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BATTERY
ALLIANCE

BATTERIES POWERING
SUSTAINABLE DEVELOPMENT

WORLD
ECONOMIC
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COMMITTED TO
IMPROVING THE STATE
OF THE WORLD

Insight Report

# A Vision for a Sustainable Battery Value Chain in 2030

## Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation

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# Contents

# Preface

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The need for urgent and more intensive actions against climate change is broadly recognized. In support of this agenda, this report presents a simple yet profound vision: a circular, responsible and just battery value chain is one of the major near-term drivers to realize the 2°C Paris Agreement goal in the transport and power sectors, setting course towards achieving the 1.5°C goal if complemented with other technologies and collaborative efforts.

With the right conditions in place, batteries are a systemic enabler of a major shift to bring transportation and power to greenhouse gas neutrality by coupling both sectors for the first time in history and transforming renewable energy from an alternative source to a reliable base. According to this report, batteries could enable 30% of the required reductions in carbon emissions in the transport and power sectors, provide access to electricity to 600 million people who currently have no access, and create 10 million safe and sustainable jobs around the world.

This report provides a quantified foundation for a vision about how batteries can contribute to sustainable development and climate change mitigation over the coming decade. The analysis underscores that this opportunity can only be achieved sustainably through a systemic approach across social, environmental and economic dimensions. It outlines key conditions and presents recommendations to realize this potential.

Batteries can serve numerous purposes – if the expected scale up of the global battery demand by more than 19 times current levels over the next decade occurs sustainably. Indeed, although batteries are required to help tackle climate change, this cannot be achieved without a fundamental change in the way materials are sourced and this technology is produced and used.

These challenges can only be addressed in collaborative efforts along the value chain. The Global Battery Alliance seeks to offer a platform to enable this collaboration. As a unique public-private partnership with over 60 member organizations, it was initiated by the World Economic Forum in 2017 with the aim to transform the value chain towards powering sustainable development and climate change mitigation.

This analytical report is a product of the Global Battery Alliance. The alliance will now determine how it can commit to actions to realize this vision of a sustainable battery value chain, in partnership with other stakeholders.

The World Economic Forum and the Global Battery Alliance are grateful for the many insights from Global Battery Alliance members and other report contributors. Analytical support was provided by McKinsey & Company, with additional work carried out on circular economy dimensions by SYSTEMIQ.

We hope you will find this work informative and invite you to become an active part of this important endeavour.

# Executive summary

## The 2030 vision: A world in which batteries power sustainable development

Batteries have tremendous potential: they are a key technology to achieve the Paris Agreement, can create new jobs and significant economic value, can increase energy access, and can drive a responsible and just value chain.

This report describes an ambitious vision for the battery value chain by 2030, the most important levers for realizing batteries' positive impact, and a set of recommendations to pivot the development of the value chain towards that vision. The report calls for immediate action to realize short- and long-term opportunities. It does not aim to be conclusive but is a foundational piece for additional analysis and consultation to identify further risks and develop implementation strategies.

The 2030 vision of the battery value chain consists of three elements (see Figure 1):

### A circular battery value chain as a major driver to meet the Paris Agreement

- Batteries are the major near-term driver to decarbonize road transportation and support the transition to a renewable power system, keeping global emissions on track to stay below the 2°C Paris Agreement target (see Figure 14). However, to achieve this and, even further, to achieve the 1.5°C Paris Agreement target, concerted action with other industries and technologies (e.g. hydrogen) are required as well.
- Batteries directly avoid 0.4 GtCO$_2$ emissions in transport and contribute to enable renewables as a reliable source of energy to displace carbon-based energy production, which will avoid 2.2 GtCO$_2$ emissions – together roughly 30% of required emission reductions in these sectors until 2030 (Scope 3 greenhouse gas (GHG) emissions).
- The battery value chain halves its GHG intensity by 2030 at a net economic gain, reducing 0.1 Gt emissions (Scope 1 and 2 GHG emissions) within the battery value chain itself and putting it on track to achieving net-zero emissions in 2050.

**Figure 1:** Vision for a sustainable battery value chain

**A circular battery value chain as a major driver to meet the Paris Agreement target**

**A circular battery value chain that is a major driver to achieve the Paris Agreement target to stay below the 2°C scenario**

Enable 30% of the required emission reductions in transport and power sector

**Transformation of the economy in the value chain, creating new jobs and additional value**

Create 10m jobs, and 150b of economic value in a responsible and just value chain

**An industry safeguarding human rights, supporting a just energy transition and fostering economic development, in line with the UN SDGs**

Provide 600m people with access to electricity, reducing the gap of people without electricity by 70%

Source: World Economic Forum, Global Battery Alliance

Transformation of the economy in the value chain, creating new jobs and additional economic value

- The battery value chain sustains 10 million additional safe, fair and good-quality jobs globally in 2030, of which more than 50% are in emerging economies.

- Approximately $150 billion of economic value are realized in 2030 by lowering battery costs, leading to 35% higher battery demand versus the 2030 base case and faster deployment of batteries, hence multiplying their benefits.

A value chain safeguarding human rights, supporting a just energy transition and fostering economic development, in line with the UN Sustainable Development Goals (SDGs)

- Batteries, in battery-solar systems and as part of microgrids and off-grid solutions, enable affordable energy access for around 600 million people, reducing the gap of households without electricity by 70%.

- The battery value chain has safe working conditions, avoids environmental impact and fosters transparency and anti-corruption practices.

- Battery value chain stakeholders demonstrate respect for human rights by taking decisive steps towards eliminating child and forced labour.

- The industry operates transparently within accepted international practices and norms that enable sustainable and profitable business models.

## Now is the time to change the trajectory of the value chain

The vision and its positive impacts will not be realized if the value chain develops along its current trajectory. The time to pivot is now as the remaining "carbon budget"[1] is running out – without batteries, this budget will be used up by 2035. If the deployment of batteries is not accelerated, decarbonization will come too late.

Acting now is also a chance to shape an emerging value chain, while acting later requires costly reconfiguration and leads to the exacerbation of social and environmental impacts.

Batteries are the major near-term driver of this pivot. Automotive original equipment manufacturers (OEMs) are launching more than 300 electric vehicle (EV) models in the next five years. Cost efficient and sustainable batteries, as well as a supporting ecosystem for battery-enabled dispatchable renewable energy deployment, and a dense charging infrastructure network are preconditions for broad customer acceptance and economically viable powertrain transition. Eventually, further complementary technologies (i.e. fuel cells) must be integrated into the transport and power sectors to stay on track to meet the Paris Agreement.

The challenges with regard to batteries are twofold: how can the deployment of batteries be accelerated and how can these batteries be produced responsibly and sustainably? To accelerate deployment, more investment needs to be attracted along the entire value chain as well as into application infrastructure (e.g. charging infrastructure). Moreover, batteries need to become more affordable through lower production costs, higher utilization and improved business cases for end users. To produce these batteries responsibly and sustainably means lowering emissions, eliminating human rights violations, ensuring safe working conditions across the value chain, and improving repurposing and recycling.

## A set of levers to achieve the vision

To pivot the trajectory of the value chain and address these challenges, the most impactful levers were identified. For example, the levers more than double the saved emissions of a mid-sized EV in China in 2030. They effectively reduce battery costs by another 20%, resulting in a 35% demand increase in the target state, enabling, for example, an additional 17 million EVs –hybrid, plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) – to be sold in 2030. They will ensure that the value chain operates transparently within accepted international practices and norms that enable sustainable and profitable business models.

The most impactful environmental levers also yield superior economic value

Moving from a linear to a circular value chain can improve both the environmental and the economic footprint of batteries by getting more out of batteries in use, and by harvesting end-of-life value from batteries. This enables a reduction in the GHG intensity of the value chain by 34 megatons (Mt), while creating additional economic value of around $35 billion. Vehicle-to-grid (V2G) solutions could lower the costs for electric vehicle charging infrastructure by up to 90% and in 2030 could cover 65% of demand for battery storage powering grids globally.[2] Five levers are expected to be most impactful: electric shared mobility; smart charging (V1G) and V2G; refurbishment and repair; the repurposing of EV batteries after use; and recycling.

### Business and technology levers reduce costs and environmental impact

Innovation along the value chain is needed to improve value creation and reduce environmental impacts. Applying them, for example in the production of active materials, other components and cell manufacturing, these levers address 70% of total GHG emissions in battery production. The following four levers are most important: switching to cleaner battery production through renewables; innovating the battery technology; improving application technology; and leveraging the value chain and finance to address sustainable impact in local communities.

### A responsible and just value chain enables batteries to do good

To deliver positive social and environmental impact, three levers are most important for the battery value chain to implement: complying with internationally accepted social and environmental norms; implementing best practices; and accessing electricity.

## Immediate actions to shift the development of the battery value chain towards the target vision

The sustainable expansion of the battery value chain offers many environmental, social and economic benefits. It will, however, not be achieved without an active shift from the current development trajectory. This requires coordinated, immediate actions by companies, investors and policy-makers, in consultation with all stakeholders.

To initiate this shift, 10 concrete actions are proposed to develop a circular battery value chain, accelerate sustainable business and technology development, and improve responsibility in the value chain.

### Circular value chain and connected business cases

- **Implement design and systems for life extension and end-of-life treatment:** International convention bodies, regulators, battery manufacturers and vehicle manufacturers need to work together to: 1) enable the exchange of data among key stakeholders to improve the economics of life extension through repair and refurbishment, and recycling; 2) foster product design and technical development to facilitate disassembly for repurposing, repair and recovery of materials; and 3) harmonize national and international rules to ensure the safe and economic transport of batteries. A battery passport would support data sharing on dimensions such as materials chemistry, origin, the state of health of batteries, or chain of custody. It could provide a powerful means to identify and track batteries throughout the life cycle and, in the near term, support the establishment of systems for life extension and end-of-life-treatment.

- **Implement V1G and V2G:** Battery manufacturers, vehicle manufacturers and utilities need to work together to make V1G and V2G technically possible on a large scale, while regulators need to allow and incentivize them.

- **Scale up electric shared and pooled mobility:** Vehicle manufacturers need to accelerate the development and commercialization of purpose-built EVs for sharing. Regulators should incentivize electric shared mobility, e.g. via preferred public procurement for EVs, fleet regulations (e.g. on taxis) and incentives for electric shared mobility.

### Sustainable business and technology

- **Increase the share of renewable energies and energy efficiency measures in the battery value chain:** Companies in the value chain should switch from fossil fuels and conventional power to renewables, as well as reduce leakages and waste during production.

- **Accelerate the roll-out of V1G infrastructure:** Public stakeholders and private companies should take concerted action to increase public charging infrastructure for EVs, allowing for V1G and V2G services, to enable a smooth economic transition to sustainable mobility.

- **Adjust regulation for battery-enabled renewables as a dispatchable source of electricity for the grid:** Regulators should review and revise the regulatory framework for battery-enabled renewables as a dispatchable source of electricity, in conjunction with V1G and other strategies to address intermittency, to make best use of batteries in the electricity grid.

- **Finance the sustainable expansion and support value creation and economic diversification in local communities:** Investors, both private and public, should require the noted sustainability elements in the development of the value chain. Instruments like “green bonds” and “blended financing”, tied to the implementation of recommendations in this report, will shift the value chain to provide financial, environmental and social returns. Comprehensive local development strategies should be advanced that support value creation and address the various dimensions of sustainable impact in local communities, including eliminating child and forced labour, fostering safe and quality jobs, and providing energy access. Public and private finance should be leveraged effectively along the value chain to support these strategies.

## Responsible and just value chain

- **Ensure consistent performance and transparency based on established sustainability norms and principles along the value chain to improve the social, environmental and economic performance of batteries:** Stakeholders across the battery value chain need to commit to established international expectations and key performance indicators on social and environmental practices, ensuring transparent impact measurement as well as the exchange of best practices. Such established expectations include the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas and the UN Guiding Principles on Business and Human Rights. Consistent due diligence and reporting are necessary conditions to improve the sustainability performance of the value chain. The aforementioned battery passport could be extended over time to provide transparency with respect to key life cycle accountability data on social and environmental dimensions. National legislation could support the implementation. Companies in the value chain, regulators across countries, as well as labour, civil society and international organizations should verify compliance with internationally accepted social and environmental practices, along with a rigorous monitoring and evaluation framework based on best practices, for sourcing to address child and forced labour and improve conditions in artisanal small-scale mining of materials used in batteries. Separately, safe production and transportation across the value chain, including at the end of life, must be verified. A comprehensive evaluation of risks should guide the decision-making across the value chain where it might cause harm and reverse the positive impact of batteries.

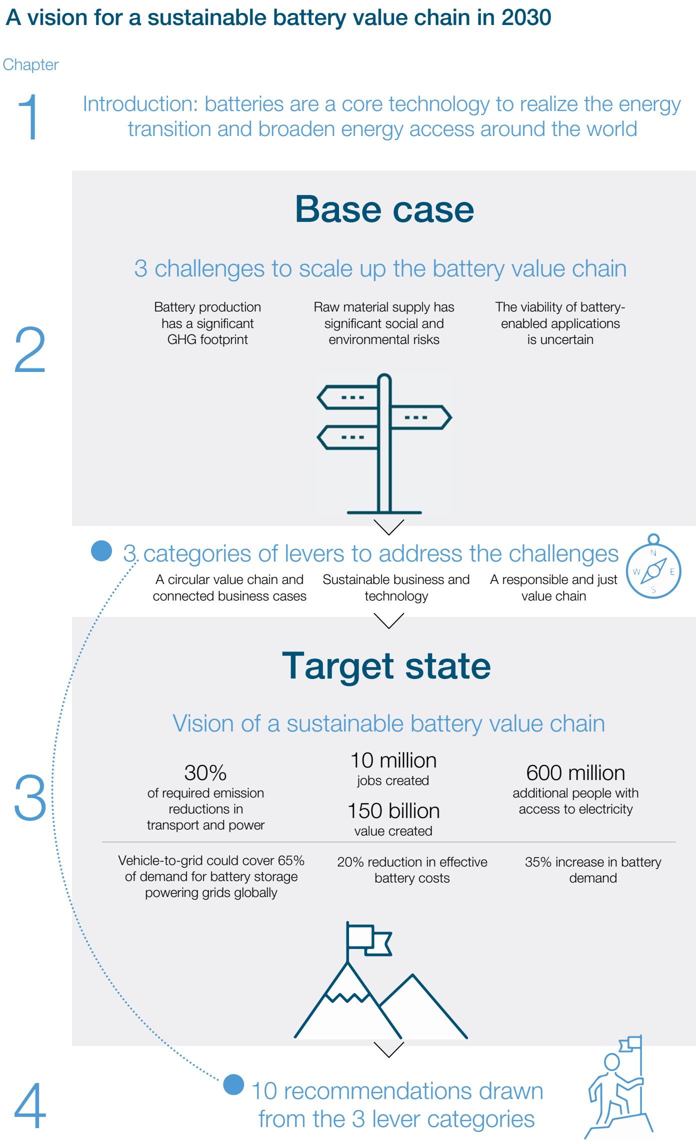
- **Establish integrated GHG disclosure and emission regulations:** To increase the focus on Scope 3 emissions, policy-makers should establish regulations based on life cycle emissions. Private-sector companies, alike, need to commit to verified GHG disclosure based on life cycle considerations.

- **Support the deployment of batteries for energy access:** Financial institutions, energy utilities and public policy-makers, in partnership with battery manufacturers, need to advance the design and deployment of affordable battery applications in mini-grid and off-grid solutions in areas so far lacking access to electricity.

As laid out, the potential of batteries is substantial. They are key to realize the Paris Agreement goals and support the UN SDGs and can create a vibrant, responsible and sustainable market.

Figure 2 summarizes the report structure.

**Figure 2:** Illustration of the report structure



# Methodology

The analysis in this report is underpinned by an analytical fact-base and a model of the battery value chain. The analysis focuses on lithium-ion batteries and their application in road transport, energy storage as well as consumer electronics. A short overview of lead-acid batteries is included as a separate section in this report.

The model focuses on a time horizon until 2030, and simulates material flows along the value chain, associated energy use and GHG emissions. It also models value flows and associated investments. Economic benefits are assessed based on value creation within the value chain. Other economic benefits or costs, e.g. societal benefits on the health system from reductions in local air pollution, were not part of the quantitative analysis. The risk assessment on social dimensions (e.g. working conditions, child labour) as well as on other environmental dimensions (e.g. water and air pollution) were not quantitatively analysed but their impacts are characterized based on interviews and research of the literature.

The fact-base and model were developed in a three-step approach. First, a "base case" was constructed, and material flows, emissions and value flows modelled.

– Material flows for the base case are based on the expected future demand of batteries. This demand, in turn, was modelled for mobility, energy storage and consumer electronics using base case assumptions for battery technology development and innovation in the mining and production processes.

– GHG emissions and value flows were modelled using energy intensities and expected cost developments for batteries, components and materials.

– For the assumptions, proprietary databases and models from McKinsey & Company (e.g. the Energy Insights Global Energy Perspective) and SYSTEMIQ were used, as well as stakeholder perspectives, research papers and expert interviews. A full list of sources appears in the bibliography.

Second, major levers that can positively influence GHG emissions and/or value flows were identified and described and their impact estimated.

– Levers were identified based on existing analyses and were augmented based on stakeholder discussions.

– Potential "target state" aspirations for each of these levers were then developed, and impact on GHG emissions and value flows simulated.

Third, after simulating both "base case" and "target state" outcomes, multiple quality and feasibility tests on the developed scenarios were conducted. On GHG emissions specifically, the model was used to estimate:

– The GHG emission reduction potential of the identified levers on Scope 1 and Scope 2 emissions within the battery value chain

– The contribution to GHG emission reduction in the transport and power sectors through additional adoption of battery-powered mobility applications and energy storage systems (Scope 3 emissions to the battery value chain).

# Chapter 1 – Batteries are a core technology to realize the energy transition and broaden energy access around the world

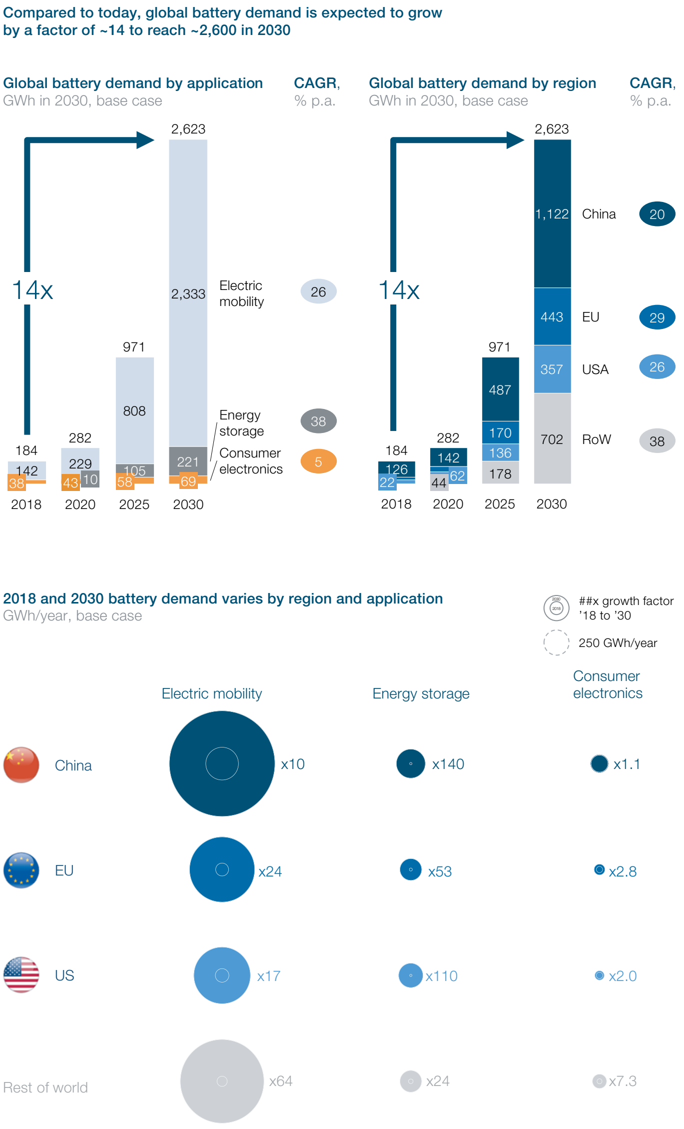
Global battery demand is expected to grow by 25% annually to reach 2,600 GWh in 2030. Batteries play an increasingly important role in three areas: 1) decarbonizing transport through electrification; 2) enabling the shift from fossil fuel to renewable power generation as a dispatchable source of electricity; and 3) helping to provide access to electricity to off-grid communities. This means batteries can fundamentally reduce GHG emissions in the transport and power sectors, which currently comprise roughly 40% of global GHG emissions, and contribute to the UN SDGs.

## Battery demand is growing rapidly

Between 2010 and 2018, battery demand grew by 30% annually and reached a volume of 180 GWh in 2018. In the base case, the market is expected to keep growing, at an estimated 25% annual rate, to reach a volume of 2,600 GWh in 2030.

The main drivers of demand growth are the electrification of transportation and the deployment of batteries in electricity grids (see Figure 3). By 2030, passenger cars will account for the largest share (60%) of global battery demand, followed by the commercial vehicle segment with 23%. Geographically, China is the biggest market with 43%. Consumer electronics, which account for more than 20% of the market today, will represent only a marginal share of the global battery market in 2030.

**Figure 3:** Global battery industry growth by application and region by 2030



Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

## Batteries are a key technology to achieve the Paris Agreement and support the UN SDGs

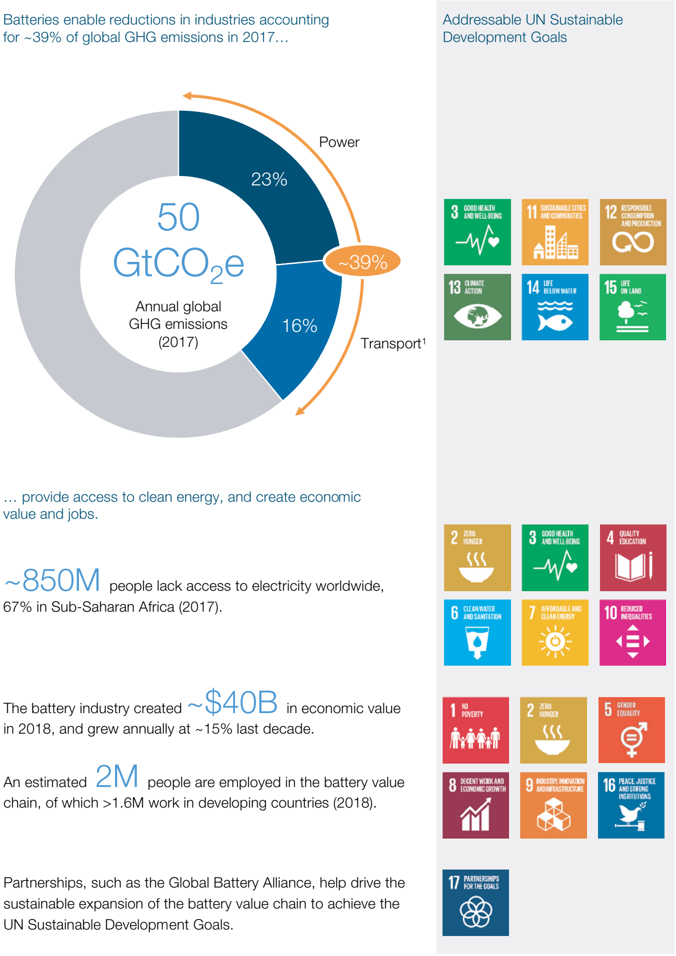
Batteries act as energy storage in EVs, and more than 34 million EVs (hybrid, PHEVs and BEVs) are expected to be sold in 2030, according to the base case scenario. They also can be an energy buffer in the power system, supporting the integration of renewable energy generation as a major base source.

This contribution is critical to realize the Paris Agreement. Together, the transport and power sectors currently comprise around 40% of global GHG emissions. The Paris Agreement has set out the ambition to "[keep] global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius". This 1.5°C target would require net-zero global human-caused $CO_2$ emissions by 2050. According to a recent Intergovernmental Panel on Climate Change (IPCC) special report,[3] 45% of global human-caused $CO_2$ emissions need to be reduced by 2030 compared to 2010 levels to achieve that objective.

Besides decarbonization, batteries also contribute to the UN SDGs directly and indirectly (see Figure 4). For example, they enable decentralized and off-grid energy solutions. Bringing energy to the 850 million people without access to electricity today can increase productivity, improve livelihoods and improve health on a large scale.

**Figure 4:** Sustainability benefits of batteries

**The impact of the global battery industry spans across a variety of UN Sustainable Development Goals**



~850M people lack access to electricity worldwide, 67% in Sub-Saharan Africa (2017).

The battery industry created ~$40B in economic value in 2018, and grew annually at ~15% last decade.

An estimated 2M people are employed in the battery value chain, of which >1.6M work in developing countries (2018).

Partnerships, such as the Global Battery Alliance, help drive the sustainable expansion of the battery value chain to achieve the UN Sustainable Development Goals.

[1] The transport sector includes road, rail, marine and aviation.

Source: EU Publications Office; PBL Netherlands Environmental Assessment Agency, 2018; IEA, IRENA, UN Statistics Division, World Bank Group, WHO, 2019; World Economic Forum, Global Battery Alliance

## Batteries enable the decarbonization of road transport

Road transport emissions account for 5.8 $GtCO_2e$ per year – almost 75% of all transport GHG emissions and 11% of global GHG emissions. Within road transport, passenger road transport is the largest emitter with 4.0 $GtCO_2e$, followed by commercial road transport with 1.8 $GtCO_2e$.

Electrification is the key decarbonization lever for road transport. In use, EVs currently emit 30-60% fewer emissions than combustion engines depending on the power mix. Without action, global road transport emissions would continue to grow as a result of increased transport needs supplied by fossil fuels. However, electrification helps to decouple growth and $CO_2$ emissions (see Figure 5). Next to reducing $CO_2$ emissions, EVs also help to improve local air quality by avoiding other toxic emissions, for example, nitrogen oxide or particulate matter.

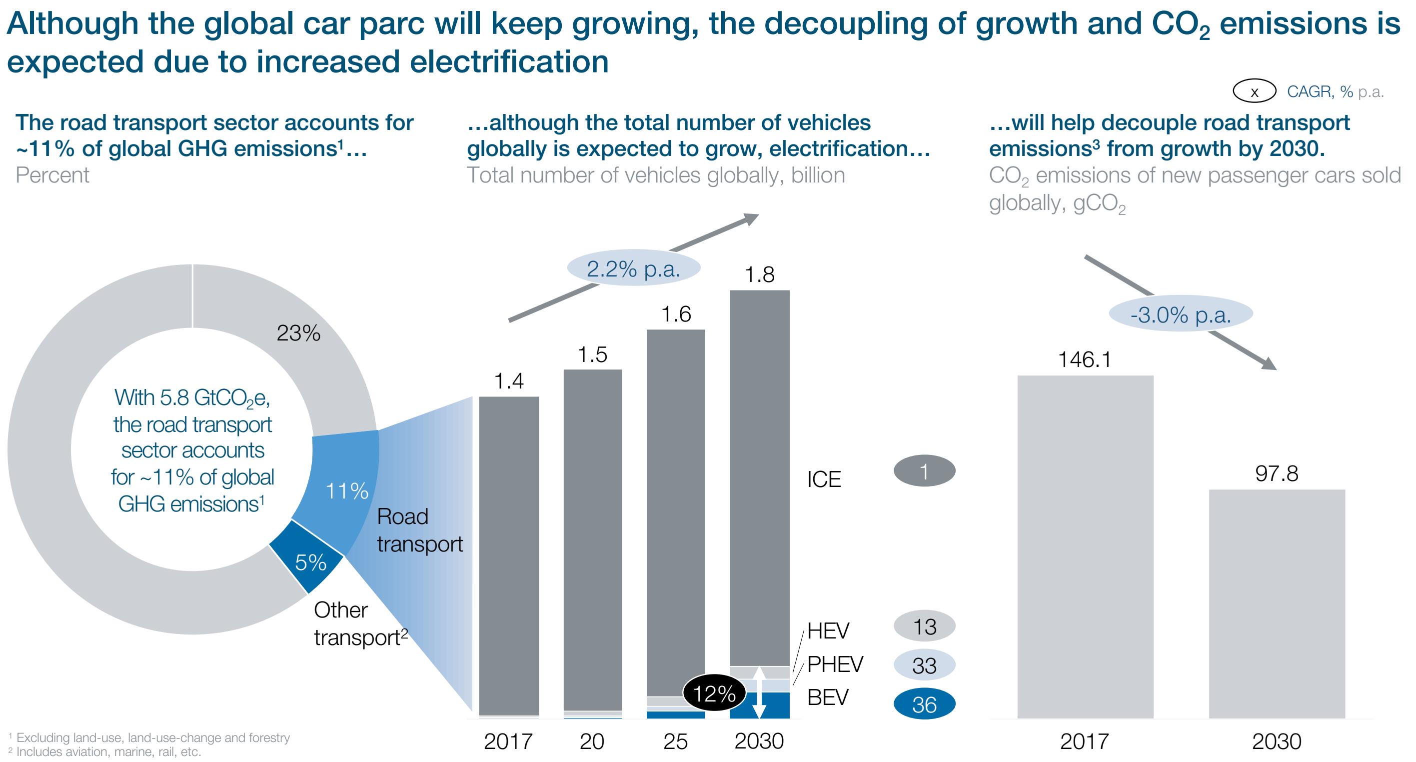
Electrification is affecting all modes of road transportation. A rough breakdown of road transport presents three segments: passenger cars, commercial vehicles (low-, medium- and heavy-duty trucks and buses) and 2-3-wheelers. This report focuses on the implications of batteries on passenger cars.

However, electrification is also experiencing strong momentum within commercial vehicles. The electrification of city buses, for example, is growing significantly faster than that of passenger cars and trucks. For 2030, a market share of e-buses of 75% is expected in Europe. However, the largest e-bus market in the world is China. Already today, some 380,000 e-buses operate in China compared to only 1,500 in Europe. While commercial vehicle unit sales per year are factor 15 below passenger cars, their share in emissions in road transport accounts for roughly 30%. An electrification of commercial vehicles, therefore, has an overproportionate effect on emission avoidance in road transport.

> **“In use, EVs currently emit 30-60% fewer emissions than combustion engines depending on the power mix.”**

Passenger car transport is expected to electrify at a fast pace. In the base case, 215 million electric passenger vehicles (including hybrid, PHEVs and fully electric vehicles) will be on the road by 2030. This implies a 23% growth in new sales of electric passenger vehicles every year from 2018 to 2030. The principal drivers behind this demand growth are favourable regulations as well as increased consumer demand.

**Figure 5:** Electrification to decouple growth and $CO_2$ emissions, despite global car parc growth



[1] Excluding land-use, land-use-change and forestry
[2] Includes aviation, marine, rail, etc.
[3] Tank-to-wheel emissions

Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

Over the medium term, the main driver behind increased consumer demand for EVs is their improved value proposition. EVs will become both cheaper and more convenient. On a total cost of ownership (TCO)[4] basis, EVs are expected to achieve parity with fossil fuel-powered vehicles across the globe within the next decade. The timing of this breakeven varies based on different fuel and electricity prices, taxes, use cases, vehicle segments and subsidies. When EVs are used a lot, for example when they operate as taxis, their lower operating expenses result in TCO parity in most segments and regions already today.

Along with lower costs, customer convenience improves as more public (fast-) charging stations are deployed. The expanding charging network also unlocks wider EV use cases, including applications such as long-distance travel.

Governments have a range of policies to boost adoption. Financial subsidies and non-financial incentives (e.g. priority parking) increase consumer pull. Regulation placed on producers create a supply push. For example, Brazil, China, Europe, India, Mexico and North America have enacted low carbon fuel standards (LCFSs) targeting lower GHG emissions from new cars and imposing financial penalties if these are not met. In Europe, for example, emissions are capped at 95 $gCO_2$/km from 2020 onwards and are required to fall another 37.5% to 59 $gCO_2$/km in 2030.[5] To hit the 2030 target, 25-40% of new vehicle sales need to be EVs. Some national governments have even defined targets for banning ICE vehicle sales as soon as 2025.

Besides reducing carbon emissions, the reduction of local emissions is also a key driver for electrification. Cities seek to protect their populations against harmful local emissions, such as particulates, and have started to enact zero- and low-emission-zones. Another driver is energy security; EVs that do not require fossil fuels reduce the dependency on energy imports.

## Batteries facilitate the uptake of intermittent renewable energy sources by acting as a flexibility solution

With 11.9 $GtCO_2$, the power sector accounted for 23% of global GHG emissions in 2017. Across most markets, the energy mix is shifting towards intermittent renewables. In 2030, it is expected that 380 GW of additional renewable power generation capacity will be added, while generation from global fossil sources will decrease.[6] In some markets, e.g. Germany and California, more than 50% of energy supply will come from renewables and intermittent renewable generation will account for more than 50% of the electricity supply post-2035.

> “Grid-connected batteries are expected to be the dominant flexibility and stability solution in 2030.”

The intermittent nature of renewables will drive strong growth in demand for balancing-solutions that enable renewable energy to be available when needed. Batteries are ideal short-term energy buffers and can be used both at large scale (“front-of-meter”) as well as close to an energy user (“behind-the-meter”). They are more flexible than other options, such as pumped hydro, as they do not require special geographical circumstances and they can be deployed both on large and small scales. They have a very low response time, making them suitable for grid stabilization measures.

Grid-connected batteries are expected to be the dominant flexibility and stability solution in 2030 with roughly 220 GWh expected to be installed. From 2015 to 2018, energy storage battery demand grew by 60-70% per year. The main underlying drivers of growth are:

- Higher shares of intermittent renewables – beyond a certain share of intermittent renewables, depending on the individual country, every additional GW of wind capacity implies the need for roughly 1 GWh of battery capacity, and every additional GW of solar capacity around 3 GWh of battery capacity.[7]

- Transmission and distribution investment deferral – grid batteries represent an alternative to expensive upgrades of power transmission and distribution infrastructure in peak capacity constraint regions.

- Power system decentralization – the power system becomes increasingly decentral with consumers becoming energy producers (e.g. using rooftop solar systems). The more decentral the energy systems become, the larger the benefit of batteries in balancing loads.

- Frequency control – short-time energy production fluctuations of renewables caused by changing weather can unbalance the grid frequency; batteries enable the availability of renewable energy during these circumstances.

- Commercial and industrial solar plus storage – large roof surfaces of commercial and industrial buildings make it financially attractive for solar power generation combined with storage technologies.

## Batteries enable decentralized energy solutions, driving access to reliable energy for off-grid communities

From 2010 to 2017, tremendous progress was made in providing electricity to more than 350 million people who lacked electric power previously. Most progress was made in Asia, where 91% of the population now has access to electricity. Electrification rates across Africa remain low, however, with roughly 45% of the population lacking access.[8]

Bringing electricity to the remaining 850 million people who lack access will be more challenging for three reasons: 1) remaining populations are scattered/dispersed, making an at-scale approach more difficult; 2) remaining populations are located further away from electricity grids, making infrastructure investments higher; and 3) remaining populations have a relatively low income, making market-based solutions less viable.

Batteries can help to overcome these challenges and increase the supply of affordable access to clean and reliable energy through microgrids, solar home systems and solar lanterns (see Figure 6).

The benefits of bringing electricity to off-grid communities reach beyond access to affordable clean energy (as defined in SDG 7). Providing power solutions to these communities contributes to the following SDGs, in particular:

– 2. Zero hunger: batteries enable better food storage through refrigeration and enable the use of electric pumps for land irrigation.

– 3. Good health and well-being: battery-based replace fuel-based lighting and cooking sources, thereby reducing toxic fumes; batteries also help to stabilize the medical cold chain and to power remote local health centres.

– 4. Quality education: batteries enable children to study after sunset and provide electricity to schools in remote areas.

– 6. Clean water and sanitation: batteries improve clean water supply as they enable the use of electric pumps.

– 10. Reduced inequalities: batteries help improve economic opportunities as they provide access to basic services, such as lighting, phone charging and access to (nutritious) cold chain products.

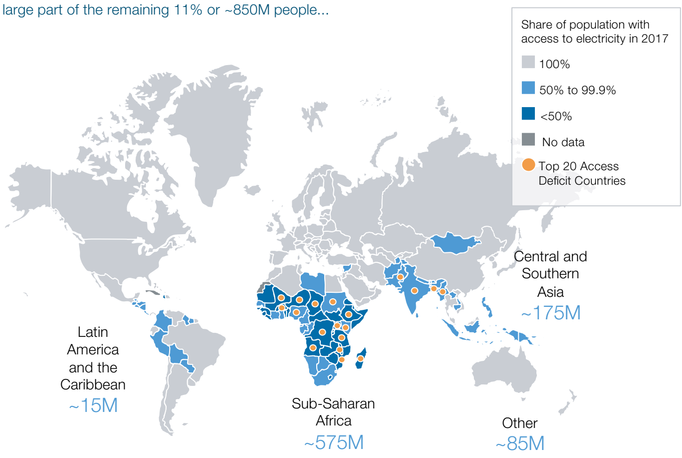
In addition, developing a basic electricity infrastructure for these underserved regions can create further opportunities by attracting new businesses, creating well-paid jobs and providing the infrastructure for (micro) e-mobility solutions.

To summarize, batteries play a crucial role in driving the energy transition by enabling EV uptake, facilitating intermittent renewable uptake and driving access to electricity to communities with no or poor access to the electricity grid. However, expanding the battery value chain related to this increasing role comes with several challenges that must be addressed. This report aims to highlight these challenges and provide a clear vision of how to overcome them.

**Figure 6:** Battery solutions to provide 850 million people with access to electricity

**Batteries enable solutions that could provide ~850M people with access to electricity**

89% of the global population has access to electricity, a large part of the remaining 11% or ~850M people...



… can gain access through a combination of battery enabled microgrids, solar home systems and solar lanterns.

| Type of technology | What it would take | Population characteristics | Power provision |
|---|---|---|---|
| Microgrid | Solar panels covering an area of >100K football fields | Populations in communities that reach sufficient scale (e.g. >80 households) | Similar service to basic on-grid that provides light, charging, TV, etc. (e.g. 250-500 watts) |
| Solar home system (SHS) | Investment of >$10B in SHS (>60M units) | Populations in dispersed communities (e.g. <80 households) | 1 SHS per household with multiple options available, most charge 4 lights, a torch, a radio and cell phones, and some charge TVs as well (e.g. 50-150 watts) |
| Solar lantern | About ~70M solar lanterns | Populations in very rural areas or who are nomadic and require mobility | ~2 lanterns per household that can be single function (lighting) or multifunction (mobile charging and lighting) |

Source: World Bank, 2017; McKinsey analysis

# Chapter 2 – The base case: Scaling the battery value chain to meet a 14-fold growth in demand is a tremendous opportunity that comes with a variety of challenges

This chapter describes a scenario of *unguided* value chain growth over the coming decade. Scaling battery production by a factor of 14 to 2,600 GWh in 2030 in this base case scenario is a tremendous opportunity for each step of the value chain. Annual battery production revenues are expected to grow to $300 billion in 2030 and, over the next decade, $440 billion in cumulative investments along the value chain will be required.

However, without deliberate interventions, this growth will go hand-in-hand with a high social and environmental toll as well as with untapped economic potential. Three specific challenges stand out: 1) battery production has a significant GHG footprint; 2) the battery value chain has significant social, environmental and integrity risks; and 3) the viability of battery-enabled applications is uncertain.

To meet the base case demand of 2,600 GWh in 2030, supply and production capacities need to increase along all steps of the value chain, from mining through cell production and recycling.[9] The following examples illustrate the expected increase.

**Raw material mining:** The raw material demand driven by battery applications will experience unprecedented growth in the coming years. The supply of major raw materials for batteries will need to increase by factors between 4 (cobalt) and 24 (class 1 nickel[10])[11].

- **Lithium:** Almost half of today's lithium is mined for battery-related purposes. With the steep increase in battery demand, lithium supply will need to increase by a factor of 6 from 2018 to 2030. Lithium is well distributed in the Earth's crust, and the major deposits with high grades are in Australia, Chile and Argentina. Owing to the relatively low capital-intensive operations, when lithium prices were high, many new entrants announced projects and started their production, resulting in a currently oversupplied market.

- **Nickel:** Nickel reserves are relatively scattered around the world with seven countries accounting for 7-20% of the volume each (Australia, Brazil, Canada, Indonesia, New Caledonia, the Philippines and Russia). Today, major applications for nickel mostly fall outside of batteries (e.g. stainless-steel fabrication) that, to a large extent, use class 2 nickel with low purity levels. With the growing demand for batteries in EVs, however, batteries' demand for high-purity class 1 nickel will increase by a factor of 24 in 2030 compared to 2018 levels, putting the market under pressure in the next few years. It will be crucial for enough investment to be directed into new mines and refinery complexes for class 1 nickel to ensure timely and sufficient supply in the coming years.

- **Cobalt:** Cobalt's demand for use in batteries is expected to increase by a factor of 4 in 2030 versus today's levels (the doubling of overall global demand is predicted in 2030). Cobalt is almost exclusively a by-product commodity, obtained mostly from copper and nickel mines. While overall demand is increasing, the share of cobalt in future cell chemistries is continuously decreasing, causing less optimistic demand growth for this mineral. Approximately 70% of today's mined cobalt originates from the DRC. Most of the refining operations for cobalt, however, are situated in China, accounting for 60% of the refined cobalt supply in 2018.

**Cell production:** Today, an estimated 350 GWh of cell production capacity is in operation. Another 510 GWh of capacity is announced through 2025, totalling 860 GWh of cell production capacity of which 60% will be located in China. To meet the demand of 2,600 GWh in 2030, however, another 1,700 GWh of capacity is required. Based on current investment levels, an additional investment volume of $140 billion until 2030 would be needed to meet the base case demand.

**Recycling:** In the base case, an estimated 54% of end-of-life batteries are expected to be recycled in 2030, thereby contributing 7% to the overall demand for raw materials for battery production in that year. This will require recycling capacities to be increased by a factor of more than 25 in 2030 compared to today.

This expansion has the potential to create annual revenues of $300 billion along the value chain in 2030 – a factor of 8 more than today (see Figure 7). The largest revenue pool (45%) is in cell manufacturing, followed by refining operations accounting for 24% of global revenue pools; revenues from recycling and repurposing operations will only account for 4% of global revenues in the base case but are expected to grow exponentially beyond. China is expected to play a strong role in the battery industry, capturing 41% of the revenues from operations inside China. This corresponds approximately with the global EV demand from China, accounting for 43% in 2030.

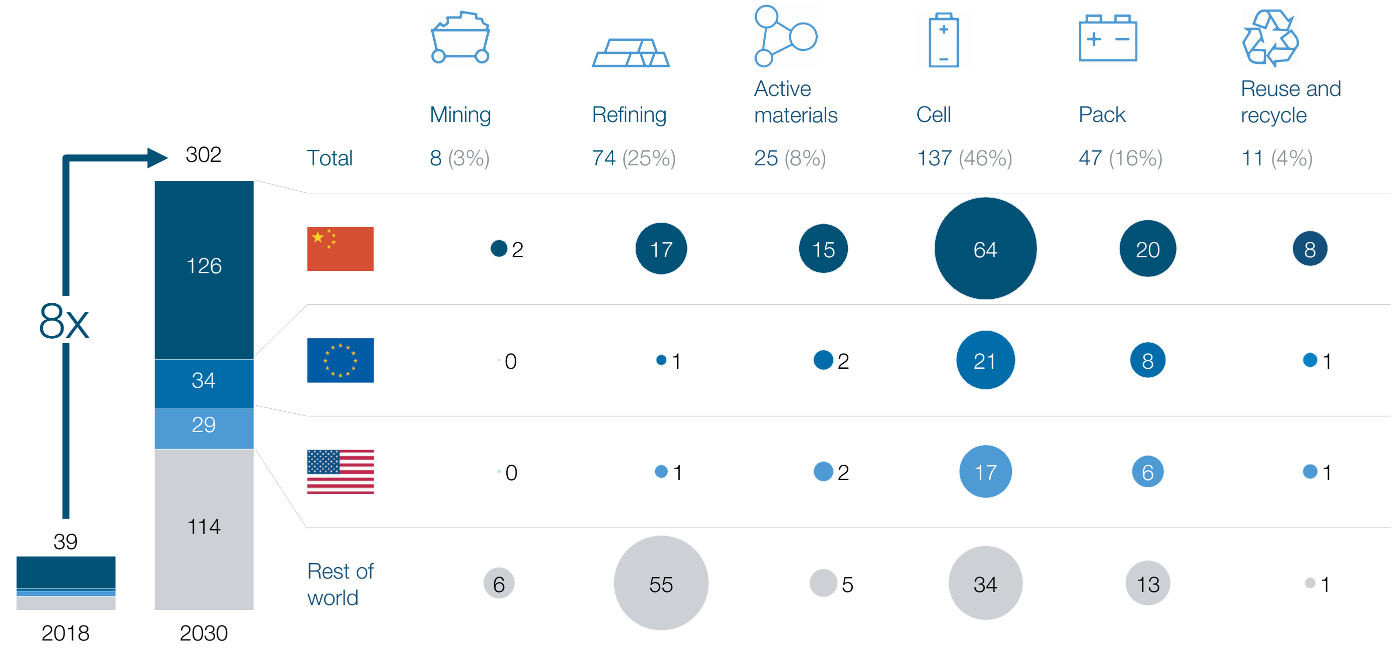


**Figure 7:** Battery value chain opportunities of $300 billion in 2030

**Lithium-ion battery value chain provides revenue opportunities of $300 billion by 2030**

Revenues, base case 2030, $ billion

NOTE: Calculated based on demand from mobility, energy storage and consumer electronics applications as well as battery pack prices for 2030 (not including lead-acid batteries)

Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

To create the 2030 revenue potential, $440 billion of cumulative investments will be required over the next decade. Among the largest investment opportunities are cell production ($200 billion) and raw materials mining and refining ($100 billion). Where such investments occur will not only influence the direct revenue opportunities but also the indirect economic benefits associated with the activities across the battery value chain.

## Lead-acid batteries

### Introduction

The primary focus of this report is lithium-ion batteries, given the expected exponential growth of this battery chemistry over the next decade. However, a vision of the battery value chain is incomplete without providing a perspective of the other large battery market segment: lead-acid batteries (LAB). In 2018, approximately 72% of the world rechargeable battery capacity (in GWh) was provided by LABs.[12]

Approximately 65% of global demand for LABs is currently driven by automotive applications, with nearly every vehicle on the road currently requiring a LAB for starter, light and ignition (SLI) functions.[13] The remainder of uses are as industrial batteries, with lead-based batteries becoming popular for off-grid energy renewable storage used in developing countries as a key enabling technology to deliver on SDG 7 for affordable and clean energy for all.

LABs will be employed in cars, including EVs, for many years and the global market for them is expected to further grow, although at a significantly slower rate than the lithium-ion market.

### Analysis of lead-acid batteries

Today, global LAB demand of around 450 GWh in 2018 is employed in a wide variety of applications, ranging from vehicle starter batteries, mobile industrial applications (e.g. forklifts and other automated guided vehicles) to stationary power storage (e.g. uninterruptable power supply and off-grid energy storage). Driven by expected global volume growth in cars and battery energy storage systems (ESSs), the global market is expected to grow to 490 GWh by 2030 (see Figure 8). Other sources project an even higher growth to about 550 GWh.[14] LABs are, therefore, an integral part of the global battery market and will continue to be so for a long time.

Lead is a toxic heavy metal that can accumulate in the environment. Inappropriate management of lead can therefore result in contamination and damage to ecosystems. Critically, even at relatively low exposures, lead has been reported to cause neurological damage, cardiovascular disease, anaemia and other health problems. Children are particularly vulnerable and can suffer from permanent IQ penalty even when exposed to low levels of lead. Lead has been estimated to contribute to as much as 1% of the total global burden of disease, particularly affecting children, and may account for an estimated 540,000 deaths in 2016.[15] It is also recognized as one of 10 chemicals of major public health concern by the World Health Organization. Forthcoming research shows that 680 million children, about one-third of all children globally, have lead exposures of concern, with the main source of these exposures being traced to improper ULAB (used lead-acid battery) recycling in several regions.

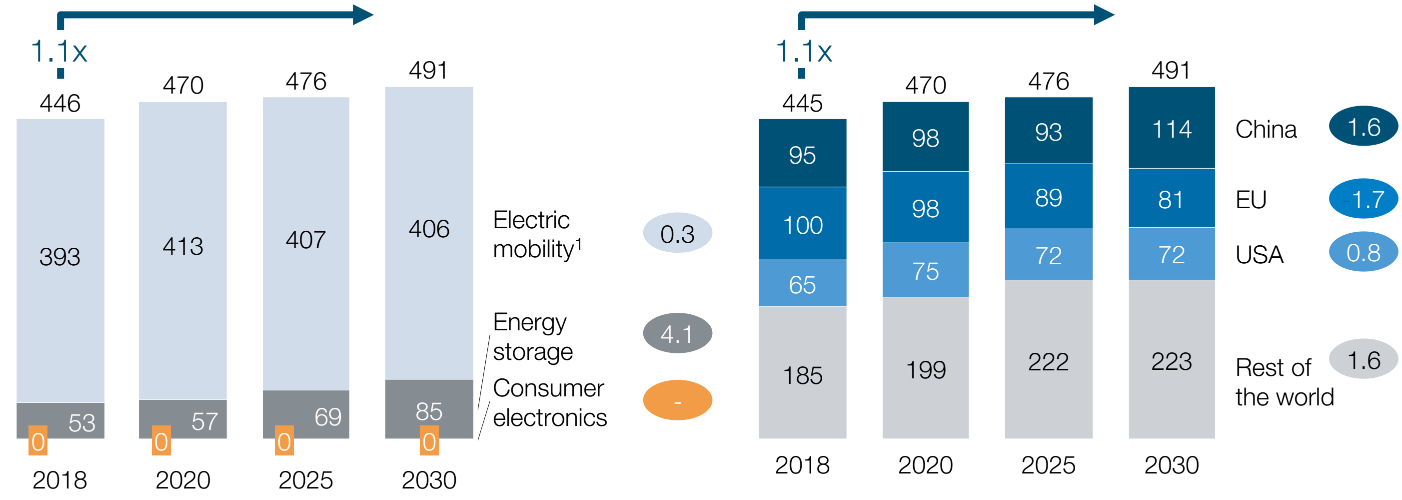
While lead is on the way to being phased out of other applications like gasoline and paints,[16] lead batteries are still considered to be an important and critically needed technology in many automotive and energy storage applications. Therefore, the environmentally sound management of LABs through their life cycle is crucial. In mature economies, such as those in Europe and North America, used lead batteries are managed very well today: they operate in perfectly closed loops with up to 99% of used batteries collected via efficient point of sale return systems, transported and recycled by highly regulated operations that have high standards for worker safety and strive to continually advance practices to protect workers, communities and the environment. As such, LABs can be considered a good example of a well-functioning circular economy with end-of-life products being used to create value through effective recycling into new batteries, thus reducing the demand for virgin resources. The same cannot be said in many economies in transition, however, where appropriate and environmentally sound collection and recycling systems are often lacking. In several countries, up to 50% of end-of-life lead batteries are recycled in informal, or below standard, facilities, leading to substantial releases of lead into the environment and high levels of lead exposure. Often affected countries lack the knowledge, regulation and sometimes political will to deal with this issue.

**Figure 8:** Global demand for lead-acid batteries by application and region by 2030

**Compared to today, global lead-acid battery demand is expected to grow by a factor of ~1.1 to reach ~490 GWh in 2030**

**Global lead-acid battery demand by application** GWh in 2030, base case — **CAGR** % p.a.

**Global lead-acid battery demand by region** GWh in 2030, base case — **CAGR** % p.a.



[1] Including industrial applications, e.g. forklifts

Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

Tested approaches to improve the safe management of LABs are well documented.[17] Additional measures to reduce effects created by the inappropriate management of LABs in low- and middle-income countries include providing financial and regulatory stimuli to transition the informal collection and recycling sector to well-controlled licensed operations, adding a small recycling fee to the cost of a new battery to ensure that battery manufacturers have some financial responsibility for encouraging the environmentally sound recycling of their products, and ensuring that any regulated facility licensing scheme and associated pollution and occupational control measures reflect good practice in the environmentally sound management of used lead-acid batteries.

Lastly, legacy pollution from former, inappropriate LAB management needs to be addressed and reduced to mitigate long-term exposure risks to the environment and local populations.

## Key challenges for the battery value chain

Along with the massive expansion of the battery value chain comes a wide array of challenges throughout the value chain. This report outlines three challenge areas that are the most critical to address. Further comprehensive analysis of these challenges is necessary, along with stakeholder consultations to identify the actions required in more detail.

### 1. Battery production has a significant GHG footprint

$CO_2$ emissions during the production of batteries are significant, while the full life cycle emissions of batteries including its use phase are lower compared to traditional vehicles. Reducing the production footprint is a significant opportunity and major obligation to address. Improvements in the $CO_2$ footprint can help make arguments for switching to battery applications even more compelling.

### 2. The battery value chain has significant social, environmental and integrity risks

The massive expansion of raw material demand, with a near-term focus on cobalt but also on nickel and lithium, will cause the value chain to face social, environmental and integrity risks, involving child labour and potentially forms of forced labour in the cobalt supply chain, unsafe working conditions, local air, water and soil pollution, biodiversity loss and corruption. Separately, the risks associated with the safe production and transportation of batteries across the value chain, including at the end of life, must be addressed.

### 3. The viability of battery-enabled applications is uncertain

Uncertainty regarding infrastructure, technology and consumer preferences poses a significant business risk to the value chain. Automotive OEMs and suppliers have invested more than $100 billion in EVs over the past three years, yet profitability is not yet guaranteed, requiring the rapid introduction of coherent infrastructure and ecosystem. Without it, critical investments in the battery value chain will remain on the sidelines.

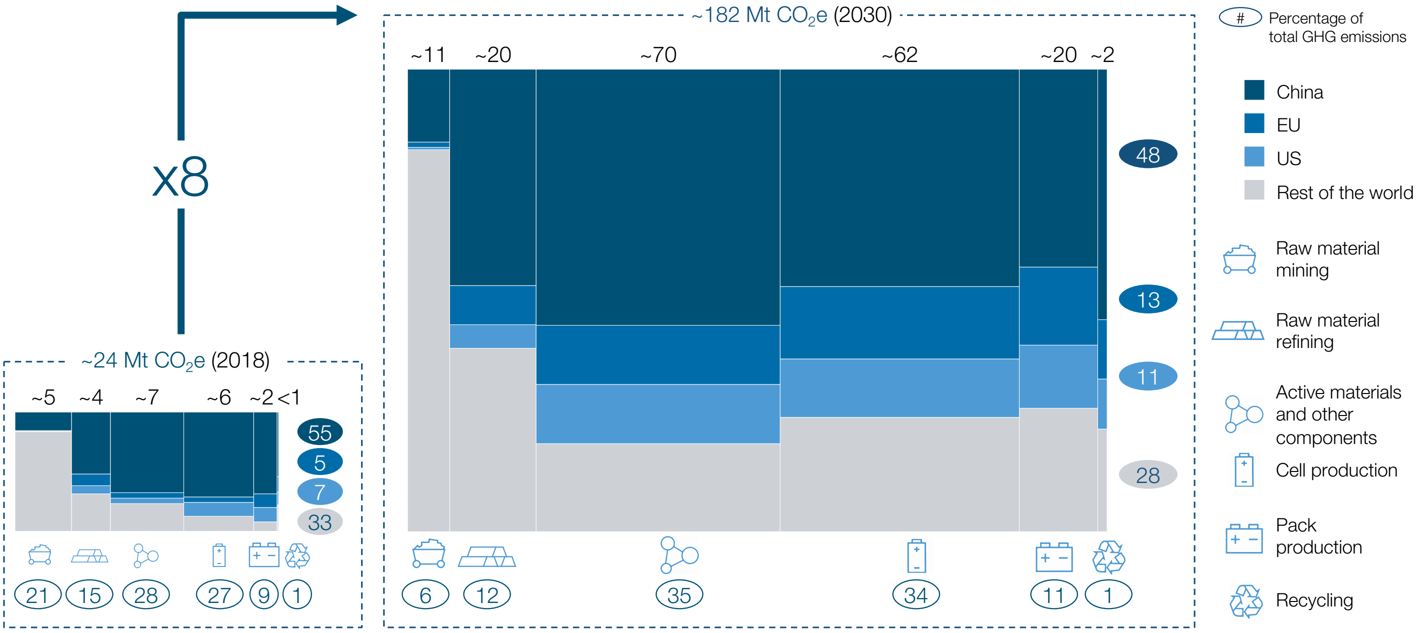
## Challenge 1: Battery production has a significant GHG footprint

The production of batteries requires significant amounts of energy – and therefore causes $CO_2$ emissions. In the base case scenario 2030, the battery value chain emits 182 Mt $CO_2e$ (see Figure 9), more than the annual emissions of the Netherlands today. The manufacturing of active materials and other components, as well as the manufacturing of cells, are the most GHG emission-intense steps in the battery value chain.

The $CO_2$ footprint of producing a fully electric vehicle, for example, is higher than that of a vehicle with an internal combustion engine (ICE). But the lower direct and indirect emissions during the EV's use lead to an overall $CO_2$ footprint advantage over its life cycle against a traditional ICE vehicle. In the base case analysis, this holds true for all three focus regions in 2030: China, Europe and the USA.

The relative $CO_2$ advantage over the life cycle is, however, highly dependent on the share of renewable energies in the energy mix of the respective country (see Figure 10). Depending on the carbon intensity of the electricity mix of different countries, vehicle size and use case, the $CO_2$ advantage over the life cycle of an EV in the base case 2030 ranges from 19% to 60% versus an ICE vehicle during the first life of the battery. To illustrate, this means that an EV will have compensated for the relative $CO_2$ disadvantage as early as after driving approximately 24,000 km on the road in the case of a small vehicle in the EU. The analysis shows that, particularly in China and the USA, an opportunity to make EVs even better still exists.

**Figure 9:** Battery production GHG footprint



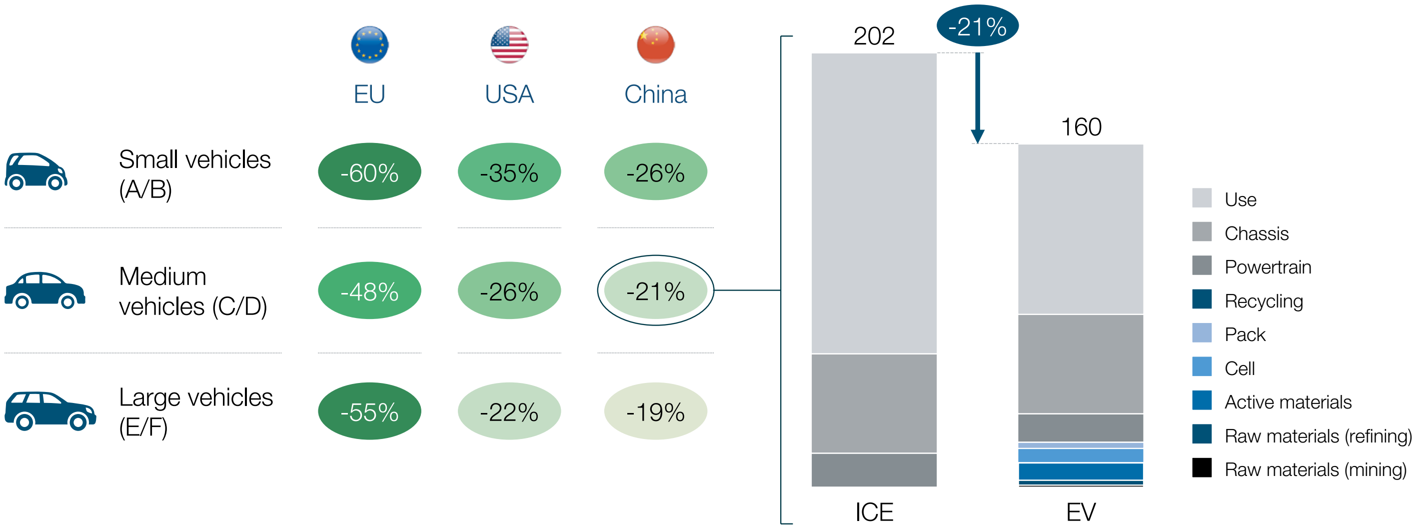
### Battery production with significant $CO_2$ footprint, mainly driven by active materials and other components as well as cell production in China

Greenhouse gas emissions by value chain step, Mt $CO_2e$ per annum (2030)

Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

**Figure 10:** EV emission benefits compared to an internal combustion engine vehicle in base case 2030 by vehicle size and geography

### EV emission benefits compared to ICE vary across vehicle size and geography



**EV emission benefit compared to ICE by vehicle size and geography, base case 2030**

percent life cycle $CO_2e$ emissions reduced

**Life cycle GHG emissions for Chinese medium-sized vehicles, base case 2030**

$gCO_2e/km^1$

[1] Key assumptions: Vehicle lifetime: 200,000 km = 13 years x 15,000 km p.a.; BEV energy consumption (kWh/km): small (0.13), medium (0.16), large (0.18); battery sizes (kWh): China - small (30), medium (60), large (80), EU/USA - small (35), medium (75), large (100); battery production emissions (kgCO2e/kWh): China (71), EU (67), USA (69); electricity carbon intensity (gCO2e/kWh) in 2030: China (411), EU (114), USA (302); ICE use emissions (gCO2e/km): China - small (99), medium (116), large (133), EU - small (88), medium (93), large (140), USA - small (93), medium (106), large (120); emission factor of fuel production: 21%

Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

## Challenge 2: The battery value chain has significant social, environmental and integrity risks

Scaling up raw material production for batteries over the next decade will come at an unprecedented pace. Four battery metals are impacted the most by this growth towards 2030: lithium by a factor of 6, cobalt by a factor of 2, class 1 nickel by a factor of 24,[18] and manganese by 1.2 (see Figure 11). This requires, primarily, a significant increase in infrastructure in specific geographies (e.g. approximately 50% of global cobalt mine reserves are in the DRC, and 99% of lithium reserves are in Chile, Argentina, Australia and China[19]). It imposes a significant challenge to the battery value chain to manage the increase in raw material supply responsibly across different geographies and stakeholders. This concerns both terrestrial and deep seabed mining.

### Terrestrial mining

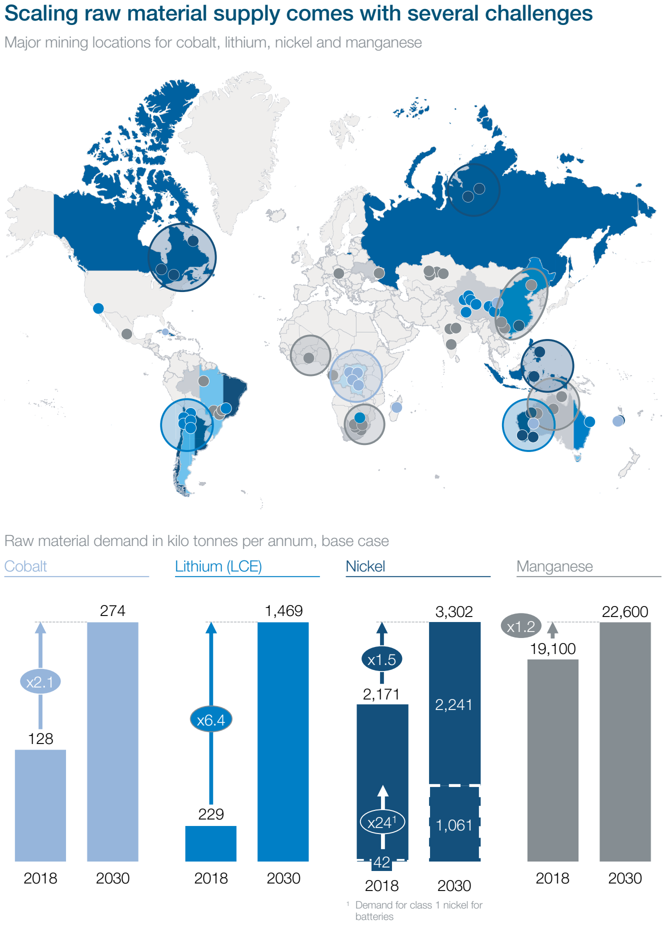
The increase in raw material supply comes with great potential for economies that are well endowed with battery minerals. Equally, however, it poses significant challenges, as the scale-up in mineral sourcing might be accompanied by negative social, environmental and integrity impacts across different geographies. Detailed impact assessments and the macroeconomic potential of the key battery material supply chains are beyond the scope of this report. As the cobalt supply chain has been linked to particularly severe challenges, it is discussed in greater detail here.

### Risks related to cobalt extraction

The DRC is one of the world's least developed countries.[20] Cobalt is a core pillar of its economy, where between 10 and 12 million people depend directly or indirectly on mining and 80% of exports are mining products. Most of the cobalt mined there originates from industrialized operations. Large-scale, industrial mines account for the lion share of the DRC cobalt market and are an important source of national economic value. However, environmental, social and integrity risks have been documented in such operations.[21]

In addition to material mined in large-scale operations, 15-30% of the DRC's cobalt supply is extracted by hand using basic tools in so-called artisanal small-scale mines. These mines are often informal and basic international human rights expectations are often not implemented or enforced. However, artisanal mining is an important livelihood for communities. In 2017, an estimated 40.5 million people globally were directly engaged in artisanal mining, compared to 7 million in industrial mining.[22]

**Figure 11:** Demand for cobalt, lithium, nickel and manganese by 2030



**Scaling raw material supply comes with several challenges**

Major mining locations for cobalt, lithium, nickel and manganese

Raw material demand in kilo tonnes per annum, base case

¹ Demand for class 1 nickel for batteries

Source: USGS, 2019; McKinsey analysis; expert interviews

Severe social risks have been well documented in the DRC's artisanal mining industry. They include hazardous working conditions; deaths due to poorly secured tunnels; potentially various forms of forced labour; the worst forms of child labour; and exposure to fine dusts and particulates and DNA-damaging toxicity.[23]

Over 250,000 people are estimated to work in dangerous conditions, of which approximately 35,000 are children, with some estimates proposing that as many as 1 million children are affected across the DRC's mining industry.[24] The root cause of child labour is that average households in mining communities are poor and vulnerable to income shocks.[25] Different forms of child labour require different interventions, always with a focus on serving children's best interest.[26]

Integrity risks, including corruption, need to be addressed. Environmental impacts across the DRC's cobalt mining industry also pose significant risks to local ecosystems, particularly soil and water pollution due to poor waste management.

### Risks related to lithium, nickel and manganese extraction

While further research is required to uncover the social and environmental impacts of these minerals, anecdotal evidence suggests that further analysis of the specific risks of these materials is required. In lithium, the nature of effects varies across the major lithium-producing regions. The extraction from brine in the "lithium triangle" in the Atacama Desert across Argentina, Bolivia and Chile raises very different risks than those from lithium mining from hard rock in Australia and other countries. For nickel, the management of acid leaching processes in extraction requires further scrutiny, for example in the Philippines and Indonesia. Manganese mining requires intensive land use and may disperse airborne contaminants.[27]

### Deep seabed mining

The surging demand for battery materials is leading to increasing interest in deep seabed mining. Until recently, mining the deep ocean for these minerals was neither technologically or economically feasible, but recent innovations and technological advancements are making the deep seabed more accessible and are triggering greater interest among private-sector actors and countries, who sense the potential for significant ocean resource-driven revenue, new sources of investment and growth.

However, the environmental effects of deep seabed mining on ocean ecosystems are not fully understood and could be irreversible, triggering wider direct and indirect negative consequences across the ocean system, and could impede the ocean's capacity to sequester $CO_2$. This is further compounded by the overall paucity of information and understanding of the deep ocean globally.

It is expected that minerals from deep seas could be established as a source for raw material demand starting in 2030. This suggests that the economic viability of exploration and extraction in the deep sea as of 2030 must be carefully evaluated in light of advances in battery and other technology as well as circular economy benefits (as discussed in Chapter 3). More research is required to thoroughly consider the environmental implications before increasing the exploitation of these resources.[28]

## Challenge 3: The viability of battery-enabled applications is uncertain

Current levels of battery costs do not allow profitability in many applications; for example, automotive manufacturers are facing high pressure on margins of EVs. The main reasons for the lack of profitability are: 1) high upfront costs of large battery packs; 2) the "chicken-and-egg" problem: the lack of charging infrastructure and the low utilization of existing charging infrastructure; and 3) limited customer acceptance of EVs versus ICE vehicles. The quick expansion comes at the cost of process inefficiencies, resulting in even higher costs. Without further battery cost reductions, purpose-built EV designs, rapid infrastructure increases and new business models, EV profitability for car manufacturers remains at risk.

There are, however, other use cases linked to the battery value chain for which economic opportunity is not yet entirely certain. Examples include:

- Recycling processes are currently costly. The need for high safety precautions due to the fire hazard of large lithium-ion batteries and the toxic properties of some materials creates substantial hurdles to economic recycling practices. The recovery of materials, other than the most valuable ones like cobalt, copper or nickel, is limited in most current processes, lowering the benefits of recycling. Improved recycling technologies will be key to recover more materials, and at higher quality. Not all recycling processes currently deployed are environmentally advantageous, potentially emitting substantial GHG and pollutants into water and air. Significant technology and process improvement for higher recovery rates and better environmental performance are needed.

- Batteries intended to be repurposed in second-life applications, such as ESSs, will have to compete, at the end of their first life, with improved battery technologies that are likely produced at lower costs. This increases the risk of some potential use cases for second-life batteries.

- Similarly, batteries intended to be used in microgrid and off-grid solutions to provide access to electricity need to compete on price with alternative solutions, such as diesel generators, or lighting sources such as candles.

- V2G applications as an important driver of increasing battery utilization, and hence profitability, face considerable challenges in revealing their full economic potential. Impediments include the technical readiness of vehicles, the limitations of current power grids, and power market regulations that prevent the wide-spread adoption of V2G applications across countries.

## Now is the time to change the trajectory of the value chain

The vision and its positive effects will not be realized if the value chain develops along its current trajectory. The time to pivot is now as the remaining “carbon budget”[29] is running out – without batteries, this budget will be used up by 2035. If the deployment of batteries is not accelerated, decarbonization will come too late.

Acting now is also a chance to shape an emerging value chain, while acting later requires costly reconfiguration and leads to the exacerbation of social and environmental impacts.

Batteries are the major near-term driver of this pivot. Automotive OEMs are launching more than 300 EV models in the next five years. Cost efficient and sustainable batteries, as well as a supporting ecosystem for battery-enabled dispatchable renewable energy deployment and dense charging infrastructure networks are preconditions for broad customer acceptance and economically viable powertrain transition. Eventually, further complementary technologies (i.e. fuel cells) must be integrated into the transport and power sectors to stay on track to meet the Paris Agreement.

The challenges with regard to batteries are twofold: how can the deployment of batteries be accelerated and how can these batteries be produced sustainably? To accelerate deployment, more investment needs to be attracted along the entire value chain as well as into application infrastructure (e.g. charging infrastructure). Moreover, batteries need to become more affordable through lower production costs, higher utilization and improved business cases for end users. To produce these batteries sustainably means lowering emissions, eliminating human rights violations, ensuring safe working conditions across the value chain, and improving repurposing and recycling.

# Chapter 3 – The 2030 vision: A world in which batteries power sustainable development

As shown, batteries have tremendous potential, but the required expansion of the value chain faces significant challenges if continued along the current trajectory.

An alternative development towards a sustainable battery value chain is possible. This chapter lays out a vision for the battery value chain in 2030, in which batteries are produced at lower costs, with lower raw material needs, fewer emissions and improved societal outcomes. This, in turn, significantly accelerates the positive environmental benefits of batteries in use and enables closing 30% of the gap to the 2°C Paris target. While some of the levers require initial investments, overall the scenario is also good for business, and society. It leads to higher revenues in the industry, more sustainable profits and better outcomes for workers and communities.

## The 2030 vision: A world in which batteries power sustainable development

The vision of the battery value achieves positive impact above and beyond the base case described in Chapter 2 (see Figure 12). In the target case, the battery value chain expands 19-fold over today's levels, requiring a substantive scale-up from mining to cell production and recycling (Figure 13). Batteries directly avoid 0.4 GtCO$_2$ emissions in the transport sector and contribute to enable renewables as a reliable source of energy to displace carbon-based energy production, which will avoid 2.2 GtCO$_2$ emissions. Moreover, the GHG intensity of the battery value chain is almost halved from 180 Mt to 100 Mt.[30]

Driven by lower costs, the adoption of batteries will be accelerated, leading to an increase in battery demand by another 35% and, therefore, doubling the economic value created to an estimated $130-185 billion.

Along with environmental and economic benefits, social benefits will also increase. Around 600 million people could gain energy access. Employment across the value chain will be transitioned to safe, fair and good-quality jobs, and local air, water and land pollution will be reduced.

## Batteries enable emission reductions in transport and power

Batteries are a key technology to decarbonize transport and support decarbonization in the power sector (see Figure 14). The challenge is enormous: to get on track for the Paris Agreement 2°C target, the transport and power sectors have a joint remaining carbon budget until 2050 of 430 GtCO$_2$e. Without batteries, this budget will be used up by 2035 and with batteries in the base case by 2040.

**Figure 12:** The target vision for a sustainable battery value chain

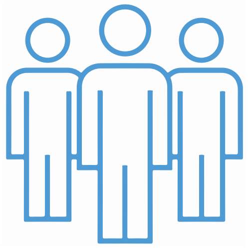
### A circular battery value chain as a major driver to meet the Paris Agreement target

**A circular battery value chain that is a major driver to achieve the Paris Agreement target to stay below the 2°C scenario**

Enable 30%

of the required emission reductions in transport and power sector

**Transformation of the economy in the value chain, creating new jobs and additional value**



Create 10m jobs, and

150b of economic value in a responsible and just value chain

**An industry safeguarding human rights, supporting a just energy transition and fostering economic development, in line with the UN SDGs**

Provide 600m

people with access to electricity, reducing the gap of people without electricity by 70%

Source: World Economic Forum, Global Battery Alliance

**Figure 13:** Scaling battery production opportunity

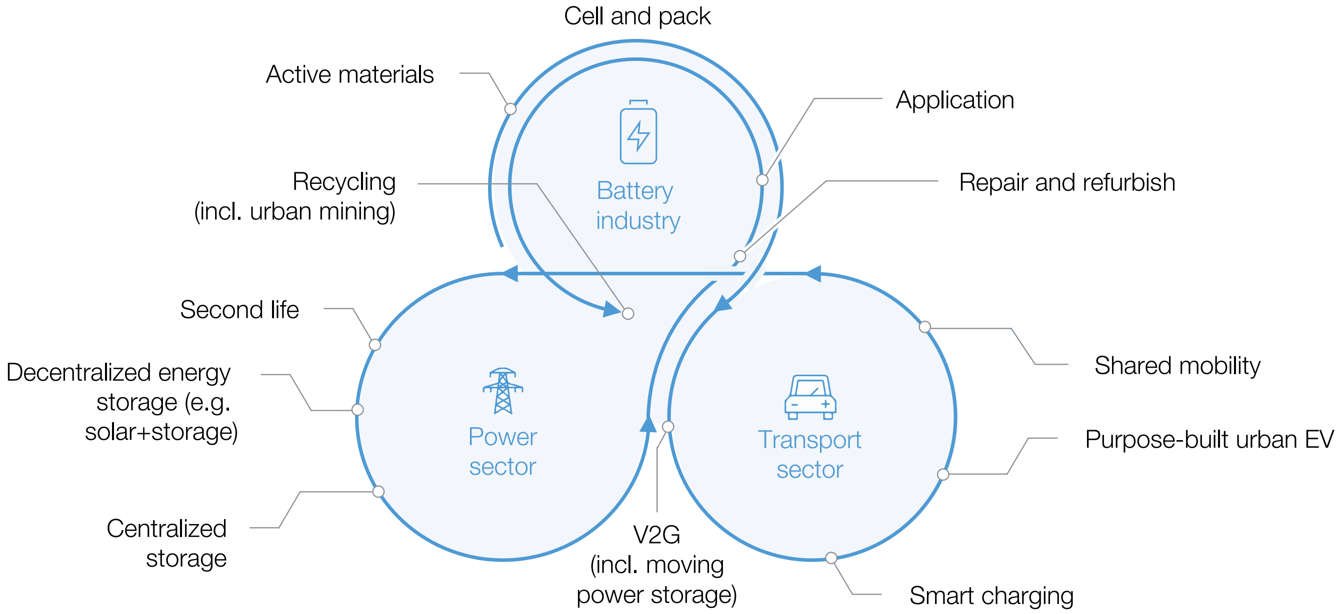
### Scaling battery production by a factor of 19 is a major opportunity for every step of the value chain

| Raw material mining | Raw material refining | Active materials | Cell production | Recycling |
|---|---|---|---|---|
| 5-40x | 14x | 15x | 19x | 15x |
| The mining industry needs to extract a volume equivalent to >300 Great Pyramids of Giza per year in 2030 | A weight equivalent to >110K Boeing 787s (Dreamliners) is refined per year in 2030 | Active materials produced in 2030 are enough to produce >800B battery cells (AA type) | ~120 additional Giga Factories (today's largest) must be operational in 2030 | An equivalent of >10B mobile phone batteries are expected to reach end-of-life in 2030 |

Source: World Economic Forum, Global Battery Alliance

**Figure 14:** Circular battery value chain to couple the transport and power sectors

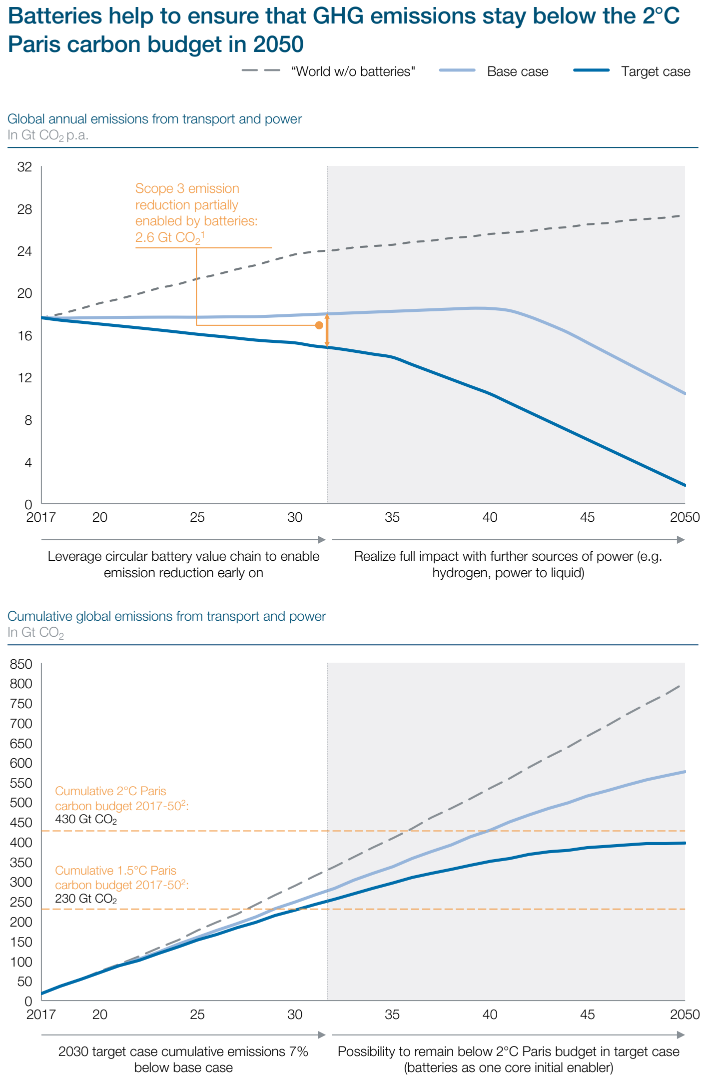
### Establish a circular value chain that quickly couples the transport and power sectors



A circular battery value chain to couple the transport and power sectors by 2030 globally, foundation for further sources of energy post 2030 (e.g. hydrogen, power to liquid) to stay below the 2°C Paris Agreement target

Source: World Economic Forum, Global Battery Alliance; McKinsey and SYSTEMIQ analysis

**Figure 15:** Target state transport and power sector emissions to stay below the Paris Agreement goal



[1] 1.0 Gt out of 2.6 Gt of reduction directly or indirectly enabled by batteries
[2] Budget to meet with 50% likelihood

Source: World Economic Forum, Global Battery Alliance; McKinsey analysis, IEA, 2018b; IPCC, 2018

An acceleration of uptake of battery applications can support getting back on track for the 2°C target. To achieve it and, even further, to achieve the 1.5°C Paris Agreement target, concerted action with other industries and technologies (e.g. hydrogen) are required as well (see Figure 15).

Batteries contribute — directly and indirectly — to emission reductions of 2.6 $GtCO_2e$ in the transport and power sectors. This is roughly equivalent to the current total emissions of Japan. In the base case, the transport and power sectors combined emit approximately18 $GtCO_2e$ (transport 7.4 $GtCO_2e$ and power 10.5 $GtCO_2e$) annually. In the target state, emissions are reduced to about 15 $GtCO_2e$ in 2030. The three main drivers of the target state emission reductions are:

- 0.4 $GtCO_2e$ emission reductions, directly enabled by batteries through increased EV penetration (0.4 $GtCO_2e$) and battery-enabled peak shaving in power grids (<0.1 $GtCO_2e$).
- 0.5 $GtCO_2e$ emission reductions, indirectly enabled by batteries; they help to resolve the intermittent nature of renewable power sources by means of their energy storage capabilities (e.g. battery storage systems or V2G technology).
- 1.7 $GtCO_2e$ emission reductions, achieved through higher degrees of renewables; these renewables comprise non-intermittent sources such as hydro, as well as intermittent sources such as wind and solar.

In the case of intermittent sources, other flexibility options, e.g. existing power plants, could balance the grid in times when these sources do not produce. However, these additional emissions savings are a second-order effect of batteries because in the target case batteries are assumed to have been deployed at sufficient scale by 2030 to push the roll-out of renewables beyond the limits of what would be possible with other flexibility options alone. These other flexibility options will thus require, as a necessary complement, already installed battery capacity to realize high shares of renewables in the grid in order to stay within the power sector's emissions budget for the 2°C scenario of the Paris Agreement.

## GHG emissions intensity in the battery value chain can almost be halved in 2030

By applying a set of circular economy and sustainable technology levers, the battery value chain can both reduce emissions and create more economic value. Figure 16 visualizes the impact and costs of the improvement levers as a carbon abatement cost curve, with the most economic measures on the left. Several levers are shown with negative costs, which means that these levers lower the costs of production. Consider, for example, V1G and V2G; this lever enables 17 Mt of emission reductions while providing opportunities for positive business cases as vehicles connected to power grids can create revenues and provide storage capacity to the grid at low costs. Combining the analysed levers, GHG emissions can be halved from 182 Mt to around 100 Mt at negative costs (Scopes 1 and 2).[31]

To illustrate how the outlined circularity and innovation levers reduce emissions, consider a Chinese mid-sized vehicle in the target state versus the base case. In the base case, this EV has a 20% life cycle emission advantage over ICE vehicles (see Figure 17). In the target state, the life cycle emissions are further reduced, leading to a total advantage of over 50%, more than doubling the advantage compared to the base case.

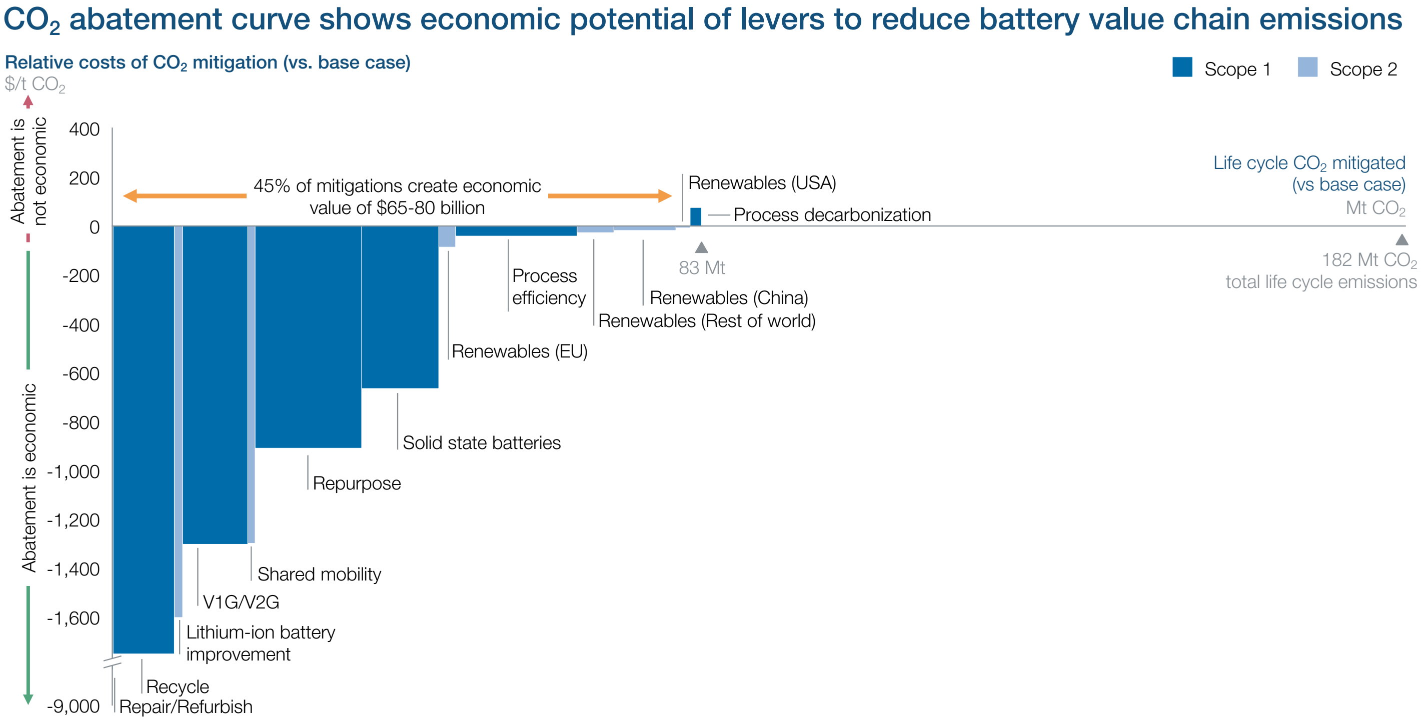
## The economic impact of batteries can be doubled

In the vision, battery costs can be reduced leading to an acceleration of battery deployment and a multiplication of benefits. The cost reduction stems from using batteries more intensively (e.g. through V2G and shared mobility), repurposing, recycling and technological improvement, resulting in a reduction of battery pack costs from $90 per kWh to $70 per kWh in 2030 (see Figure 18).

Although the target state's battery pack cost reduction may seem marginal, it is expected to have an exponentially accelerating effect on the demand for batteries. This battery cost reduction pushes global demand in 2030 by another 35% to around 3,600 GWh and value creation from $65-105 billion to around $130-185 billion (see Figures 19 and 20).

Reaching the target state for batteries also means improved end-of-life handling through the variety of circular economy levers. Vehicle manufacturers could benefit from a reduction of legally required accruals for the end-of-life management of EV batteries by up to an estimated $7 billion per year in 2030 alone.

**Figure 16:** Circular economy and innovation lever impact on life cycle GHG intensity of battery production in 2030

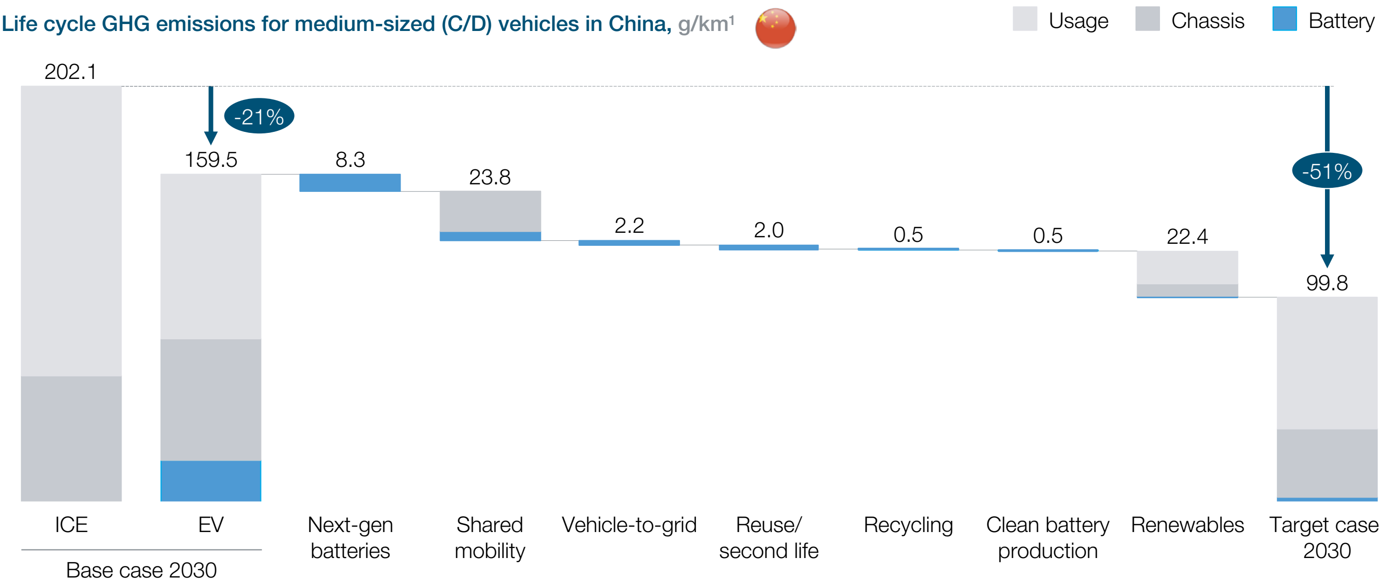


**$CO_2$ abatement curve shows economic potential of levers to reduce battery value chain emissions**

Source: World Economic Forum, Global Battery Alliance; McKinsey and SYSTEMIQ analysis

**Figure 17:** Circular economy and technology levers in 2030

## Target case life cycle EV emissions can improve significantly due to circular levers and more renewable energy deployment across the value chain



**Life cycle GHG emissions for medium-sized (C/D) vehicles in China,** g/km[1]

Note: Impact of selected levers shown based on emissions for an exemplary vehicle of the C/D segment in China; $CO_2$ advantage in EU and USA much higher already in the base case (see Figure 16)

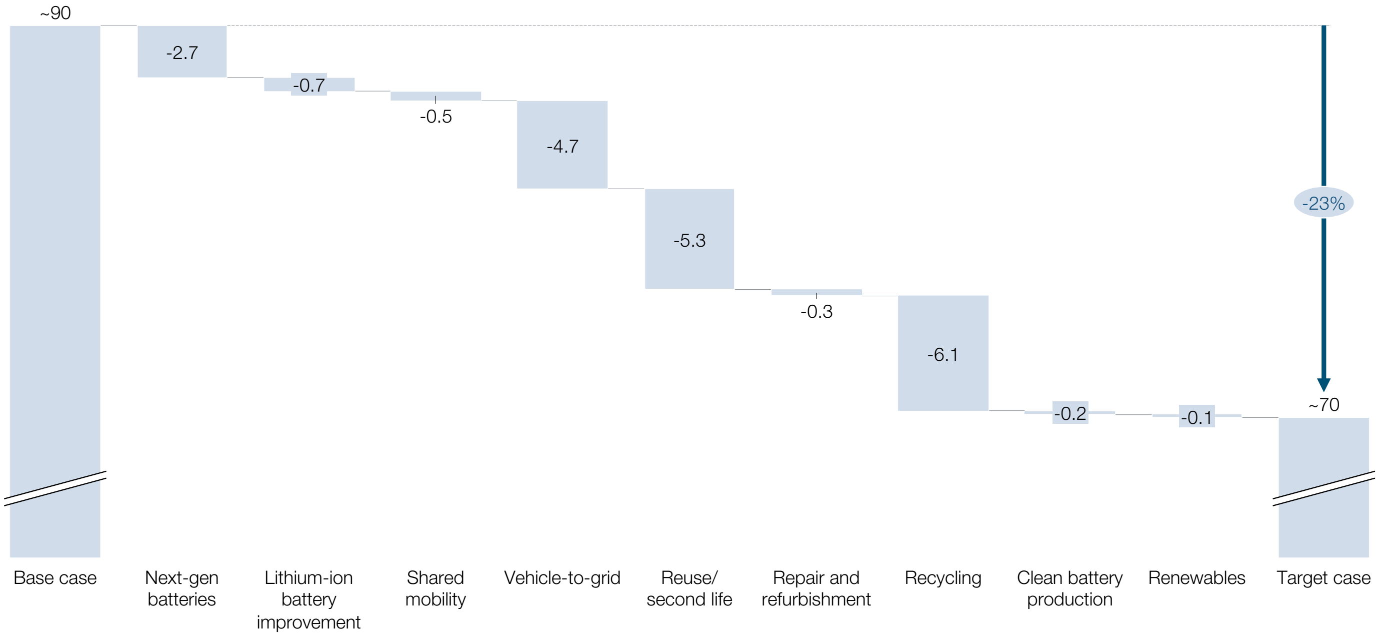
[1] Key assumptions: vehicle lifetime: 200,000 km = 13 years x 15,000 km p.a.; BEV energy consumption (kWh/km): 0.18 (2018), 0.16 (2030); battery sizes: 50 (2018), 60 (2030); battery production emissions (kgCO2e/kWh): 138 (2018), 71 (2030); electricity carbon intensity (gCO2e/kWh): 655 (2018), 411 (2030); ICE use emissions (gCO2e/km): 146 (2018), 116 (2030); emission factor of fuel production: 21%

Source: World Economic Forum, Global Battery Alliance; McKinsey and SYSTEMIQ analysis

**Figure 18:** Effective battery cost of the target state reduction in 2030

## Applying target case levers results in 23% additional battery cost reductions in 2030

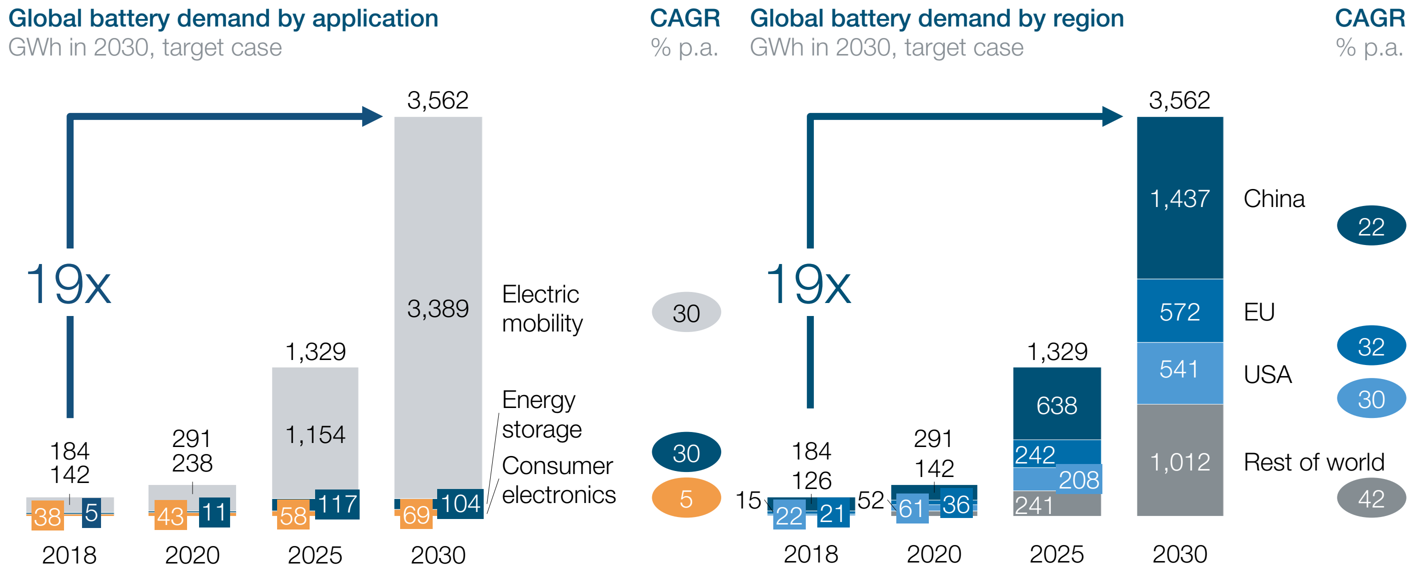
Example passenger car, average battery pack cost, in US$/kWh



Source: World Economic Forum, Global Battery Alliance; McKinsey and SYSTEMIQ analysis

**Figure 19:** Battery demand in the target state by application and region by 2030

## Compared to today, global battery demand is expected to grow by a factor of ~19 to reach ~3,600 GWh in a 2030 target case

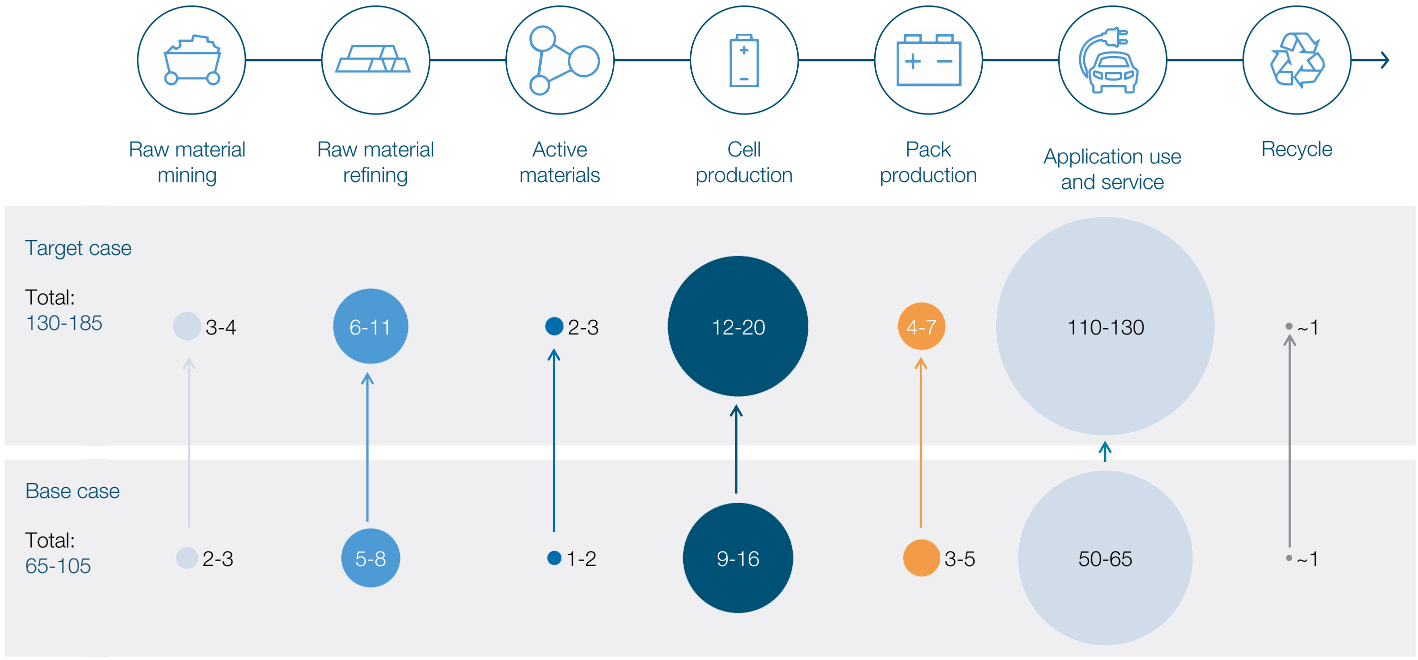


Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

**Figure 20:** Economic value in the target state in 2030

## The target case doubles economic impact compared to the base case

$ billion earnings before interest and tax



Source: World Economic Forum, Global Battery Alliance; McKinsey analysis

In addition, the increased competitiveness of batteries, along with better standards, will create additional jobs. Employment in the battery value chain is expected to increase to a total of 10 million jobs, with more than half of these jobs in developing countries. They are safe, fair and good-quality jobs, as accepted international practices get established and best practices are shared and implemented. To realize this job transformation, specific focus and support need to be put on reskilling and upskilling workers from traditional forms of employment that might be replaced.

## Social, environmental and governance benefits will scale

More affordable batteries enable off-grid energy solutions for more people. The vision targets to provide access to electricity for around 600 million people, growing the share of the world's population with access to electricity from 89% today to at least 96%. Providing electricity access has a variety of societal benefits (see Chapter 1).

The battery value chain stakeholders have taken substantial steps towards eliminating child and forced labour and safeguarding human rights. Safety, environmental and social impacts in the production and transportation of batteries are fully addressed. Broad-based compliance with sustainability and responsible sourcing expectations, and best practices, will also help to reduce local air, water and land pollution. Overall, the companies across the value chain operate transparently within accepted international practices that enable sustainable and profitable business models.

## A set of levers to achieve the vision

To overcome the challenges in the base case and achieve the outlined vision, this report has identified 12 key levers, grouped in 3 categories (see Figure 21): levers to build a circular value chain, sustainable business and technology levers, and levers to establish a responsible and just value chain.

## Circular economy – optimizing resource productivity along the entire value chain

Moving from a linear to a circular value chain can improve both the environmental and the economic footprint of batteries by getting more out of batteries while in use, and by harvesting end-of-life value from batteries (see Figure 22). Five prioritized levers have been analysed in detail: electric

**Figure 21:** Prioritized levers to overcome the challenges

**Levers: A variety of levers address the challenges and support the achievement of the target state**

■ Direct ▨ Indirect □ Not applicable

| Action areas | Levers | Challenges | | |
|---|---|---|---|---|
| | | Battery production with significant GHG footprint | Social and environmental risks in raw material supply | Viability of battery-enabled applications |
| Circular economy | Electric shared mobility – Increase lifetime distance | ■ | ▨ | ■ |
| | Smart charging and vehicle-to-grid – Utilize batteries during idle time | ■ | ▨ | ■ |
| | Repair and refurbishment – Extend lifetime of batteries in use | ■ | ▨ | ■ |
| | Repurposing (2nd life) – Increase deployment in second life in energy storage applications | ■ | ▨ | ■ |
| | Recycling – Maximize material recovery from manufacturing and end-of-life batteries | ■ | ▨ | ■ |
| Sustainable business and technology | Clean battery production – Switch to electricity-based processes, increase renewables | ■ | ■ | ▨ |
| | Battery technology improvements – Drive development of existing and new technologies | ▨ | ■ | ■ |
| | Application technology – Introduce purpose-built EVs (e.g. smaller size batteries) | ■ | ■ | ■ |
| | Local value creation – Support value creation in local communities | ▨ | ■ | ▨ |
| Responsible and just value chain | Sustainability excellence – Ensure performance and transparency along sustainability criteria | ■ | ■ | □ |
| | Implementation of best practices – Foster social and environmental best practices | ■ | ■ | □ |
| | Access to electricity – Provide increased access to electricity through off-grid solutions | ▨ | ▨ | ▨ |

Source: World Economic Forum, Global Battery Alliance; McKinsey and SYSTEMIQ analysis

shared mobility; V1G and V2G; repair and refurbishment; repurposing of EV batteries after use; and recycling.

Data traceability and digital technology will act as a major overarching enabler to key circular economy actions. They help to extend the life of batteries, to repurpose them, to recover materials and to transport them across borders. Data can also help verify compliance with human rights as well as social and environmental responsibilities across the battery value chain. Immediate opportunities for data management should be put into place as soon as possible to enable the optimum end-of-life management of batteries.

### Electric shared mobility

Electric shared mobility concepts, such as car-sharing and vehicle fleet management, could have positive effects on both vehicle demand and life cycle design. They could slow global vehicle sales growth and, as ownership of batteries would remain with operators, help incentivize an increased focus on asset productivity, vehicle longevity as well as design for purpose and disassembly. Loss of information across battery life would be mitigated as ownership changes are reduced.

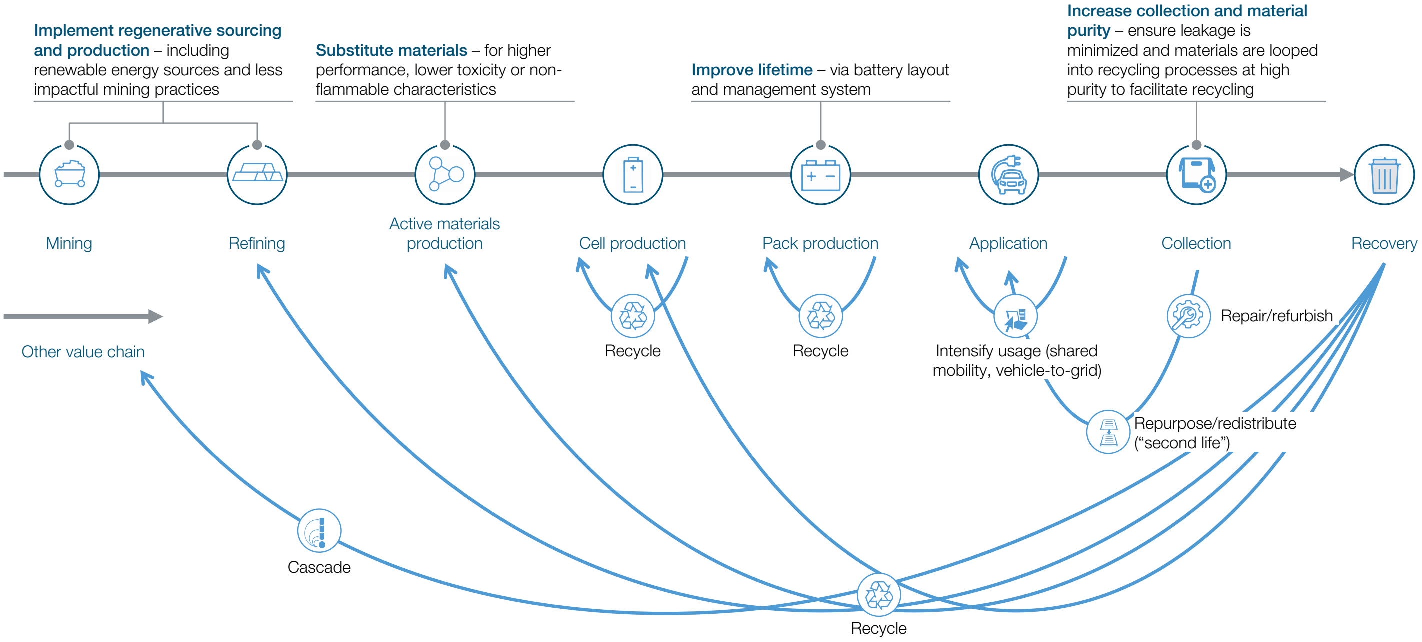
In the target state, it is expected that 16% of all passenger cars sold in 2030 would be managed in shared mobility offers. This creates 3 Mt $CO_2$ savings through battery demand reduction. An estimated 250 GWh battery capacity would be dedicated to electric shared mobility purposes, enabling total system savings of $4.5 billion.

Key enabling conditions for this case include:

- **Regulatory environment:** Legislation in major automotive markets supports sales and operation of vehicles in shared mobility fleets as well as operating under autonomy (i.e. without human intervention).
- **Business model and user acceptance:** Sufficient business cases and revenue streams exist to support the integration of existing forms of electric shared mobility, such as taxis, as well as new forms, such as autonomous ride hailing services.
- **Technological innovation:** Purpose-built vehicle design as well as rapid advancements in technologies allow vehicles to operate efficiently.

**Figure 22:** The circular economy for batteries

## Overview of circular economy levers for batteries



Source: World Economic Forum, Global Battery Alliance; McKinsey and SYSTEMIQ analysis

### Smart charging (V1G) and vehicle-to-grid (V2G)

When plugged in for charging, EVs and their on-board storage become a part of the electricity system in two ways: first, via V1G, peak loads can be optimized to lower strain on grids, improving grid system efficiency; second, by feeding electricity back into the system via V2G, EV batteries can participate in various power markets. Together, these have two systemic effects:

- By integrating EVs into electricity grids, they can create additional revenue streams for vehicle owners. Therefore, the business case for electric mobility becomes stronger, driving uptake and, in turn, accelerating economies of scale in the industry and higher utilization of infrastructure.

- By providing de facto additional energy storage capacity to power grids, EVs allow for higher integration of intermittent renewable energy into the grid, effectively reducing the need for storage, and driving down overall system costs and emissions in the power sector.

In the target state, it is assumed that both industry and policy-makers act to realize benefits of V1G/V2G. Approximately 50% of EVs would be enabled to integrate into grids in most major markets for up to half of daytime. It is assumed that up to 65% of ESS could feasibly be covered by V1G and V2G services, resulting in an equivalent of 250 GWh storage capacity in 2030. By offsetting this amount of traditional ESS demand, V1G/V2G applications could provide $CO_2$ savings of 17 Mt per year and generate additional value of $22 billion in 2030.

Key enabling conditions for this case include:

- **Technical readiness:** Industry standardization and the proliferation of V1G/V2G technology, including the large-scale deployment of bidirectional inverters within EVs and corresponding grid readiness, allow for the proliferation of V1G/V2G applications. Smart battery management ensures that the additional degradation of batteries from V2G integration is minimized.

- **Regulatory environment:** Power system regulation allows for grid integration across all major markets (e.g. widespread structural market access for V2G services and permission of small-scale market participants individually or aggregated as virtual powerplants).

- **User acceptance:** Via widespread deployment of consumer-friendly IT-infrastructure and interfaces, V1G and V2G participation becomes highly convenient and benefits are made clear to private and business users alike.

In contrast to effects from circular economy levers at the end of life, the benefits of electric shared mobility and V1G/V2G occur at the start of a battery's lifetime, making these levers highly effective already in 2030. V1G/V2G solutions could lower costs for electric vehicle charging infrastructure by up to 90%.[32]

### Repair and refurbishment

Repair and refurbishment can extend the lifetime of EV and ESS batteries, reducing the demand for new capacity and improving costs over their lifetime. While repair affects batteries that fail during the intended lifetime, refurbishment applies to batteries reaching the regular end of life. In each case, it is assumed that a part of degraded or faulty battery modules are exchanged to enable the capacity of the remaining modules to be used further in an EV or alternative function.

As for all circular economy levers affecting end-of-life batteries, recollection is the key gateway to allow further productive use. Thus, concerted action is needed to maximize battery collection rates – lifting them from an estimated average 61% in the base case to 79% in the target state.[33]

It is assumed that refurbishment will be limited in the long term to 5% of end-of-life EV and ESS batteries because the trend to homogenous battery ageing undermines the business case for exchanging deteriorated modules. Limited incentives for automotive companies to optimize battery design for repair and refurbishment further shifts the case in favour of second life or recycling.

In the target state, it is assumed that battery design for disassembly and lifetime extension is a high priority for industry, supporting repair and refurbishment. The share of repaired faulty batteries is assumed to rise from 80% to 95%. Nonetheless, given the above reasons, the effect will remain limited to 30 GWh battery capacity retained, resulting in a $CO_2$ reduction of 2 Mt and a total cost reduction of $2 billion in 2030.

Key enabling conditions for this case include:

- **Battery analytics technology:** The development of this technology embedded within batteries or as separate tools, and the sharing of key information derived from them (e.g. via a battery passport), will help to efficiently determine the state of health and chemistry of battery cells or modules as well as the chain of custody, and will help to manage them appropriately.

- **Design for disassembly:** Via this design, batteries will be easy to open, and modules can be exchanged with a high degree of automation – ideally with little variation between different manufacturers, so that tools can be harmonized.

- **Logistics operators** and **service stations:** This ecosystem will make repairs convenient and will keep transaction costs low.

## Repurposing of end-of-life batteries

Some EV batteries may be repurposed for ESSs after their end-of-life (i.e. second-life application). For this, batteries are removed from vehicles, tested, refurbished if needed and, after being recertified for performance and safety, repurposed as-is or in parts.

This has two major system effects: First, it may recover residual battery value at the end of life, helping improve the economics of batteries and thus accelerate market output. Second, repurposing can reduce the need for new batteries in the power sector. While there is a short-term trade-off with battery recycling, analysis suggests that life extension would be environmentally more beneficial and, therefore, preferable over immediate recycling.

Challenges include potentially high transaction costs, lack of information about remaining battery health, and concerns regarding unwanted thermal events and performance compared to new batteries. The considerable uncertainty regarding the development of these factors means targeted action is required to enable key conditions for repurposed batteries.

In the target state, a conscious effort by the industry and policy-makers to foster second-life applications of EV batteries is assumed. Consequently, 61% of EV batteries collected at the end of the first life would enter a second life, replacing 20 GWh of ESS that would otherwise have been installed. This would represent 6% of that year's global demand for stationary battery storage, so that no demand constraint is expected. The effect would remain limited to 1 Mt $CO_2$ saved and a cost reduction of $2 billion in 2030 but is expected to increase substantially in the long term.

The main enablers for the target state are:

- **Substantial R&D efforts:** These efforts in battery optimization, chemistry and layout allow for the meaningful residual life of most EV batteries for ESS after first life.

- **Battery diagnostic systems and shared data systems (battery passport):** They make the assessment of a battery's performance after its first life transparent, quick and economical – supported by battery management systems and analytical tools that provide relevant battery state of health data and chemistry, and thus enable the selection and assessment of suitable batteries.

- **Scaling of repurposing for second-life business models:** This improves the economics of second-life applications and provides commercial markets for low transaction costs, leading to the wide-scale application of second-life batteries.

## Recycling

Recovering materials from end-of-life batteries and from manufacturing scraps during production limits the need for virgin resources long term, ensures economical and safe end-of-life management and prevents losses of valuable materials.

The viability and economics of battery recycling depend first on the costs of collecting, handling and disassembling the batteries that enter the recycling process, and second on the scale of reliability and material value of batteries recycled.

In the target state, the regulation of and investment into collection and material recovery incentivize the development and wide-spread application of high-quality recycling processes currently in early-stage development. This raises recovery rates across all major markets. Consequently, battery recycling can provide 13% of the global battery demand for cobalt, 5% of nickel and 9% of lithium in 2030.

The share of recycled materials is relatively low even in the target state because of the surge in battery production towards 2030. As the EV market matures later on, vehicles could become the largest stock of critical battery materials, disrupting the mining sector. It will be important to ensure that material recovery takes place both in an environmentally friendly fashion and at a quality apt for battery applications.

Four underlying enablers make the target state possible:

- **Concerted regulatory action** is taken, including harmonized regulations related to the transboundary movement of batteries; tightened recycling targets differentiated by material (rather than by average battery weight); and improved Extended Producer Responsibility schemes. Financial incentives support the use of secondary materials. Public support for and industry commitments to improved recycling processes support vastly enhanced material recovery rates across all materials.

- Batteries and corresponding industry ecosystems are **designed for disassembly**. Via battery construction that allows for swift dismantling and standardized tooling, and pushes for automation and extensive training available across a widespread web of qualified service stations, up to 50% lower cost of collection, transport and handling for recycling are achieved.

- **Efficient and safe collection, transport and recycling of batteries** is enabled technically, in particular via digital measures such as battery passports and tracing and tracking technologies, leading to decreased transaction costs and higher collection rates.

- **Accrediting of the environmental advantages of** secondary raw materials strengthens the cost and climate competitiveness of recycling by creating demand and new quality standards.

## Sustainable business and technology – using the force of renewal to decarbonize and boost efficiency

Innovation along the value chain is needed to improve value creation and reduce environmental impacts. There are four main technological levers that help decarbonize battery production while improving battery economics as well as social and other environmental impacts.

### Clean battery production technology

The battery value chain uses fossil fuels for a number of its processes, which could be electrified. For example, the electrode drying process during cell manufacturing typically uses gas, but already today equipment using electricity as the main power source is available on the market. Another example is the use of diesel-powered trucks in mining, which could be switched to hydrogen or battery electric trucks.

A second lever is the increased use of renewable energies in the value chain. For example, mining is often undertaken in remote areas without grid access, where electricity is produced from natural gas turbines or diesel generators. Using solar panels can be an economic alternative. Chile, for example, has extensively promoted the wide-spread use of solar panels for mining.

### Battery technology improvements

Technological innovation for batteries primarily aims at increasing their energy density. Improved energy density has multiple advantages. It typically reduces the cost of batteries as fewer materials are needed and, hence, also reduces GHG emissions and the sources of other environmental pollution in the value chain.

Two main battery technology levers help drive improvements on energy density: incremental advancements in lithium-ion batteries and the introduction of next-generation batteries. Advances in existing lithium-ion batteries include switching to more efficient chemistries (e.g. from NMC622 to NMC811).

The introduction of next-generation batteries switches the underlying materials and components used for battery cells. The potential next-generation technologies include:

- “Next-generation NMC”, such as solid-state electrolytes, lithium-metal anodes, high-voltage spinel cathodes

- “Post-NMC”, such as lithium-sulphur, lithium-air chemistries

- “Post-lithium”, such as sodium-ion, manganese-ion, calcium-ion.

The commercialization of such technologies could lead to a radical improvement in energy density or other characteristics. Large-scale industrialization of “next-generation NMC” technologies is expected towards 2030. “Post-NMC” and “Post-lithium” have not passed the research stage yet, and large-scale commercialization is expected only after 2030.

### Application technology

Especially in the application of EVs, specific levers can help improve the impact of batteries. Purpose-built vehicles (e.g. for specific use in electric shared mobility fleets) can promote the faster adoption of battery technology in this area. Purpose-built elements can include the downsizing of vehicle specifications, battery design and management for a maximum lifetime, or convenient user interfaces to maximize customer acceptance.

### Supporting local value creation

Players in the battery value chain could help local economic development in several ways. Businesses along the value chain should operate in compliance with internationally accepted principles regarding accountability and transparency of payments and support local value creation under fair conditions. This could include, for example, the local sourcing of goods or services related to business operations.

Moreover, comprehensive local development strategies are a key enabler for the support of local value creation if they address the key dimensions of sustainable impact with actionable outcomes. These are ideally supported by mechanisms that allow companies in the value chain to direct capital at low transaction costs to these communities.

## A responsible and just value chain

Levers to advance a responsible and just value chain help to improve its social impact and the local environmental footprint, foster good governance and provide electricity to those who currently lack access. The target state addresses three main levers: consistent sustainability performance excellence along the value chain; implementation of best practices; and access to electricity.

Responsible value chain criteria should, ideally, be connected with data monitoring to enable the independent verification and assessments of key performance indicators that track batteries throughout their life cycle.

### Consistent sustainability performance excellence along the value chain

The target state envisions a value chain that not only avoids doing harm to vulnerable people, communities and the environment, but also is a force for prosperity and better living conditions.

Design elements of excellence in sustainability performance along the value chain include, for example:

- **Ensuring consistent performance and transparency based on established sustainability norms along the value chain.** There is inconsistent compliance and performance along the value chain regarding social, environmental, governance and other key sustainability expectations, and limited third-party monitoring. In addition, material flows in the battery value chain lack transparency due to three main, underlying root causes: a diffuse and complex supply chain; lack of information management in sourcing and refining countries; few trusted and independent certification authorities. Separately, the safety, environmental and social issues during production and transportation must be assured.

- **Addressing child labour in the cobalt supply chain.** Child-labour-free batteries cannot be guaranteed today, specifically with respect to artisanal and small-scale cobalt mining in the DRC. To effectively address child labour and the circumstances of forced labour, the root causes need to be addressed in a systematic manner.

- **Ensuring safe and healthy working conditions.** Occupational safety cannot be guaranteed at every step of the battery value chain today, particularly in the segment of artisanal and small-scale mines in cobalt. Main root causes include high costs and the limited availability of safety equipment, limited professional mining knowledge and a lack of checks and controls.

- **Minimizing local environmental burdens.** Environmental burdens, such as air pollution, water use and contamination as well as ecosystem destruction, vary across locations. Main root causes include weak law enforcement or limited regulation, the lack of financial incentives to minimize environmental burdens, and limited local expertise of waste handling and impact on ecosystems. Capacity for managing end-of-life of batteries in emerging markets must be established.

- **Accepting artisanal mining in the value chain under certain conditions.** The conditions are necessary to ensure artisanal mining is a source of decent livelihoods for local mining communities. This will require investments in capacity building for suppliers' management systems capable of exercising robust due diligence and contributing to the formalization of artisanal and small-scale mining within their supply chains.

- **Addressing governance and integrity challenges.** Companies need to operate in conformance with international accepted principles regarding the public disclosure and accountability of payments and other transactions. This is facilitated by conducting thorough due diligence on business counterparts in line with the OECD Due Diligence Guidance.

### Implementation of best practices

Players in the battery value chain should compete on a set of dimensions. However, in other areas businesses can work together with governments and civil society organizations in certain areas to reduce environmental and social burdens, e.g. through best practice sharing.

Some examples of best practice sharing are the deployment of renewable power generation close to mining sites (e.g. solar power use in Chile), the formalization of workers, community development and the improvement of conditions in artisanal mining, the use of recycled content in materials refining (e.g. copper refining in Sweden), and the use of desalination technologies to avoid exploiting too many water resources.

Best practice sharing can further be strengthened through commonly agreed frameworks that allow companies and organizations to consistently address the root causes of social and environmental challenges.

### Access to electricity

The battery value chain can contribute to access to electricity by reducing the cost of distributed energy solutions by: 1) reducing the costs of batteries through better economies of scale and design, thereby ensuring that the competitiveness of decentralized energy solutions (e.g. solar home systems and mini-grids) against legacy technologies (e.g. diesel generators, candles and kerosene lamps) is reached earlier; 2) supporting the safe and transparent repurposing of EV batteries in decentralized energy solutions (e.g. mini-grids); and 3) encouraging stakeholders of the value chain to directly support or finance the set-up of battery storage systems and microgrids as key enablers for decentralized energy solutions in regions without access to electricity.

In the target state, the proportion is expected to increase to 60-70%, allowing for a total of approximately 600 million people to gain access to electricity. The increased access to electricity could support local value creation, enable grid investments more economically viable, increase the productivity of business, increase education opportunities and increase health through displacing diesel generators and advancing clean cooking units. Additional battery deployment creates the need to ensure local end-of-life management capacity.

# Chapter 4 – Immediate actions are needed to shift the development of the battery value chain towards the target vision

The sustainable expansion of the battery value chain offers many environmental, social and economic benefits. It will, however, not be achieved without an active shift from the current development trajectory. This requires coordinated, immediate actions by companies, investors and policy-makers, in consultation with all stakeholders.

To initiate this shift, 10 concrete actions are proposed to develop a circular battery value chain, accelerate sustainable business and technology development, and improve responsibility in the value chain.

## Circular value chain and connected business cases

- **Implement design and systems for life extension and end-of-life treatment:** International convention bodies, regulators, battery manufacturers and vehicle manufacturers need to work together to: 1) enable the exchange of data among key stakeholders to improve the economics of life extension through repair and refurbishment, and recycling; 2) foster product design and technical development to facilitate disassembly for repurposing, repair and recovery of materials; and 3) harmonize national and international rules to ensure the safe and economic transport of batteries. A battery passport would support data sharing on dimensions such as materials chemistry, origin, the state of health of batteries, or chain of custody. It could provide a powerful means to identify and track batteries throughout the life cycle and, hence, support the establishment of systems for life extension and end-of-life-treatment.

- **Implement V1G and V2G:** Battery manufacturers, vehicle manufacturers and utilities need to work together to make V1G and V2G technically possible on a large scale, while regulators need to allow and incentivize them.

- **Scale up electric shared and pooled mobility:** Vehicle manufacturers need to accelerate the development and commercialization of purpose-built EVs for sharing. Regulators should incentivize electric shared mobility, e.g. via preferred public procurement for EVs, fleet regulations (e.g. on taxis) and incentives for electric shared mobility.

## Sustainable business and technology

- **Increase the share of renewable energies and energy efficiency measures in the battery value chain:** Companies in the value chain should switch from fossil fuels and conventional power to renewables, as well as reduce leakages and waste during production.

- **Accelerate the roll-out of V1G infrastructure:** Public stakeholders and private companies should take concerted action to increase public charging infrastructure for EVs, allowing for V1G and V2G services, to enable a smooth economic transition to sustainable mobility.

- **Adjust regulation for battery-enabled renewables as a dispatchable source of electricity for the grid:** Regulators should review and revise the regulatory framework for battery-enabled renewables as a dispatchable source of electricity, in conjunction with V1G and other strategies to address intermittency, to make best use of batteries in the electricity grid.

- **Finance the sustainable expansion and support value creation and economic diversification in local communities:** Investors, both private, semi-public and public, should require the noted sustainability elements in the development of the redundant value chain. Instruments like “green bonds” and “blended financing”, tied to the implementation of recommendations in this report, will shift the value chain to provide financial, environmental and social returns. Comprehensive local development strategies should be advanced that support value creation and address the various dimensions of sustainable impact in local communities, including eliminating child and forced labour, fostering safe and quality jobs, and providing energy access. Public and private finance should be leveraged effectively along the value chain to support these strategies.

## Responsible and just value chain

- **Ensure consistent performance and transparency based on established sustainability norms and principles along the value chain to improve the social, environmental and economic performance of batteries:** Stakeholders across the battery value chain need to commit to established international expectations and key performance indicators on social and environmental practices, ensuring transparent impact measurement as well as the exchange of best practices. Such established expectations include the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas and the UN Guiding Principles on Business and Human Rights. Consistent due diligence and reporting are necessary conditions to improve the sustainability performance of the value chain. The aforementioned battery passport could be extended to provide transparency with respect to key life cycle performance data on social and environmental dimensions. National legislation could support the implementation. Companies in the value chain, regulators across countries, as well as labour, civil society and international organizations should verify compliance with internationally accepted social and environmental practices, along with a rigorous monitoring and evaluation framework based on best practices, for sourcing to address child and forced labour and improve conditions in artisanal small-scale mining of materials used in batteries. Separately, safe production and transportation across the value chain, including at the end of life, must be verified. A comprehensive evaluation of risks should guide the decision-making about commercial activity where it might cause harm and reverse the positive impact of batteries.

- **Establish integrated GHG disclosure and emission regulations:** To increase the focus on Scope 3 emissions, policy-makers should establish regulations based on life cycle emissions. Private-sector companies, alike, need to commit to verified GHG disclosure based on life cycle considerations.

- **Support the deployment of batteries for energy access:** Financial institutions, energy utilities and public policy-makers, in partnership with battery manufacturers, need to advance the design and deployment of affordable battery applications in mini-grid and off-grid solutions in areas so far lacking access to electricity.

As laid out, the potential of batteries is substantial. They are key to realize the Paris Agreement goals and support the UN SDGs and can create a vibrant, responsible and sustainable market.

# Endnotes

1. The carbon budget is the maximum cumulative GHG emissions until 2050 that will ensure staying within the Paris Agreement target.
2. International Renewable Energy Agency, 2019.
3. IPCC, *Global Warming of 1.5°C*, 2018.
4. TCO describes the sum of all costs incurred by the owner of a product across its entire life cycle, including financial costs, capital costs, operational costs and costs for end-of-life treatment.
5. Emissions target derived from existing data measured based on the New European Driving Cycle (NEDC).
6. McKinsey analysis.
7. Ibid.
8. World Bank, 2017.
9. Lead-acid batteries are addressed in a separate section.
10. Class 1 usually contains more than 90% nickel content.
11. These minerals are the most significant for the production of lithium-ion batteries, but many others are also required (e.g. copper, graphite, rare earth elements).
12. Avicenne Energy, 2019.
13. Ibid.
14. Ibid.
15. See WHO, 2017.
16. Only a handful of countries still allow leaded fuel, and the WHO and the United Nations Environment Programme (UNEP) have launched the Global Alliance to Eliminate Lead Paint and have defined it as a priority action for governments (WHO, 2017).
17. See US Department of Labor, OSHA, 2019.
18. Battery demand for class 1 nickel; the total demand for nickel will grow by a factor of 1.5.
19. US Geological Survey, 2019.
20. The country has a per capita income of $561.8, according to the World Bank, and a ranking of 176th in the UN Human Development Index (World Bank, 2018).
21. SOMO, 2016; IndustriALL, 2018; Farchy and Mazneva, 2019. A large-scale mining risk assessment framework has recently been developed (Cobalt Institute, 2019).
22. IISD, 2017.
23. Amnesty International, 2017; Canavera, 2018; Kara, 2018; Frankel, 2016; Nkulu et al., 2018; UNEP, 2013.
24. Kara, 2018; Radert et al., 2018.
25. Faber et al., 2017.
26. ILO Convention 182 (1999) and OECD Practical actions for companies to identify and address the worst forms of child labour in mineral supply chains (OECD, 2017).
27. IEA, 2019; Levin Sources, 2019; Katwala, 2018.
28. Heffernan, 2019; IUCN 2018.
29. The carbon budget is the maximum cumulative GHG emissions until 2050 that will ensure staying within the Paris Agreement target.

30. Using base case emissions as a reference; in this report, the GHG protocol is used to assess the emission reduction potential of the production and use of batteries. The GHG protocol defines three “Scopes” of emissions. A short description of their relevance to the battery value chain follows:

    – Scope 1: includes emissions related to the production of batteries. These are direct emissions of players in the battery value chain and include, for example, heat generation from fossil fuels or transport fuels for mining vehicles.

    – Scope 2: includes emissions related to the production of inputs needed for battery production. These emissions associated with battery production include, for example, electricity production emissions, emissions of feedstock, etc..
    – Scope 3: includes emissions related to up- and downstream emissions of the battery value chain. These are emissions associated with the use of batteries and include, for example, enablement of intermittent renewable energy sources in grids, and transitions to low-carbon mobility.

31. Using base case emissions as a reference; negative costs mean that circularity and innovation provide solutions that have better cost performance compared to base case alternatives.

32. IRENA, 2019.

33. While consumer electronics batter recollection is historically poor (below 20%) and has shown to be difficult to increase, vehicle/stationary battery recollection is expected to be more successful at 65% in the base case and even 90% in the 2030 target case.

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# Acronyms

| | |
|---|---|
| B | Billion |
| BEV | Battery electric vehicle |
| CAGR | Compound annual growth rate |
| $CO_2$ | Carbon dioxide |
| $CO_2e$ | Carbon dioxide equivalent, metric of GHG emissions |
| DRC | Democratic Republic of the Congo |
| ESS | Energy storage system |
| EV | Electric vehicle, here used for battery electric, hybrid and plug-in hybrid vehicles |
| G | Gram |
| $gCO_2$ | Gram of carbon dioxide |
| GHG | Greenhouse gas |
| Gt | Gigatonne |
| $GtCO_2e$ | Gigatonne of equivalent carbon dioxide |
| GW | Gigawatt |
| GWh | Gigawatt hours |
| H2 | Hydrogen |
| HEV | Hybrid electric vehicle |
| ICE | Internal combustion engine |
| IPCC | Intergovernmental Panel on Climate Change |
| K | Thousand |
| Km | Kilometre |
| LAB | Lead-acid battery |
| LCFS | Low carbon fuel standard |
| M | Million |
| Mt | Megatonne |
| NMC | Nickel-manganese-cobalt oxide-based cathodes |
| NMC622 | NMC cathode composed with 6 parts of nickel, 2 of cobalt and manganese |
| NMC811 | NMC cathode composed with 8 parts of nickel, 1 of cobalt and manganese |
| OECD | Organisation for Economic Co-operation and Development |
| OEM | Original equipment manufacturer, in this case automakers |
| PHEV | Plug-in hybrid electric vehicle |
| R&D | Research and development |
| RoW | Rest of the world |
| SDG | United Nations Sustainable Development Goal |
| SHS | Solar home system |
| SLI | Starter, light and ignition |
| T | Ton |
| TCO | Total cost of ownership |
| ULAB | Used lead-acid battery |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| V1G | Smart charging |
| V2G | Vehicle-to-grid |
| W | Watt |

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Further information about the Global Battery Alliance, including a full list of member organizations, is available at https://www.weforum.org/global-battery-alliance/home or from gba@weforum.org.

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