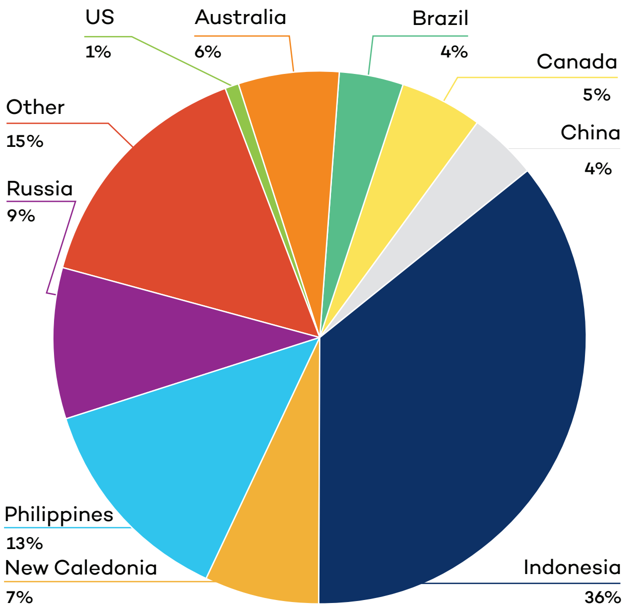
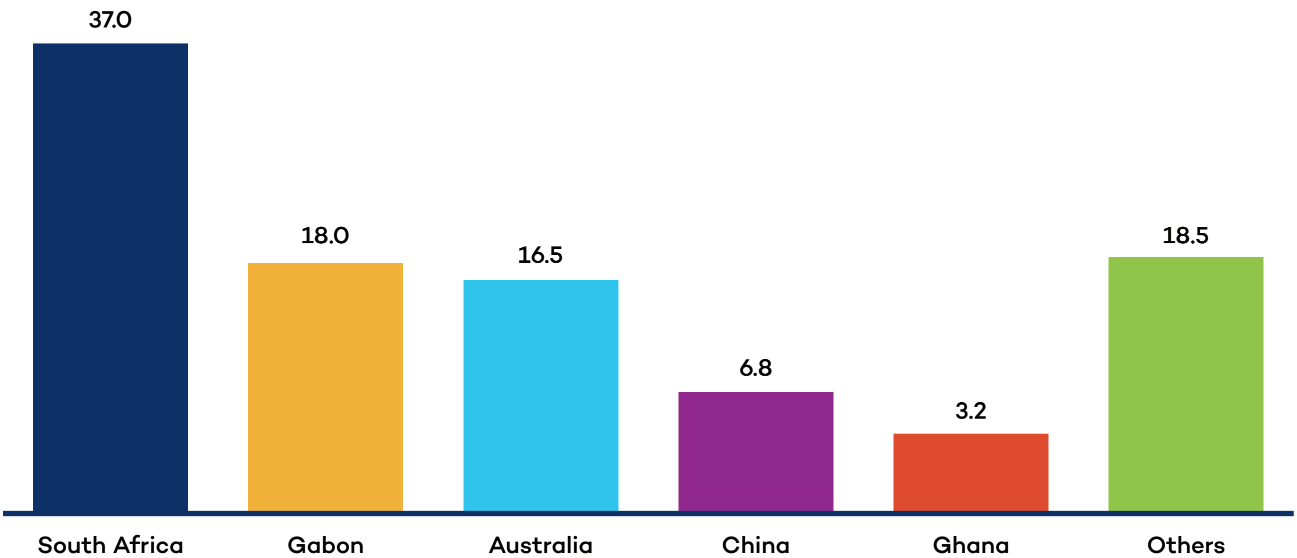


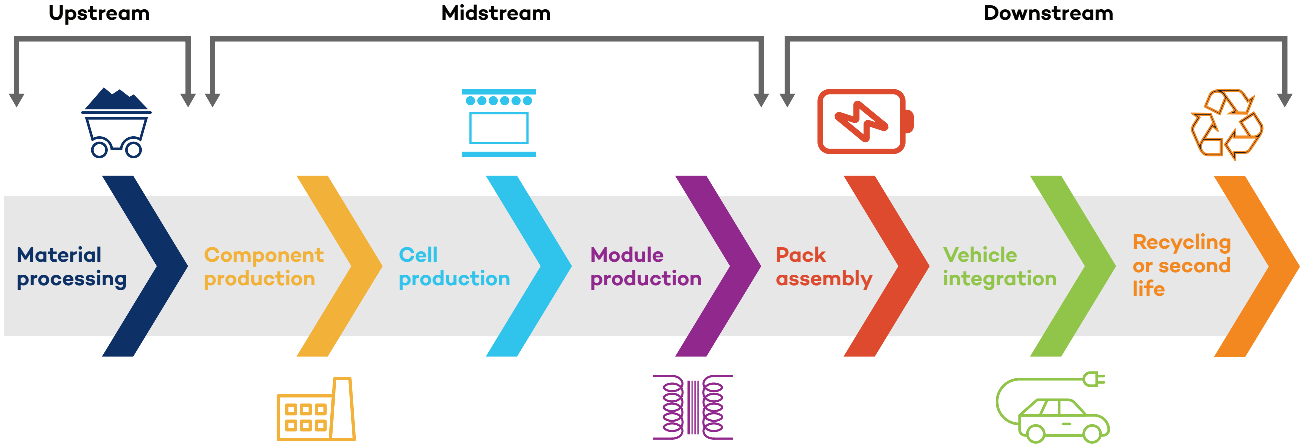
Figure 6. Manganese: % share of total global production, 2021



Figures 2 to 6 show which countries are key producers of the critical minerals used in Li-ion batteries. China dominates the production of natural graphite, with 82% of global production in 2021. The Democratic Republic of the Congo is the main global producer of unprocessed cobalt, with 72% of the global market share. The lithium market is relatively less concentrated, although Australia currently accounts for 53% of global shares of production. Indonesia accounts for a third of the nickel market. Other important metals used in batteries are aluminum, iron, steel, and copper, mainly used for the casing (aluminum and iron) and in current collections (aluminum and copper).

5. What Does the Mineral-to-Battery Value Chain Look Like?

Figure 7. The battery supply chain



Source: Author

A "value chain" refers to the different steps in the process of transforming raw materials into a finished good; it also considers the sustainability concerns of end-of-life disposal. These different steps culminate to confer a higher market value on the transformed products (hence the term "value chain").

In the case of batteries, the value chain has three main components:

The **upstream** component of the value chain refers to the activities from mineral extraction through to material production/processing.

In the **midstream** component of the value chain, mineral proceeds (often in the form of concentrates) are sent to smelters and refineries to obtain refined products that can then be used as inputs in industrial applications. In the case of batteries, different refined inputs are used to manufacture the battery cells and modules.

The **downstream** component of the value chain is more complex. Batteries have many applications and are widely used across different industries and sectors. The downstream value chain includes different industrial processes. It is likely to take more strategic prominence as batteries become key enablers in the shift toward low-carbon-emitting technologies across all industries.

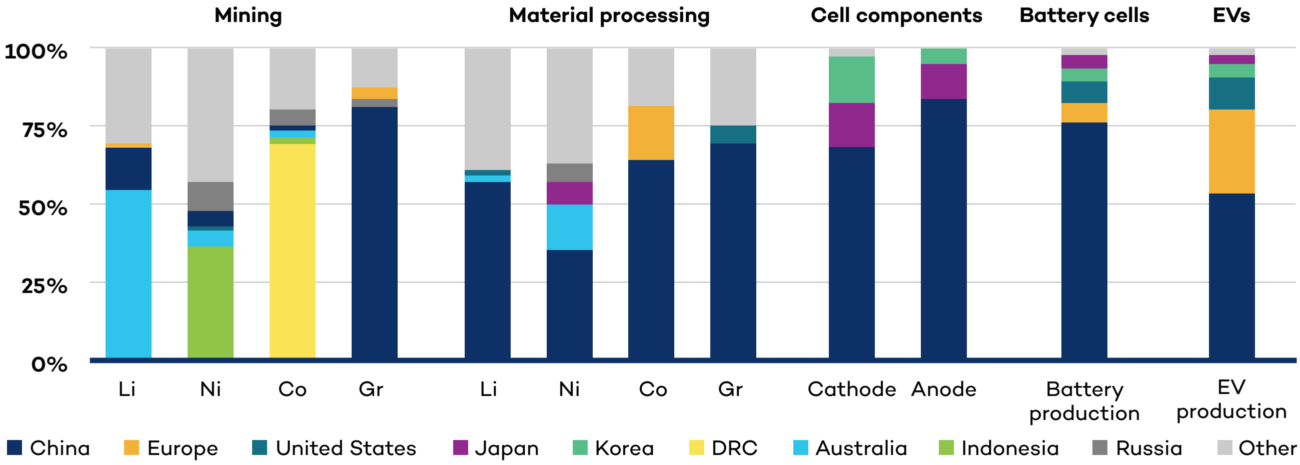
A network of industries and entities is involved along the entire chain. These "supply chain actors" are involved in the operational management of industrial activities.

6. Who Controls the Supply Chain?

As shown previously, the production of unprocessed critical minerals is concentrated in a handful of countries. In fact, there is also a high degree of corporate concentration in those countries as well, given that there are only a handful of companies that extract those resources.

Most exports of battery minerals are directed to China, which has the largest capacity to refine and smelt unprocessed minerals into the ingredients that go into anodes and cathodes. As Figure 8 shows, there is a clear shift in dominance away from mineral producers and toward industrial hubs in the midstream and downstream parts of the value chain.

Figure 8. Geographic Distribution of the Global Electric Vehicle Supply Chain[5]



Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of Congo. Geographic breakdown refers to the country where the production occurs. Mining is based on production data. Material processing is based on refining production capacity data. Cell component production is based on cathode and anode material production capacity data. Battery cell production is based on battery cell production capacity data. EV production is based on EV production data. Although Indonesia produces around 40% of total nickel, little of this is currently used in the EV battery supply chain. The largest Class 1 battery-grade nickel producers are Russia, Canada and Australia.

Source: IEA. (2022). Global supply chains of EV batteries.

The midstream value chain, in particular, is dominated by China, which owns significant capacities in refineries and smelting (material processing) and more than 75% of cell components and battery cells manufacturing capacity. These parts of the value chain are of strategic importance, as they create import dependency for global EV manufacturers located outside of China.

[5] Source: IEA. (2022). *Global supply chains of EV batteries*. https://iea.blob.core.windows.net/assets/4eb8c252-76b1-4710-8f5e-867e751c8dda/GlobalSupplyChainsofEVBatteries.pdf

7. What Does the Future of Battery Technology Look Like?

In recent years, with the electric mobility revolution, investments in research and development to improve performance and seek alternative sources of raw materials for battery technology have increased substantially. This is partly driven by strategic considerations to address the supply chain vulnerabilities highlighted above.

R&D efforts point to emerging innovations that are at a relatively advanced stage of development and could potentially enter the automotive market in the near future. Two are worth highlighting.

The first generation of **sodium-ion batteries** is expected to come to market in 2023 to be used in EVs and other stationary storage. They are an alternative to Li-ion batteries, as they do not use lithium, cobalt, or nickel, whose demand and prices have risen exponentially and whose supply chains are dominated by China. They also have safety advantages over Li-ion batteries because they present no risk of catching fire. They would be suitable for energy storage facilities and for small EVs like e-scooters. Their downsides are their lower energy capacity and weight, as sodium is three times heavier than lithium.

Solid-state batteries represent a revolutionary technology for battery chemistry, as the liquid electrolyte (which allows the transfer of lithium ions) is replaced by a solid compound. Like sodium-ion batteries, they offer a major safety improvement as they are non-flammable when heated, unlike their liquid counterparts. They are lighter, have a longer life shelf, and have a high power-to-weight ratio, making them ideal for use in EVs. The key advantage is performance. However, they do not address the critical minerals supply issues, as they have similar cathode technologies (NMC, NCA, and LNMO) and use similar anode materials (graphite, with a large amount of silicon) as current batteries.

Appendix A. Why Do We Need to Understand Battery Chemistry?

By changing the composition and materials used to build anodes, cathodes, and electrolytes, we obtain different types of battery chemistries. Understanding battery chemistries enables us to design different types of battery cells with different properties that are adaptable to different applications.

What are the main types of battery cells?

There is a wide range of battery types based on different chemistries that are suited to different types of applications. Broadly, batteries can be classified into four types.

Table A1. Types of batteries

1. Primary/ disposable batteries	These are non-rechargeable batteries that can only convert chemical energy to electrical energy and not vice versa. They are discarded after discharge. The most common type of primary batteries is *alkaline batteries* (from coin cells to AAA batteries), which are typically used in remote controls, wristwatches, cameras, etc. Primary batteries currently account for **20% of the battery market**.[6]
2. Secondary/ rechargeable batteries	Unlike primary disposable batteries, secondary batteries can convert chemical energy to electrical energy and convert electrical energy back to chemical energy again once the appliance is plugged into electricity for charging. Secondary batteries fall into two sub-categories based on their intended use: • Batteries that are used as *primary sources of energy*. They can be *small-capacity batteries*, such as those used to power portable electronic devices like **mobile phones**, portable electronics, and laptop computers. They can also be *heavy-duty batteries*, like those used to power **electric vehicles** and other high-drain applications, such as energy storage for electricity generation Batteries that are used for *energy storage* deliver energy on demand. They are usually connected to primary sources of energy. Examples include emergency and stand-by power sources.
3. Reserve batteries	These are special types of batteries used in specific applications. Essentially, they are kept as a reserve (stand-by), and the electrolytes remain inactive. They have a very low self-discharge rate. They are essentially used in timing-, temperature-, or pressure-sensitive devices, such as military weapon systems (missiles, torpedoes, etc.).
4. Fuel cells	The main difference in this type is that active materials are not an integral part of the device. Instead, they are fed into batteries from an outside source. Fuel cells produce electrical energy if active materials are supplied to the electrodes. However, they stop producing energy in the absence of such materials. Fuel cells have been used in space vessels. The development of hydrogen for the green transition will offer new applications for fuel cells in utility power, load levelling, on-site generators, and electric vehicles.

[6] Source: Petrovic, S. (2021). *Battery technology crash course*. Springer Nature Switzerland AG.

Appendix B. What Are the Different Types of Battery Chemistries, and What Are They Used For?

There are different types of rechargeable batteries, classified according to their chemistry. Understanding battery chemistry is crucial, as it is what determines the key characteristics of the battery—such as its energy intensity, durability, and stability, among others—which in turn determine its applications. The most widely used secondary batteries are as follows:

Lead-Acid batteries are the oldest type of battery in consumer use. The widest application is in *conventional vehicle engines*, where they enable the traction, starting, lighting, and ignition of vehicles. Lead-acid batteries are *rechargeable*.

Nickel-based batteries, in particular:

- ***Nickel-cadmium (Ni-Cd) batteries*** were the first rechargeable batteries before the use of lithium-ion batteries. They are used in power tools, torches, and portable devices. The anode is made of cadmium, and the cathode is made of nickel oxide hydroxide. Nickel-cadmium batteries have some weaknesses. First, they do not recharge completely if the batteries are not properly discharged. Second, they have a high self-discharging rate (about 20% per month), which means that they would lose their charge if not used for a few months. Finally, they are relatively expensive and contain a heavy toxic metal (cadmium), which creates challenges for waste disposal.
- ***Nickel-metal hydride (Ni-MH) batteries*** replaced cadmium with hydrogen in the anode, partly to address the challenges linked to toxicity. These batteries share similar characteristics to nickel-cadmium batteries in terms of voltage and capacity. They are still widely used as the standard for rechargeable AA batteries.

Lithium-ion (Li-ion) batteries have become the most commonly used battery chemistry used for electronic devices, storage facilities, and electric vehicles. Li-ion batteries are more energy efficient than nickel-based batteries and are light and compact, making them good fits for portable devices. Their high energy density and their light weight make them good candidates for the battery packs—which are stacks of battery cells—currently used in electric vehicles.

Lithium-sulphur batteries are a cheaper alternative to Li-ion batteries, given the abundance of sulphur, the material used in the cathode. Lithium is the main material for the anode. This chemistry has a good voltage and higher energy density and has the advantage of being lighter weight than Li-ion batteries. One of its main shortcomings is that it has a short shelf life.

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