Chapter 2
Principles of a Circular Economy for Batteries

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Contents

2.1 Definition of Circular Economy

The rapidly growing market for batteries in mobility and stationary applications leads to increasing amounts of battery material demand and returned waste batteries [45]. Battery materials like cathodes, anodes, the separator and electrolyte, connectors, casing and housing, safety equipment, and the battery management system cause environmental impacts in their supply chain, in the mining, processing, and fabrication stage [32]. These environmental impacts cause concern, not only because of the greenhouse gas (GHG) emissions related to resource extraction and processing [22] but also exposure to toxic substances, air pollution, water depletion, and land use [12]. One strategy to reduce these material-related impacts is to use products longer and use more recycled materials in their production—subsumed under the label of circular economy measures [42]. Other strategies include improving

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batteries' energy and power density, extending their cycle stability, reducing fabrication waste, and reducing battery production's energy and carbon intensity. Such strategies, however, are not the focus of this chapter.

The circular economy is a concept to keep materials in the loop. It is an alternative to a conventional, linear economy in which resources are used in production and consumption to provide utility to people and society. In contrast, the circular economy generates less to no waste, minimizing the need for final disposal and raw material extraction from the lithosphere [2]. In the circular economy, materials are still used in production and consumption, but their wastes are used again for the same or different purposes. This cycling, or at least cascading, minimizes the amount of material extracted from the lithosphere. Ideally, mining and quarrying would be limited to what is required to expand in-use stocks and replace unavoidable irreversible material losses [39]. The expansion of in-use stocks has been the norm for most material systems in the past century [25], and it is likewise crucial for modern technologies, like batteries [45], that have not yet reached some level of demand saturation [44].

Cyclical ecosystems formed by the circular economy are considered more sustainable than linear ecosystems because they reduce resource consumption and environmental impacts and provide an economic benefit. The reduction of primary material requirements comes from the increased use of materials recovered from waste, replacing materials mined or quarried from the lithosphere. Recycling generally reduces energy requirements, carbon footprints, and other environmental impacts. Of course, there is a risk for a circular economy rebound, nullifying the environmental savings [47]. For very high recycling rates, high energy requirements for collection, sorting, and processing can also reduce secondary production's environmental and cost benefits [41]. Implementing a circular economy reduces the negative environmental impacts of material extraction and expansion and increases raw mYaterial supply security. Therefore, the circular economy addresses resource scarcity concerns and reduces environmental impacts. In addition, it is also expected to provide economic benefits due to the value generation of material recovery, savings from extraction reduction, and avoidance of disposal [28].

Various definitions for the circular economy exist [24]. The interdisciplinary nature of the challenge can partially explain this. Closing the material loops is not just about understanding the material flows in society or developing recycling processes and long-living products designed for recycling. It also includes policy aspects of providing the proper legislative framework to foster the use of materials recovered from waste, installing take-back schemes, and many other material efficiency measures. Sociological aspects of understanding how behavior changes contribute to the use of fewer products, the use of more sustainable products, and the most efficient use of waste management systems also play their role in establishing a circular economy. An actual circular economy can be implemented by combining the micro-, meso-, and macro-systems perspectives [24].

The overall status of the implementation of the circular economy can be measured with two simple metrics: first, a perfect circularity would be achieved if recovered end-of-life material outputs met all material demand, and second, in an ideal circular economy, this would be happening without material quality losses, meaning that no extra energy would be required to recover materials [6]. Of course, this ideal is not practically achievable because of numerous material, metallurgical, and product design challenges [39]. Every loop in the circle creates dissipation and entropy, attributed to losses in quality (mixing, downgrading) and quantity (material losses, by-products) [20], making a fully closed loop impossible. Nevertheless, for the various reasons outlined above, it is desirable to close the loop as far as possible [6]. In addition, the technical, economic, and sociological challenges to closing material cycles of different materials, like base metals, specialty metals, plastics, pulp and paper, or construction minerals, are fundamentally different.

Batteries are an exciting sector for establishing a circular economy because they represent a rapidly growing market, with significant material demand, in parts, even Critical Raw Materials [19]. The battery sector is currently subject to technological changes, and the realization of circular economy benefits within this technological change would foster the transition to low-carbon technologies.

2.2 R-Imperatives of the Circular Economy

Many measures to install a circular economy are subsumed under so-called R-imperatives. Starting with short lists of just three "3Rs" like "reduce, reuse, recycle" and "recycle, remanufacture, reuse," the lists have gotten longer [24]. One list even consists of ten R-imperatives: refuse, reduce, resell/reuse, repair, refurbish, remanufacture, repurpose, recycle materials, recover energy, and re-mine [38]. Probably, talented wordsmiths will be able to extend these lists almost indefinitely. According to Walter R. Stahel, the R-imperatives in the concept of circular economy replace production with sufficiency: "reuse what you can, recycle what cannot be reused, repair what is broken, remanufacture what cannot be repaired" ([42], p. 435). In the Waste Hierarchy, a concept from the Waste Framework Directive of the European Union, waste prevention comes before preparation for reuse, recycling, recovery, and disposal [11]. Therefore, the R-imperatives can be hierarchical. Each R-imperative's potential for the circular economy depends on the maturity of a technology, its industrial sector, and inherent material properties.

Even the longer lists of R-imperatives follow three basic ideas to change the material cycles, corresponding to the three Rs of reducing, reusing, and recycling:

1. **Narrowing** material cycles (use less material overall).
2. **Slowing** material cycles (keep materials in use for longer).
3. **Closing** material cycles (keep materials in the loop).

Distinguishing between R-imperatives at different stages of material cycles ensures that various actors are addressed. Material cycles can be narrowed, slowed, and closed by bringing together consumers, producers, legislation, and the waste management sector. Figure 2.1 shows a product's different life cycle stages, from

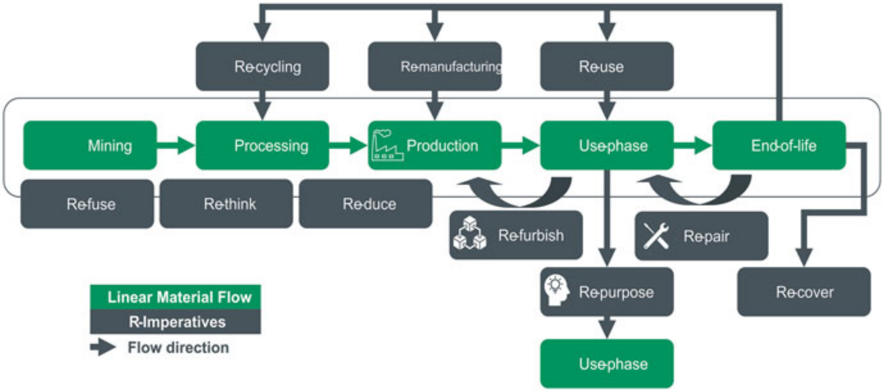

Fig. 2.1 Schematic visualization of the ten R-imperatives, refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover, and their corresponding impact on narrowing, slowing, and closing the material cycles

extraction to waste management, and ten corresponding R-imperatives along these stages.

Narrowing material cycles means that, overall, less material is used. **Refusing** to use a product is the first option to use less. An example is the “flygskam” initiative to reduce the need for air transport [5]. **Rethinking** a product in a circular economy means providing the same service with a wholly changed product design that is much less resource intensive. An example is film photography, which has been largely replaced with digital photography, making the production of photographic films obsolete, resulting in significantly lower demand for film development, reducing silver losses [8]. **Reducing** material use can be achieved by making products smaller and lighter or making the production process more efficient. For example, reducing floor space in private households reduces the construction material requirements and the energy demand for heating and cooling the building [35].

Slowing material cycles is achieved by implementing measures to prevent a product from becoming end-of-life waste. **Reusing** products means despite the will to dispose of a product by one consumer, the product in its current state still has value for another consumer and can still be used by someone else [4]. The used clothing market is the most prominent example. **Repairing** products extends their usage by investing just a minimal maintenance effort, much smaller than what would be needed for a replacement. Repair is common practice for valuable, intensively used mechanical products like cars, machines, and infrastructure [40]. **Refurbishing** goes a bit further than repairing as you don’t just want to reestablish functionality, but you might also invest in modernization. Apartments and houses are typically refurbished [37]. **Remanufacturing** means that parts of a product are used in a new product. The market for classic cars has a lot of experience with remanufacturing, and modular desktop PCs allow the reuse of individual components [15]. **Repurposing** extends the material life by changing the purpose of the product.

Batteries of electric vehicles can still be used in stationary applications if their capacity is not satisfactory for mobility applications anymore [13].

If the product and its components are unsuitable for these lifetime-extending measures, its materials can still be valuable. **Recycling** means obtaining materials that can be used as inputs for new products. Although that is desirable, recycled materials do not necessarily have to be of the same quality. Even downcycling counts as recycling [20]. Metals are materials where quality is generally maintained, and low loss rates result in relatively high recycling rates [14]. Some materials may be hard to recycle but provide a heating value. In these cases, thermal **recovery** is the last option in the Waste Hierarchy. An example of recovery is mixed waste plastics replacing fuels for energy recovery [18].

2.3 Battery Material Flows

Annual growth rates of the battery industry were about 30% in the past decade and are expected to be about 20% in the next two decades [36]. Until 2010, most global electrochemical storage capacity was in lead-acid batteries (LAB), with about 300 GWh of new electrochemical energy storage installed yearly, used chiefly as vehicle starter batteries [36]. LABs are positive examples of the circular economy being a mature market with established take-back schemes and recycling facilities. LABs are the main reason lead achieves relatively high circularity values compared to other base metals [21].

Since 2010, however, the focus has shifted to lithium-ion batteries (LIBs). Initially, LIBs were chiefly used in portable electronic devices; now, LIBs for electric vehicles dominate the market [36]. With this rapid market growth, concerns about resource availability and the environmental impact of LIB production have become increasingly important in recent years [19, 32].

For LIBs, the challenge of installing a functional circular economy is more prominent than for LABs. LIBs have vastly different sizes, shapes, types, and material compositions, affecting waste separability and the metallurgy of the recycling process. Battery cells for LIB consist of aluminum and copper foil current collectors, cathode and anode active materials, carbon binders, the electrolyte, and a porous separator. The cell, housing cover, and connection interface form the battery module. On the pack level, you can add a management controller, cooling system, frame and crash structure, and a battery pack housing cover [26, 33].

Technologically, there have been an extensive debate and a lot of development in terms of the cathode active materials, with the most prominent options for battery electric vehicles being nickel-cobalt-aluminum, nickel-manganese-cobalt (with various stoichiometric combinations of transition metals, from NMC111 to NMC811) [27], and iron-phosphate active materials. LIBs can also contain various critical materials, for which the establishment of material cycles is even more important and challenging [3, 26, 46].

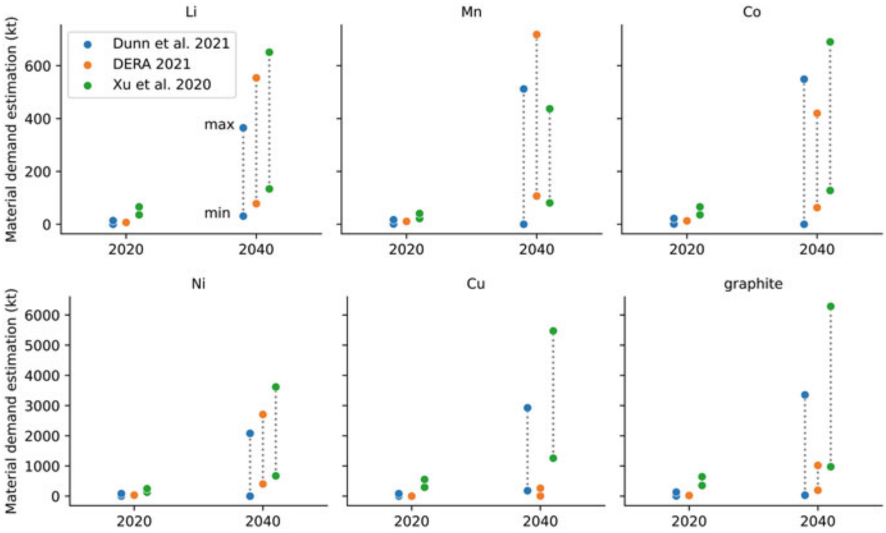

Fig. 2.2 Minimum and maximum estimations for the material demand of Li, Ni, Co, Mn, Cu, and graphite for batteries for 2020 and 2040 in scenarios of Xu et al. [45], Marscheider-Weidemann et al. (DERA 2021), and Dunn et al. [7] in kilotons (kt). The base year for material demand in Marscheider-Weidemann et al. [30] is 2018, not 2020, as no 2020 values were provided in the source. Furthermore, only one data point is specified for 2020

In the future, new battery technologies are expected to make additional raw materials and materials necessary, for example, sodium, calcium, or aluminum [1]. Some of these developments are explicitly undertaken to reduce the dependence on Critical Raw Materials, like cobalt, or other expensive metals, like nickel. It is crucial to close material loops to meet future material demands and reduce the environmental impact of battery production, especially for expensive, scarce, or environmentally harmful materials [32].

In the meantime, material demand and end-of-life material flow for lithium, cobalt, and nickel are expected to continue to increase [45]. Figure 2.2 shows the range of estimations of current and future material demand for lithium, nickel, cobalt, manganese, copper, and graphite in recent battery material flow studies. This ever-increasing material demand causes an issue in implementing the circular economy. The International Energy Agency estimates that by 2040, recycled copper, lithium, nickel, and cobalt from spent batteries could reduce the combined primary supply requirements for these minerals by around 10% [23]. The main reason is that you can only recycle what you have used in the past because of the time lag of the product's lifetime. From a resource savings perspective, product lifetimes should be extended to reduce the demand for new batteries, but the market has grown significantly when a battery becomes waste. Therefore, even with high end-of-life recycling rates for battery materials, the recycled content in batteries will remain low until some saturation level has been achieved and the in-use stock is not multiplying anymore. Such saturation is not expected to happen before the mid-century simply because of the massive demand for electrification in mobility and stationary storage applications.

2.4 Battery Design for Circularity

In the broad definition of the circular economy, more sustainable material cycles for batteries are not only a question of recycling. The goal is a holistic implementation of circular economy measures to reduce overall resource requirements and material-related environmental impacts. So how can the material cycles for batteries be narrowed, slowed, and closed comprehensively?

Narrowing material cycles in a rapidly growing market is a challenging task. However, significant efforts have already been made to reduce, for example, the required housing. Cell-to-pack technologies, for example, for LFP, have eliminated the module component and increased the battery's energy density, effectively reducing the amount of steel, aluminum, or plastic packaging that is not an active material in the battery. At its core, this is a "reduce" strategy, although here, it is chiefly used to increase the capacity of the vehicle battery. Circular economy strategies narrowing the material cycles are chiefly used for their Critical Raw Materials content, particularly for the partial or complete substitution of cobalt in batteries due to its high cost and conflict potential [3].

Battery material cycles can be slowed by prolonging battery life by designing cells that last for a long time and many charging cycles. Significant improvements have been made in terms of the aging stability of batteries, so it is now conceivable that an electric vehicle can drive on the same battery for 20 years and one million miles [16]. At the same time, electrolytes have been developed to allow faster charging without compromising cycle stability [29]. Batteries can also be leased to vehicle owners and afterward be used in less demanding applications, a strategy which can be identified as reuse, remanufacture, or repurpose strategy, depending on the amount of processing required and nature of the alternative use [3].

Battery material cycles can be closed by recycling the battery components [10]. Generally, one can distinguish many pyrometallurgical and hydrometallurgical processes and direct recycling routes [26]. The recoverability of contained Co, Ni, Li, Mn, Al, Cu, C, Fe, electrolytes, and plastics depends on the chosen process. Pack, module, and cell design also significantly impact battery dismantling and repair, remanufacture, and recycling options [43].

In general, the pyrometallurgical processes are more versatile regarding the battery chemistries and geometries. They have a high recycling capacity, require no sorting or pretreatment, and enable high recovery of valuable metals (Co, Ni, Cu). They are established and well-understood processes with industrial know-how [17]. On the downside, certain materials (graphite, plastics, and electrolyte) are burned and thus lost. The obtained products are often low purity and downcycled (e.g., Li and Al) or need further hydrometallurgical refinement. The pyrometallurgical process is expensive because of its high energy consumption and the need for off-gas treatment to remove toxins [17, 26].

Hydrometallurgical processes have high recovery rates, high purity of the products, low energy consumption, and low GHG emissions [17]. They have low recycling capacities. The batteries must be crushed to meet the purity and pretreatment requirements, which leads to safety problems. In addition, efficient methods for electrolyte deposition still need to be demonstrated industrially. The complex processes, the needed treatment of the final effluent (neutralization), the treatment of the contaminated wastewater, and other aspects of the process (e.g., solvents) lead to high operating costs [26].

Disassembly and pretreatments are always the first steps. In the case of the pyrometallurgical processes, the second step is directly smelting the pretreated LIBs. In addition, the alloy and the slag can be further refined by leaching, selectively precipitation, and solvent extraction. Alternatively, the disassembled and pretreated material can be converted into the so-called black mass through further mechanical treatment, which includes crushing, electrolyte separation, and mechanical separation. Afterward, the black mass can be processed through hydrometallurgical or direct recycling route. In the hydrometallurgical route, leaching, selective precipitation, and solvent extraction are used to recover the contained materials. In the direct recycling route, separating, regenerating, and producing new cathode active material are the goals [26]. While the direct recycling route provides the opportunity to obtain higher quality recyclates, it is not as mature as the pyrometallurgical or hydrometallurgical routes. Figure 2.3 shows the main process routes, advantages, and disadvantages for pyrometallurgical, hydrometallurgical, and direct recycling routes. For a more detailed description of the most important recycling processes and the corresponding efficiencies, the reader is referred to Chap. 4.3 of this book or to the work of Ekberg and Petranikova [9].

Mohr et al. [32] show that recycling could reduce the environmental impacts of lithium-ion battery production, both in the case of pyrometallurgical and hydrometallurgical processes. They highlight that the savings depend on the cell chemistry, particularly the cathode active material, and the environmental impact category, like abiotic depletion or global warming potential. Additionally, it is not always the process with maximum recycling depth that provides the most considerable environmental savings, which will become even more critical if the share of expensive materials in the battery decreases [32].

2.5 Circular Economy in the EU Battery Regulation

The European Commission adopted a new Battery Regulation with severe implications for the circular economy of batteries [31]. Among other things, the regulation also addresses various issues concerning the material cycles of batteries.

The Battery Regulation is meant to narrow material cycles if successful. It enables and guides the rise of batteries in electric vehicles and stationary applications, where

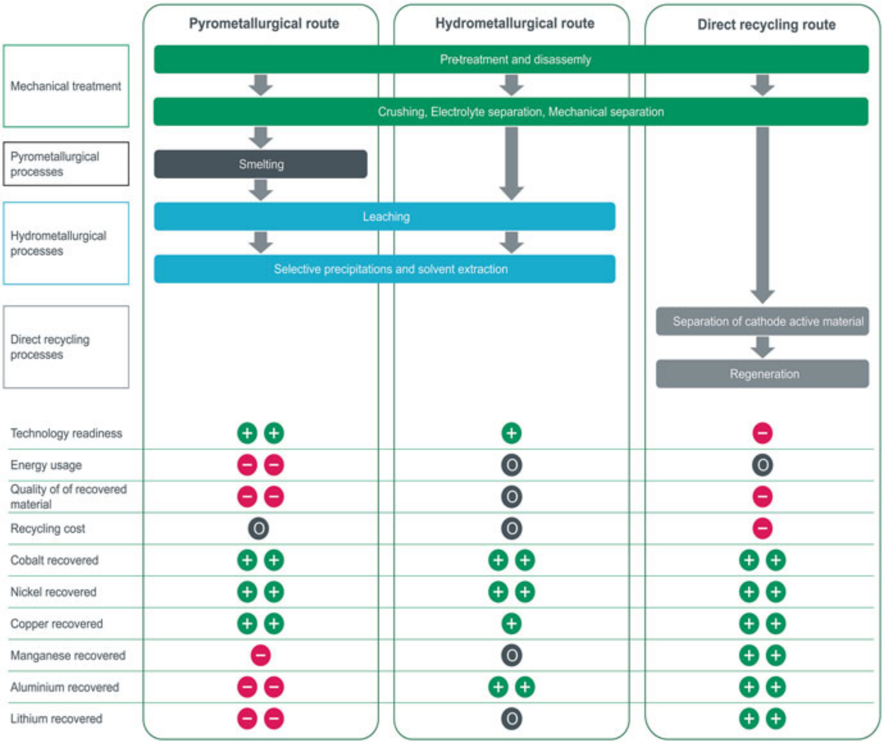

Fig. 2.3 Summary of pyrometallurgical, hydrometallurgical, and direct recycling routes for battery materials and their respective main advantages and disadvantages. (Adapted from Latini et al. [26] and Harper et al. [17])

they serve as electrochemical energy storage enabling the reliable use of renewable energy and thus replacing, at least in part, fossil fuels, which are by design not circular. Several articles of the regulation are relevant to the circular economy. The previously mentioned slowing and closing of material cycles are taken up, but the narrowing of material cycles is not considered.

Articles 9 to 11, 73, and 74 have an impact on slowing the material cycles. Articles 9 and 10 describe performance and durability requirements for batteries. Article 11 mandates the removability and replaceability of portable batteries in appliances, ensuring that the appliance stays in use in case batteries have a shorter lifetime than the appliance itself. Article 73 supports the repurposing and remanufacturing of batteries. Article 74 mandates producers to provide information on the dismantling and removal of batteries to support repair, remanufacture, preparation for reuse, treatment, and recycling.

Articles 8, 59, 69, and 71 close the material cycles. Article 8 mandates that the cobalt, lead, lithium, and nickel present in new EV batteries fulfill the requirements for minimum shares of material recovered from waste for each of the metals present.

As proposed, these minimum shares will be implemented in 2030 and raised in 2035. Article 59 sets targets for producers and article 69 for member states for minimum collection targets for waste of portable batteries. The proposed targets are gradually raised until 2030 when a 73% minimum collection rate shall be reached. Article 71, in combination with Annex XII, sets targets for recycling processes regarding their minimum recycling efficiencies based on the average weight of batteries, and levels of materials recovery, for cobalt, copper, lead, lithium, and nickel, respectively. By 2030, according to the proposal, an 80% recycling efficiency for lead-acid batteries and 70% for lithium-ion batteries shall be reached, enabling by 2031 a recovery of 95% for cobalt, copper, lead, and nickel and 80% for lithium.

The regulation is supported by various initiatives, such as the European Battery Alliance, and financial aid packages to support research and innovation along the entire battery value chain. But those benefits also come with risks, such as higher compliance costs, hindering innovation, technology adaptation, and competitiveness [31].

If implemented as the battery regulation proposal foresees, the contribution of recycling to meeting the raw material demand of battery production in Europe could be more than 40% for cobalt and more than 15% for lithium, nickel, and copper by 2040. Those numbers are based on a recycling volume of 150 to 300 kilotons of lithium-ion batteries and battery components per year in 2030 and 600 to 2500 kilotons in 2040 [34].

The Battery Regulation also proposes a battery passport with information on repair, disassembly, and, importantly, the carbon footprint of the battery from raw material extraction to the end-of-life phase, without the use phase. Such a mandatory carbon footprint, and in the future also carbon footprint classes and a threshold for marketing batteries in the European Union, supports the goal to reduce the overall environmental footprint of battery production. Therefore, the overall goal of the circular economy, avoiding unintended harmful environmental impact, is just as much tackled with the battery regulation proposal as the various mentioned R-imperative actions.

2.6 Outlook

In a way, batteries are already a contribution to the circular economy because they allow using reversible electrochemical processes for energy storage and, thereby, replacing single-use fossil fuels. However, the circular economy of batteries will be incomplete unless batteries are recycled after their product lifetime. Linear material flows for fossil fuels would only be replaced by take-make-waste processes for lithium, nickel, cobalt, natural graphite, and other battery materials. The battery regulation proposal is a cornerstone to prevent such linear material flows.

One should never forget that recycling alone cannot meet the material demand for building up the in-use stock in a growing market. Securing Critical Raw Materials supply is equally important to allow batteries to fulfill their purpose in the required transitions in the energy sector for global net zero carbon emissions. The R-strategies and recycling technologies mentioned above are necessary to reduce the total material demand for batteries, but they will not eliminate the demand. They are necessary but not a silver bullet. Therefore, the circular economy of batteries needs to be accompanied with material research and embedded in a more general sustainability strategy.

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