In Collaboration with
McKinsey & Company

Forging Ahead
A materials roadmap for the zero-carbon car

CIRCULAR CARS INITIATIVE
MATERIALS

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Cover: Getty Images

Contents

Foreword

Thomas Deloison
Director Mobility, World Business Council for Sustainable Development

Christoph Wolff
Global Head of Mobility and Member of the Executive Committee, World Economic Forum

The car has given us freedom. It has accelerated trade and made an indelible mark on modern culture and lifestyles. But cars are also responsible for ~10% of greenhouse gas emissions and a large share of global steel, aluminium, plastic, rubber, glass and increasingly battery material consumption. It is now time for a revolution in automotive sustainability.

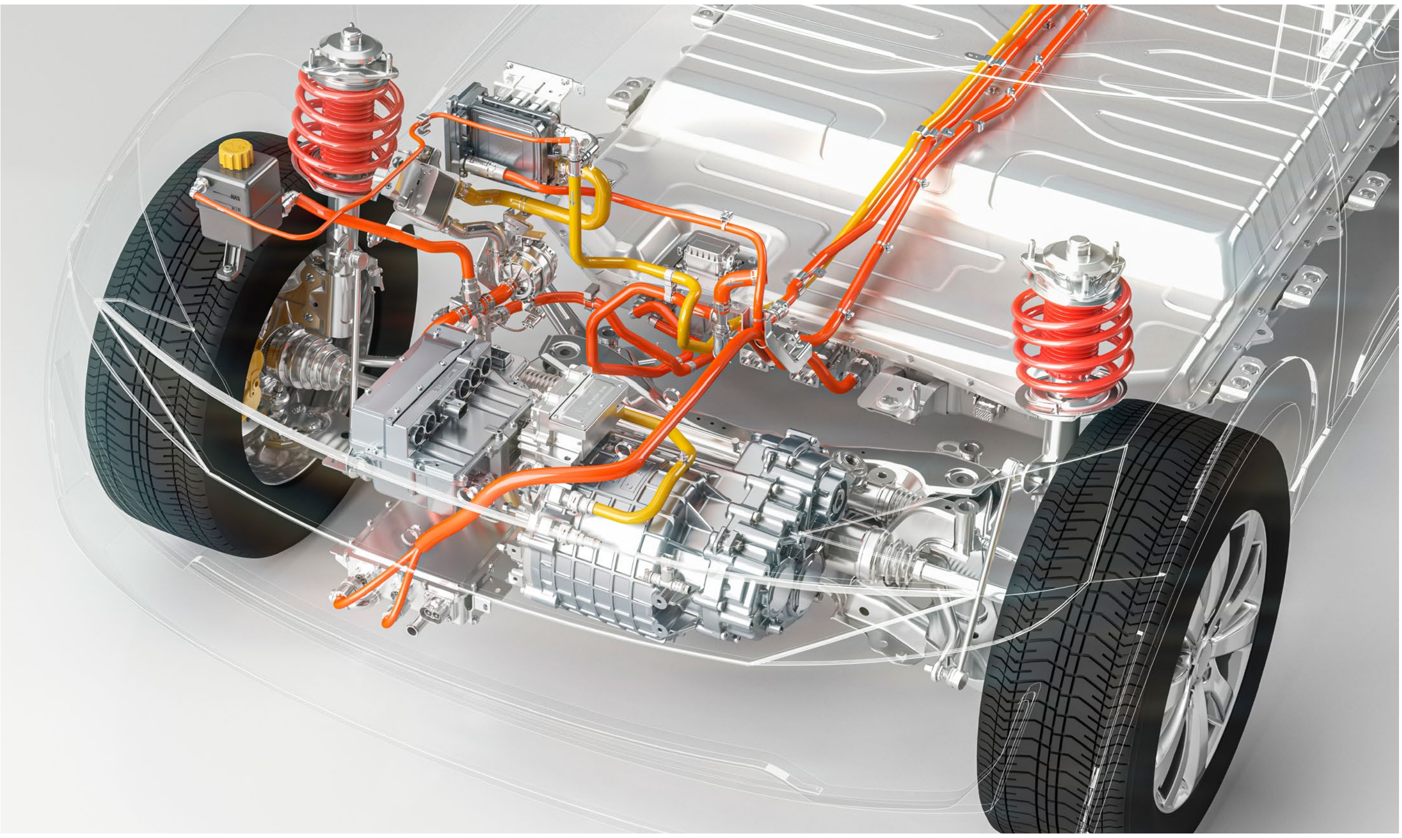
The World Economic Forum and the World Business Council for Sustainable Development (WBCSD) jointly formed the Circular Cars Initiative to accelerate this transformation. The Initiative takes a systemic approach – accounting for the build phase as well as the use phase – to automotive sustainability. It looks at how technology and business levers can maximize the resource value of the car, minimize life-cycle emissions and unlock new opportunities.

Within the Circular Car Initiative, 40 companies from the automotive value chain, several research institutes, international organizations, governmental bodies and think tanks are charting the course towards a zero-emission future through new technology, materials innovation, efficient vehicle usage and full life-cycle management.

We wish to thank Accenture under the leadership of Wolfgang Machur and Alexander Holst, and McKinsey under the direction of Fehmi Yüksel and Eric Hannon, for their in-depth analysis and thought partnership on these topics. We are also appreciative of EIT Climate-KIC's Sira Saccani and Kirsten Dunlop, and SYSTEMIQ's Matthias Ballweg, Tillmann Vahle and Martin Stuchtey, for joining early on and for their ongoing work on policy recommendations.

We also would not have come to this point at the end of 2020 without the leadership of Levi Tillemann at the World Economic Forum.

The "circular car" is now on its way to becoming a core component of the automotive future.



Letter from McKinsey & Company and the World Economic Forum

Levi Tillemann
Lead, Circular Cars Initiative, World Economic Forum

Bernd Heid
Senior Partner, McKinsey & Company

Eric Hannon
Partner, McKinsey & Company

The automotive industry has been a powerful driver of economic prosperity and individual mobility for almost 150 years. During this time, the industry has evolved dramatically and continually adapted to new technologies, business practices, opportunities and realities – from mass production to new safety measures, to electrification and digitization. The next axis of transformation will be around the imperative to decarbonize.

The scientific consensus is that limiting global warming to 1.5°C by 2050 is essential to mitigate catastrophic climate risk. This goal is embodied in the Paris Agreement's net-zero target. The automotive industry, which currently contributes over 10% of industrial emissions, must embrace life-cycle decarbonization to meet this moment.

To date, decarbonization has focused on electrifying powertrains. Since exhaust emissions make up 80% of life-cycle emissions of a standard combustion engine vehicle, this makes sense. But electrification is not the sole answer to the decarbonization challenge. The automotive industry must also tackle emissions embedded in vehicle materials – which will grow in importance in tandem with powertrain electrification. Materials used in vehicles already account for 18–22% of internal combustion engine vehicles' (ICEVs) life-cycle emissions. The growing market share of battery-electric vehicles (BEVs) – and the greener energy mix required to power them – will increase materials' share of automotive life-cycle emissions in both relative and absolute terms.

The path towards electrifying powertrains is complex, but well understood. On the other hand, eliminating carbon emissions from automotive materials is a highly complex undertaking and a consensus regarding the technoeconomic pathway for full decarbonization has not yet emerged. We project that material emissions will surpass 60% of life-cycle emissions by 2040, assuming no reduction of emissions in automotive materials production.

But there is good news. McKinsey's abatement cost curve for automotive materials shows that in some pathways to decarbonization, by 2030 about 66% of material emissions of a representative ICEV could be abated at no net material cost increase. An even larger share of material emissions from BEVs could be decarbonized at no net cost increase. Fast-acting suppliers and original equipment manufacturers (OEMs) can realize this decarbonization potential while saving money in the process.

The purpose of this report is to clarify the elements of this important task. Within the framework of the Circular Cars Initiative's (CCI) Materials Workstream, the World Economic Forum and McKinsey are collaborating with more than 70 partners from the entire automotive ecosystem[1] to elucidate potential routes towards decarbonization. The centrepiece of the McKinsey team's analysis is McKinsey's carbon abatement model, which details various materials' decarbonization levers and scenarios. This analysis covers more than 90% of automotive material emissions. Our analysis has been deeply informed by the initiative's workshops and structured discussions with community members.

There is a path to net zero and a bright future for companies that embrace this challenge. A large proportion of automotive material carbon emissions could be abated by 2030 at no net-cost increase. Many key technologies and sustainability solutions can be implemented today. However, success will depend on new collaboration models within and beyond the automotive ecosystem. There must be a fundamental rethinking of today's value chain and its incentives. The Circular Cars Initiative has already seen the willingness of many industry participants to embrace this future – and join forces to pave a new road ahead for the zero-carbon car.

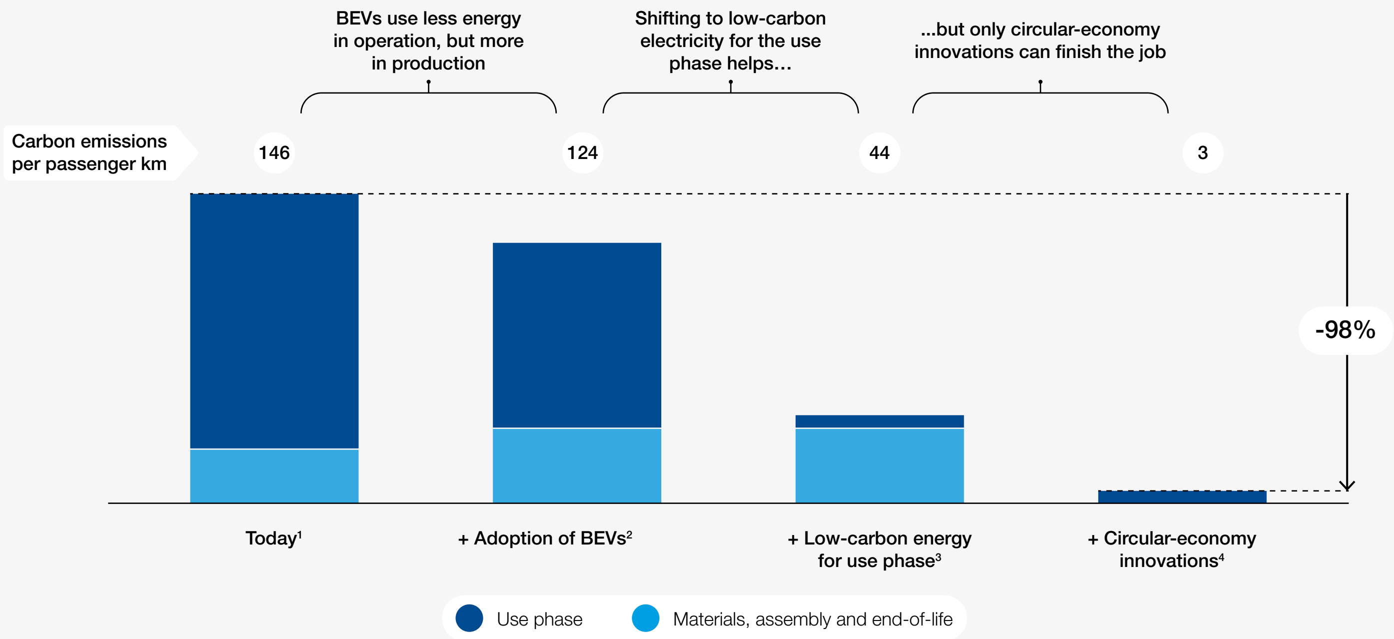
Introduction

Sustainable cars must be powered by green electricity; circular economy principles need to govern both manufacture and use phase.

The term "circular car" refers to a theoretical vehicle that has maximized materials efficiency. This notional vehicle would produce zero material waste and zero pollution during manufacture, usage and disposal – which differentiates it from today's zero-emission vehicles. While cars may never be fully "circular", the automotive industry can significantly increase its degree of circularity. Doing so has the potential to deliver economic, societal and ecological dividends.

Indeed, the convergence of technology, environmental and economic megatrends is propelling the modern automotive industry towards just such a transformation. The Circular Cars Initiative has assembled a broad coalition of participants from the automobility ecosystem committed to leading this transformation and increasing the environmental sustainability of global mobility by harnessing the power of new technologies, materials and business models.

FIGURE 1 **Decarbonizing the car**



1. ICEV hatchback (level 1) with 1.70t weight (incl. repair components), 0.90t steel, 0.15t aluminium, 0.29t plastics, 200,000 life-cycle km and average occupancy of 1.5
2. BEV hatchback (level 1) with 1.90t weight (incl. repair components), 0.70t steel, 0.19t aluminium, 0.32t plastics, 0.32t EV battery, 250,000 life-cycle km and average occupancy of 1.5
3. Requires decarbonization of electricity grid with additional renewable energy as per consumption requirement by BEVs
4. Circular-economy innovations consider level 4 circular BEV (fully circular)

Source: Accenture Strategy analysis

The Circular Cars Initiative (CCI) is comprised of three main workstreams:

– The **materials workstream**, led by McKinsey, is focused on the pressing need to decarbonize materials, institute closed-loop recycling and provide materials with a productive second life – capturing value that today is downcycled into other industries (see Figure 2).

– The **business models workstream** is led by Accenture Strategy. Its work lays out a series of strategies for achieving circularity. In collaboration with the World Economic Forum, Accenture Strategy has developed a taxonomy to guide the industry's progress on carbon and resource efficiency. The goal is to maximize the mobility output achieved per unit of resources and emissions expended (see Figure 3). The taxonomy addresses usage, vehicle lifetime, materials and energy-related aspects of circular business models.

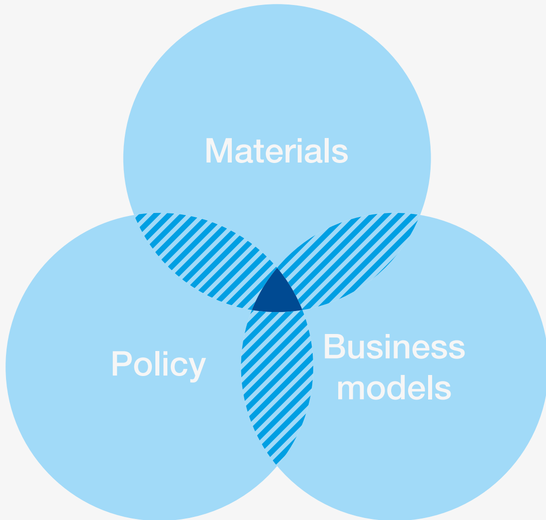
– Finally, the **policy workstream** is under development. It will connect the dots of this ecosystem and address the relevant policy tools to be taken onboard by governments globally.

Each of these workstreams has been supported by our diverse community of stakeholder organizations, including carmakers, materials suppliers, national research institutes, non-governmental organizations (NGOs) and academic institutions. They have contributed their insights through workshops and many dozens of interviews, as well as data and feedback on this multifaceted analytical process. In addition to our analytical partners McKinsey and Accenture, CCI would also like to recognize the valuable support and contributions of our CCI co-founders at the World Business Council for Sustainable Development (WBCSD), EIT Climate-KIC and SYSTEMIQ.

FIGURE 2 **The Circular Cars Initiative (CCI): organizational structure and 2020 deliverables**

CCI deliverables for 2020 include

- A five-level taxonomy for automotive circularity
- A materials transition tool to delineate pathways for material decarbonization in the sector
- Roadmaps (materials, policy and business models) outlining critical investments, milestones and policy-drivers for circularity
- Approach to start circularity-focused pilot projects among member companies



1

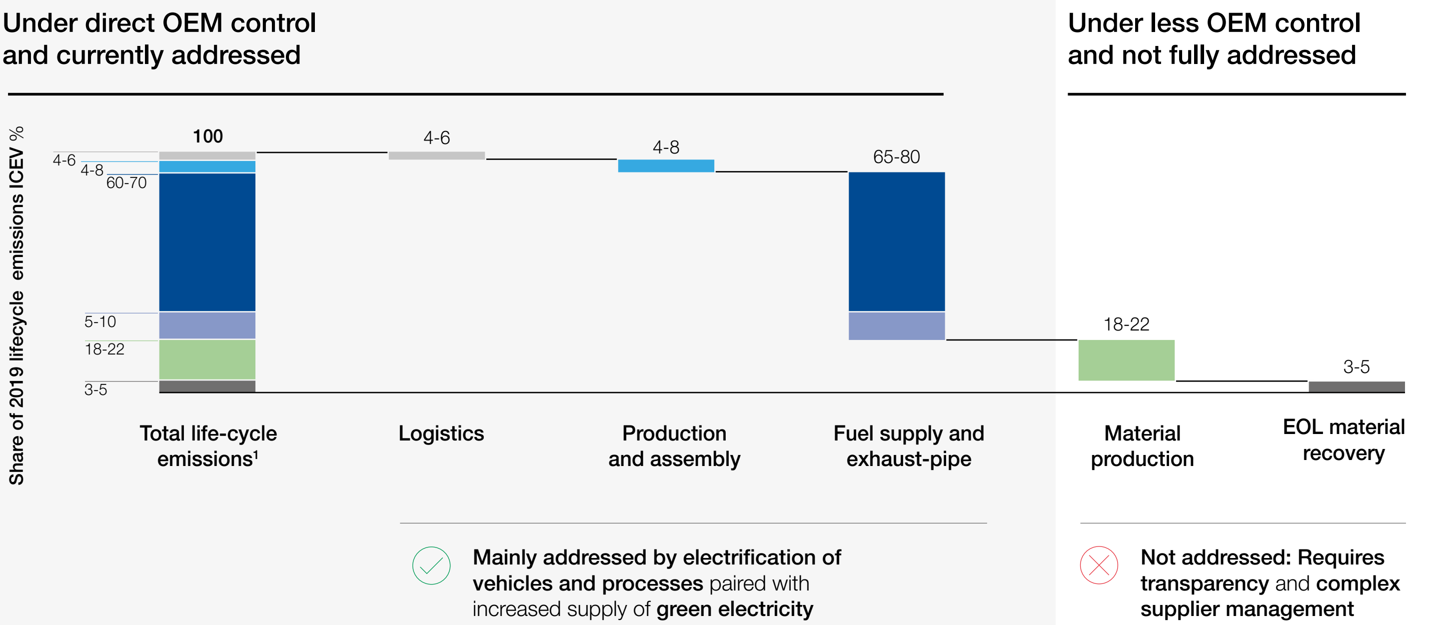
Automotive materials

The next hurdle in the quest for the zero-carbon car.

To decarbonize the automotive industry and help reach the Paris Agreement targets of cutting greenhouse-gas (GHG) emissions 50% by 2030 – reaching net-zero by 2050 – a full and detailed view of the sector's emissions throughout a vehicle's life cycle is required. Internal combustion engine vehicles (ICEVs) currently generate 65–80% of their lifetime emissions from exhaust as the car burns fuel, and another 18–22% of emissions from the production of materials (Figure 3). Because the use phase accounts for such a high proportion of emissions, the industry's focus so far has been on electrifying powertrains. A McKinsey analysis found that to achieve the 2050 net-zero goal, battery-electric vehicle (BEV) sales penetration must be close to 100% by 2040. Many countries have accordingly announced plans to ban sales of ICEVs by 2040.[2]

Beyond electrifying powertrains, achieving the full potential of automotive decarbonization requires an equal focus on materials production. While BEVs can significantly reduce use-phase emissions, especially as renewables continue to expand their share of the grid's energy mix, the energy- and emission-intensive production processes of automotive materials – particularly batteries – will place new demands on the industry's efforts to decarbonize (Figure 4).

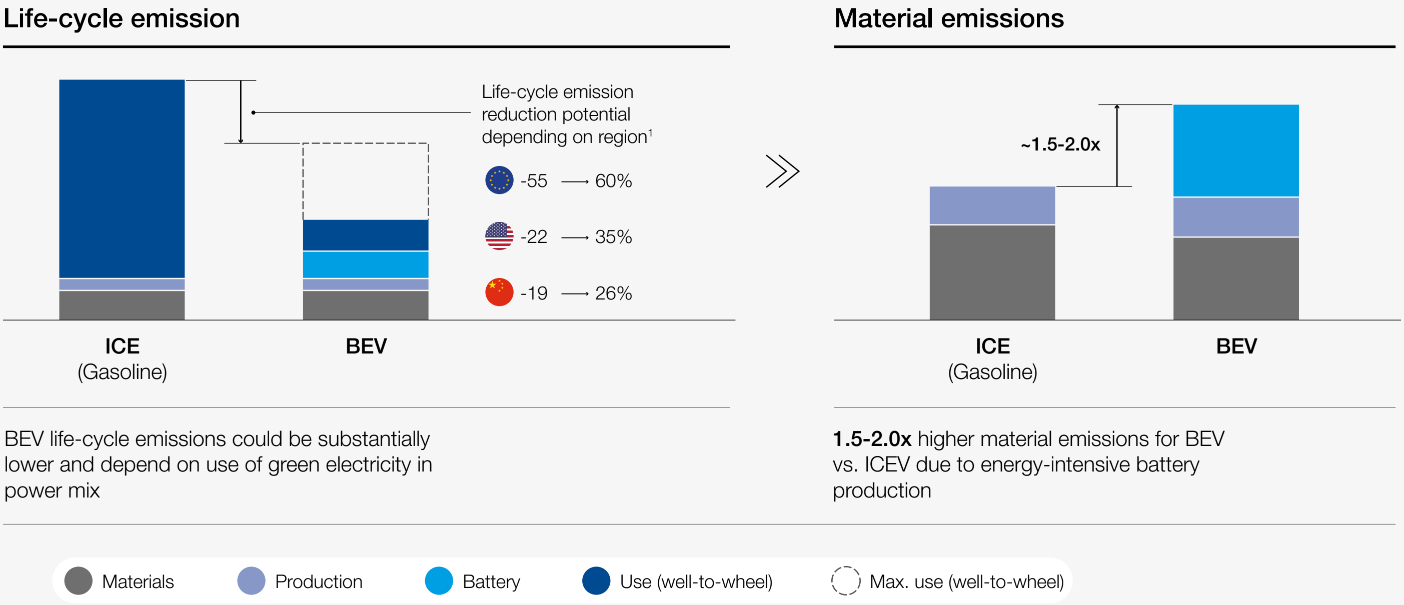
FIGURE 3 **Emissions in OEM's extended value chain and under less control**



1. C-segment vehicle

Source: NGVA, expert interviews, Decarbonization in Automotive Material Team analysis

FIGURE 4 | **Investigation into BEV vs. ICE life-cycle and material emissions**



1. Reduction potential also depending on vehicle segment with smaller vehicles with typically higher emission reduction potential

Source: World Economic Forum, Global Batterny Alliance, McKinsey analysis

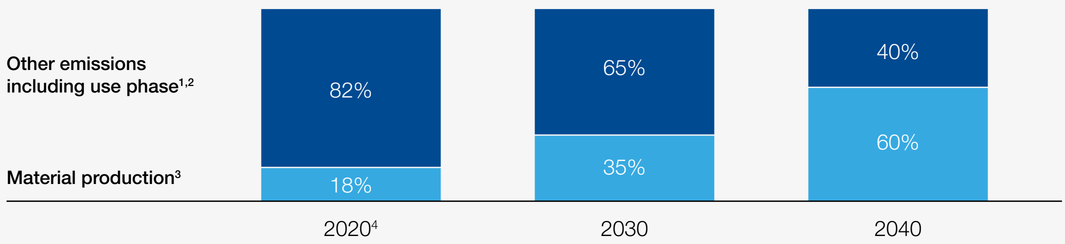
The higher material emissions for BEV production means that large-scale adoption of BEVs is not a panacea for the industry's decarbonization challenge. With a mass-market transition to BEVs, more than 60% of automotive life-cycle emissions would come from materials by 2040 (Figure 5).

These changes will shift the balance of the automotive sector's carbon footprint to materials production – creating a new challenge in the race to the true zero-carbon car

The zero-carbon car: A vehicle that has reached its full potential with respect to carbon efficiency: This likely requires net-zero materials waste and net-zero exhaust pollution. While the automotive value chain may never be entirely emission-free, a net-zero car is an aspirational vision for the automotive ecosystem that can mobilize industry participants.

FIGURE 5 | **Emissions from production materials may reach 60% of life-cycle emissions by 2040**

Emissions from material production will have higher share than other life-cycle emissions in percentage share (based on required sales volumes)



1. Assumed constant range of 15,000km/vehicle per year and 10-year lifetime as baseline – End-of-life emissions not considered here

2. 2018 average ~120g CO2/km, target today 95g CO2/km; future assumptions: 2030 75g CO2/km; 2040 50g CO2/km; 0.10-0.16kWh/km for xEV

3. Average material emissions: ICE 3,000, EV 7,400, PHEV 5,000, HEV 4,000kg CO2 per vehicle as of model (hold constant as decarbonization in focus)

4. Current BEV, PHEV, HEV penetration in relevant regions at 4–8%; 2030: BEV 33%, PHEV 12%, HEV 7%; 2040: BEV 60%, PHEV 27%, HEV 13%

Source: High-level estimation of Circular Cars Initiative (2020) for ambitious EV adoption scenario

2 The cost-effective path to materials decarbonization

Full material decarbonization requires a multi-decade strategy. Key technoeconomic decision points will shape the final scope and cost.

Addressing material emissions will first require transparency on the most efficient and effective paths for decarbonizing materials and the costs involved. The complexities of automobile manufacturing and supply chains mean that eliminating emissions will require structural changes and significant investments of time and resources throughout the industry.

To understand the costs and impact of various paths towards materials decarbonization, McKinsey developed carbon abatement cost curves detailing the amount of material emissions that can be reduced and at what costs, for both ICEVs and BEVs. Multiple paths to decarbonization are possible, some of which are mutually exclusive.

2.1 The abatement cost curve: a comprehensive perspective on materials decarbonization

Decarbonizing automotive materials is logistically complex, with long lead times. Vehicles typically take four to six years from initial concept to market. In addition, carbon-reducing or carbon-neutral material production technologies, such as electric arc furnaces (EAFs) for steelmaking, require several years for plant construction, quality assurance, scaling and regulatory approval. As such, a comprehensive view that can support individual companies' goals as well as the automotive industry as a whole can help coordinate decarbonization efforts and allocate resources effectively.

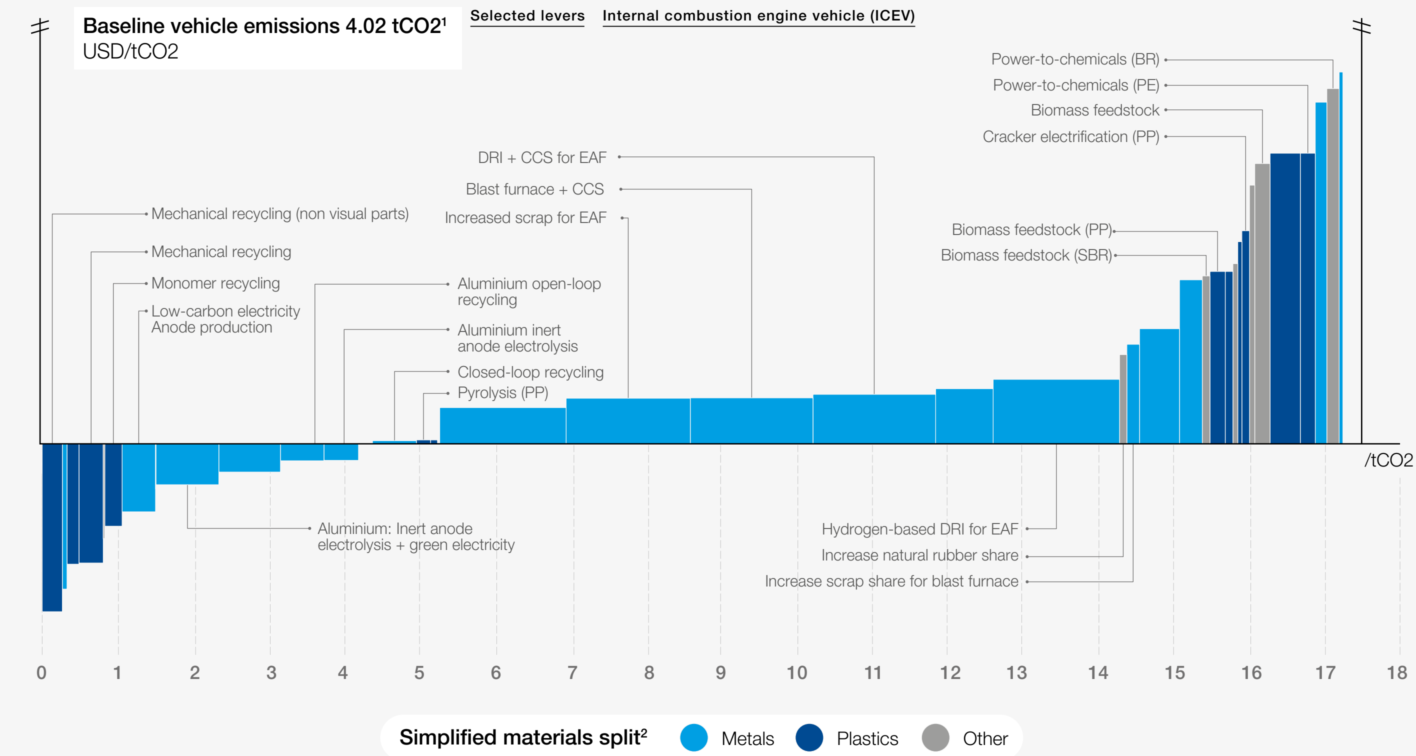
McKinsey's material abatement cost model outlines technological levers with respect to both their carbon abatement potential and the associated changes in a vehicle's material costs for various time horizons up to 2050 (Figures 6 and 7 are based on expected costs and abatement potential in 2030).

Understanding the carbon abatement curve:

The x-axis of the abatement cost curve indicates each lever's abatement potential in tons of CO_2. The y-axis displays each lever's abatement costs (or savings if the costs are negative) per ton of CO_2 for that lever. The abatement levers shown in the abatement cost curves are colour-coded and include materials that account for about 90% of a vehicle's weight and emissions.

The model focuses on three main strategies for decarbonization: demand reduction, circularity and materials decarbonization. Demand reduction refers to levers that decrease demand for the total amount of material in the vehicle in the first place and is the basis input for the model's calculations; circularity focuses on all levers that increase the use of recycled materials in the vehicle and the extension of their productive lifespan; and materials decarbonization focuses on technological levers that can reduce the emissions during material production (for more, see Appendix).

FIGURE 6 Full material abatement cost curve for ICEVs in 2030, including all levers

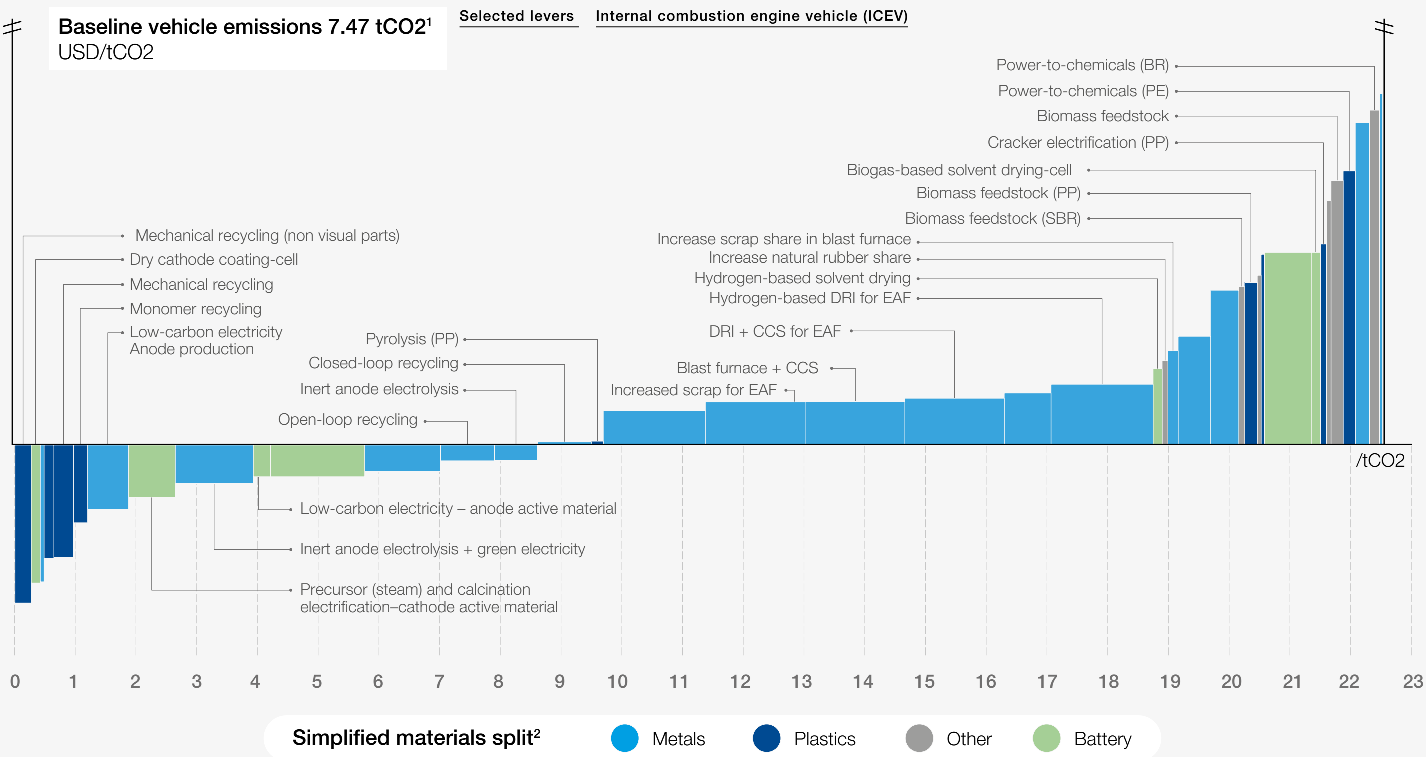


1. In this analysis, a premium C-segment vehicle with 1.95t vehicle weight: 1.04t steel; 0.29t aluminium; 0.10t rubber; 0.07t PP; 0.03t PE; 0.05t glass is considered

2. Metals including steel, high-strength steel, aluminium, alumina; plastics including polypropylene, polyethylene, polyamide 6; other materials including rubber, glass

Source: McKinsey analysis (Team, McKinsey Decarbonization Pathways Optimizer)

FIGURE 7 Full material abatement cost curve for BEVs in 2030, including all levers



1. In this analysis, a premium C-segment vehicle with 1.95t vehicle weight: 1.04t steel; 0.29t aluminium; 0.10t rubber; 0.07t PP; 0.03t PE; 0.05t glass is considered

2. Metals including steel, high-strength steel, aluminium, alumina; plastics including polypropylene, polyethylene, polyamide 6; other materials including rubber, glass

Source: McKinsey analysis (Team, McKinsey Decarbonization Pathways Optimizer)

> This analysis suggests that 97% of BEV material emissions could be abated at no net increase of material costs [by 2030].

Analysis of ICEV and BEV examples based on a 2030 carbon-abatement model suggest several courses of action that automotive players and the industry could take to coordinate their decarbonization efforts:

Prioritize long-term cost-savings. The abatement cost curves show several levers that could reduce embedded carbon emissions and material costs at the same time. These factors include mechanical recycling for different plastics components that could add 0.6-0.8t CO2 abatement potential if applied to a higher share of plastics in a vehicle. Beyond that, for aluminium production, inert anode electrolysis is a technology that could reduce emissions if implemented and scaled properly. As a general rule, powering many processes with green electricity offers high decarbonization potential while reducing material costs in the long term.

Enable high-impact green steel technologies that come with additional costs: Decarbonizing steel will be critical. Steel comprises 50–65% of a vehicle's weight and is responsible for 30–40% of an average vehicle's material emissions. Significant decarbonization could be achieved at abatement costs of $75–90 per t CO2. Technologies considered for decarbonizing current steel production include carbon capture and storage (CCS), increased scrap intake and the use of biomass as a feedstock. Alternatively, EAFs can be used for steel production and use higher scrap shares or hydrogen-based direct reduced iron (DRI) as compared to current industry standards.

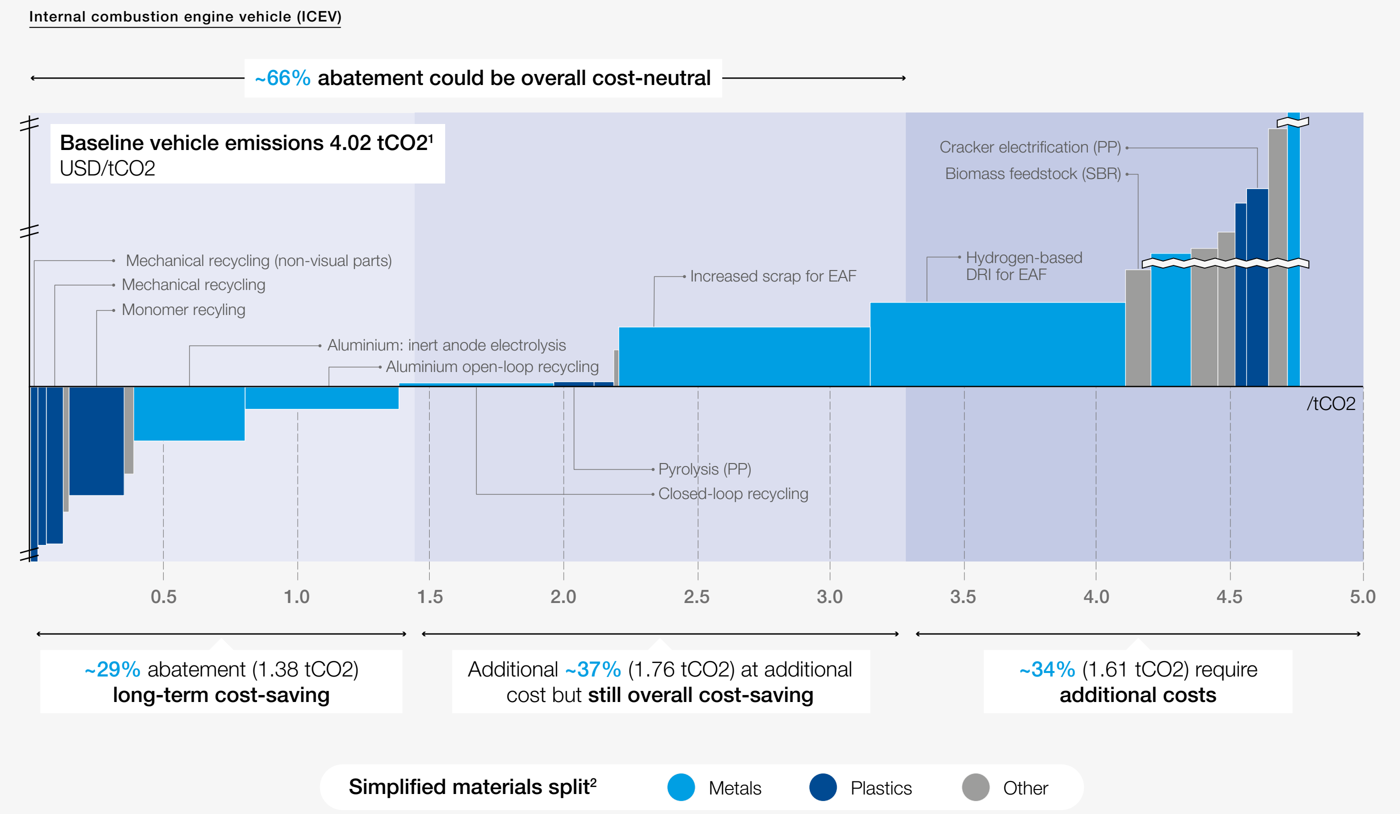
Explore further cost reductions through new technologies: A range of other emerging technologies could affect carbon abatement on a smaller scale, but come with high abatement costs. These processes are not yet mature enough to be applied at scale. For instance, green electricity can be converted into chemicals – though this requires massive amounts of green power. Biomass could also be used as feedstock for various materials production processes, but this approach would require sustainable sources of large amounts of biomass. Because these potential solutions are mainly related to plastics, automotive companies could play a role in helping chemical companies find cost-effective ways to improve emissions. Even though these actions may not have high abatement potential individually today, overall they can pave a way towards full decarbonization if technological advances and cost reductions can be achieved.

2.2 Current cost-effective pathways for ICEVs and BEVs

Because several levers are technologically mutually exclusive, diverse decarbonization pathways must be considered. In the case of steel, there are two viable but mutually exclusive pathways: CCS-based low-carbon traditional steel production through blast furnaces, and hydrogen-based direct reduced iron with electric arc furnace (DRI-EAF). Important considerations with respect to each of these technologies include: cost optimization, maximum abatement potential and circularity potential. These, in turn, depend on factors such as current production footprints, technology maturity, consumer behaviour and organizational priorities.

The modelling below details possible cost-effective pathways by 2030. For ICEVs, the automotive upstream marginal abatement cost curve applied to the standard vehicle suggests the potential to decarbonize around 66% of emissions at no additional cost, including 29% that could be abated while reducing material costs for a specific car model (Figure 8).

FIGURE 8 **Example of prioritized abatement cost curve for an ICEV in 2030**



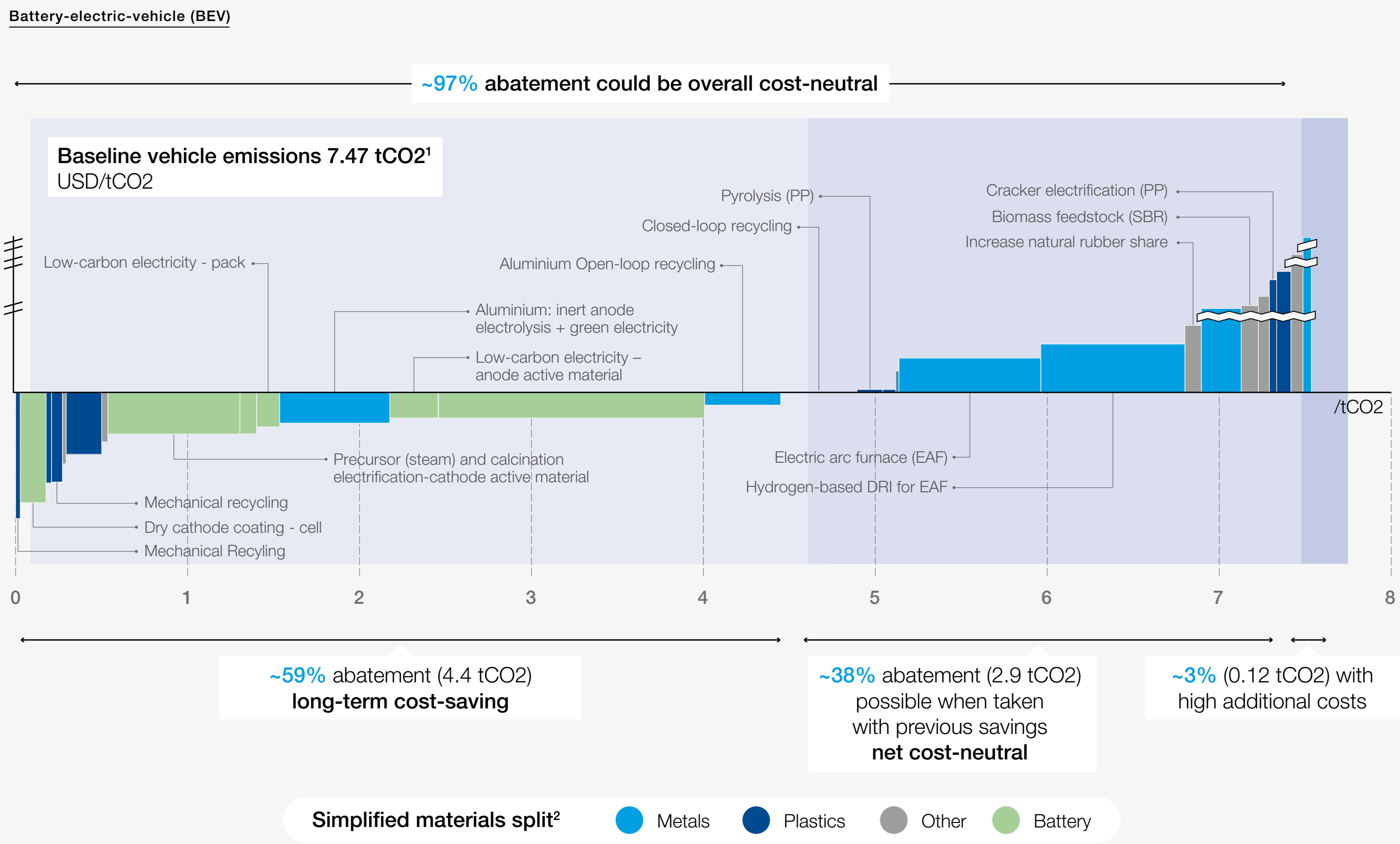
1. In this analysis, a premium C-segment vehicle with 1.95t vehicle weight: 1.04t steel; 0.29t aluminium; 0.10t rubber; 0.07t PP; 0.03t PE; 0.05t glass is considered

2. Metals including steel, high-strength steel, aluminium, alumina; plastics including polypropylene, polyethylene, polyamide 6; other materials including rubber, glass

Source: McKinsey analysis (Team, McKinsey Decarbonization Pathways Optimizer)

The model suggests a larger opportunity to decarbonize emissions at no additional cost for BEVs than for ICEVs, mainly because it assumes that battery production will shift from regions with an emission-intensive grid mix to ones with lower carbon emissions in their energy mix. In addition, the increased use of green energy sources for energy-intensive production processes could lead to high abatement at a relatively low cost. Indeed, this analysis suggests that 97% of BEV material emissions could be abated at no net increase of material costs in a 2030 scenario (Figure 9).

FIGURE 9 | Example of prioritized abatement cost curve for a BEV in 2030



1. In this analysis, a premium C-segment vehicle with 1.95t vehicle weight: 1.04t steel; 0.29t aluminium; 0.10t rubber; 0.07t PP; 0.03t PE; 0.05t glass is considered

2. Metals including steel, high-strength steel, aluminium, alumina; plastics including polypropylene, polyethylene, polyamide 6; other materials including rubber, glass

Source: McKinsey analysis (Team, McKinsey Decarbonization Pathways Optimizer)

2.3 Steel and batteries have large decarbonization potential

The largest share of a vehicle's overall material emissions come from steel and batteries. Thus, they also have the greatest decarbonization potential.

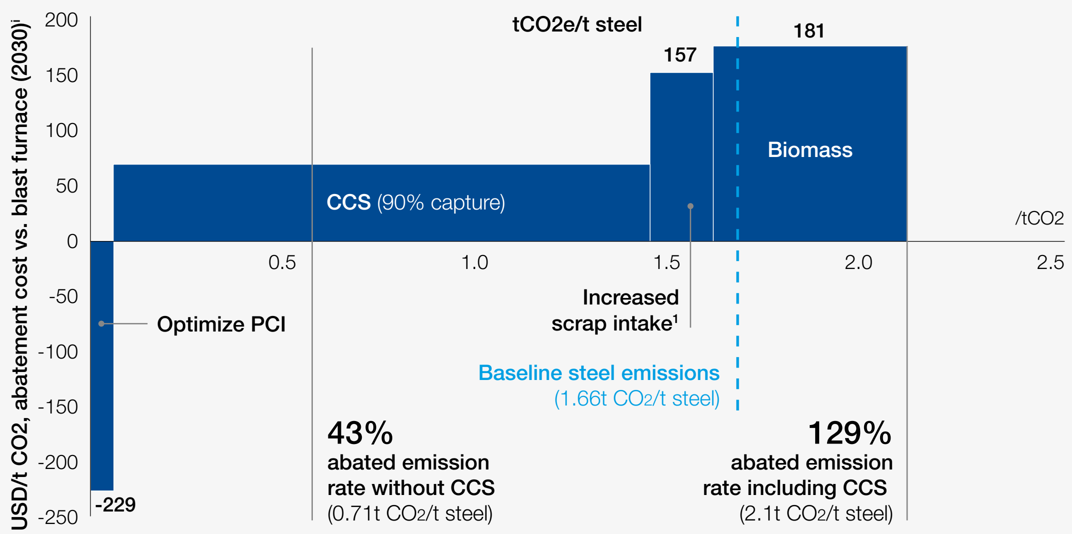
Decarbonizing these materials can follow multiple competing pathways.

Steel

Emissions from steel production can be reduced through two main paths: low-carbon traditional steelmaking (Figure 10) and hydrogen-based DRI-EAF steelmaking (Figure 11). We compare these two routes with the industry standard, steelmaking, which we estimate to produce 1.7–2.0t CO2/t steel at a cost of $310–320/t steel.

Decarbonized traditional steelmaking pathway: The fully decarbonized traditional steelmaking pathway involves four main levers – optimized pulverized coal injection (PCI); carbon capture and storage; increased scrap intake; and biomass as a feedstock. Implementing all of these levers would result in a carbon sink with an overall emission intensity of -0.5t CO2/t steel. The negative emission intensity comes from a high theoretical carbon capture potential of up to 90% of emissions and the use of biomass, which, in effect, removes carbon from the atmosphere and avoids extraction and use of coal.

FIGURE 10 **Possible steel abatement cost curve for low-carbon traditional steelmaking pathway in 2030**



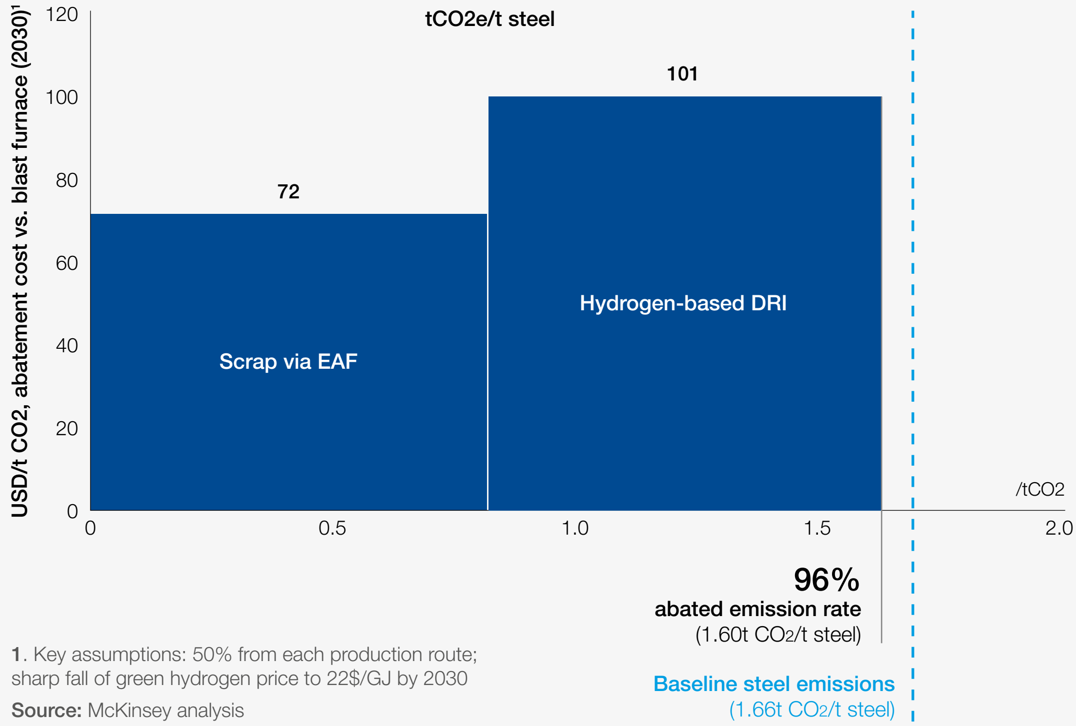
1. from average 12% to 30%

Source: McKinsey analysis

Both levers in this pathway come with constraints and obstacles. CCS does not currently achieve the assumed high capture rates. Questions regarding safety standards and the potential risks of long-term environmental hazards could make the technology a non-starter. Until such questions are resolved, it is difficult to project the possible levels of abatement and cost of CCS. Availability of sustainable and sufficient volumes of biomass is also a challenge. That said, our levelized costs for this pathway would result in production costs of $520–550/t steel.

Hydrogen-based DRI-EAF pathway: The hydrogen-based steel pathway focuses on steel production through DRI-EAF technologies. The two main levers assume higher scrap intake and the use of hydrogen-based direct reduced iron in the same proportions for the EAF. This pathway would result in total emissions of 0.1t CO2/t steel, a 96% reduction as compared to current production processes.

FIGURE 11 | **Possible steel abatement cost curve for low-carbon traditional steelmaking pathway in 2030**



1. Key assumptions: 50% from each production route; sharp fall of green hydrogen price to 22$/GJ by 2030

Source: McKinsey analysis

> **The levelized costs of hydrogen-based steelmaking would result in $420–450/t steel, which may make this pathway more plausible than the (less technologically developed and economically feasible) CCS route.**

The levelized costs of hydrogen-based steelmaking would result in $420–450/t steel, which may make this pathway more plausible than the (less technologically developed and economically feasible) CCS route. The primary obstacles for this route are building the required hydrogen supply chain and capacity and significantly reducing the cost of green hydrogen.

Production capacity for green steel may be limited in the near term, and steelmakers may have incentives to prioritize decarbonizing industries such as construction, where abatement is cheaper due to lower-quality requirements for materials. The automotive industry should preemptively develop approaches to support this complex and investment-intensive decarbonization transition and ensure access to sufficient quantities of decarbonized steel.

Steel manufacturers have the opportunity to use green steel to differentiate themselves. But successful decarbonization will require cross-sectoral support, including efforts to address sectoral bottlenecks (e.g. in areas such as green power generation and new infrastructure) and the need for heavy upfront investment.

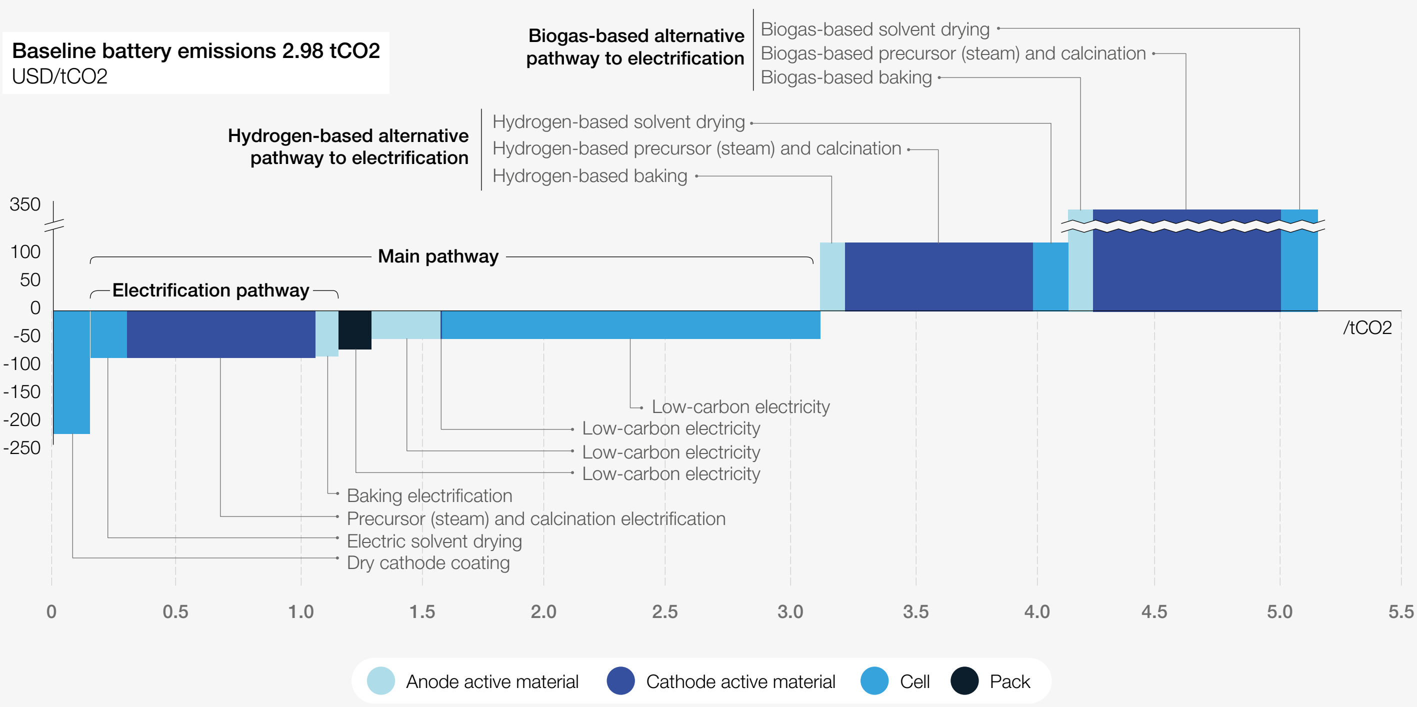
With a fast ramp-up of green power and hydrogen capacity, a tightening regulatory environment could potentially make decarbonized steel a net cost saving by 2030 – even after factoring in the significant structural operational changes and capital expenditure required. Though carbon taxes are expected to rise, a carbon tax of just $80–100/t CO2 would make the business case for decarbonized steel attractive. Steelmakers that fail to invest in these technologies risk getting left behind by evolving regulatory frameworks.

Batteries

The carbon abatement model for batteries focuses on active material (including anode and cathode), cell and pack production.[3] The main levers for decarbonization of battery production processes lie in the use of low-carbon electricity and switching emission-intensive process steps to low-carbon energy sources (Figure 12).

FIGURE 12

Full battery abatement levers



In this analysis a 92kWh battery per vehicle is considered, and only direct and indirect process emissions from fuels and electricity in the modelled production steps are included (mining or transport excluded)

Source: McKinsey analysis (Team, McKinsey Decarbonization Pathways Optimizer)

Low-carbon electricity: One of the main levers for battery production decarbonization lies in the use of low-carbon electricity, which could be achieved through a shift in production to regions with a low-carbon grid mix. With this shift, 1.5–1.8t CO2 could be abated, which would amount to about half of the emissions associated with batteries today.

For active material as well as cell production, switching from gas-powered processes to low-carbon electricity, biogas or hydrogen can significantly reduce emissions. From the perspective of the 2030 targets, process electrification could have a cost advantage compared to biogas- or hydrogen-based pathways. Electrifying processes could save money as the price of green electricity declines.

3 A path forward for the automotive ecosystem

The materials cost curves and modelled pathways provide a framework for a truly zero-carbon car. But critical decarbonization levers require extensive collaboration.

3.1 A strategic industry approach for effectively abating upstream emissions

Current approaches that emphasize competition may be an obstacle to this goal – and to other necessary structural shifts in the ecosystem. Instead, a systemic collaboration model characterized by three overarching strategies – "lead, share and follow" – could create the right incentives for decarbonizing materials as an industry (Figure 13).

FIGURE 13 **Lead, share, follow framework to define areas of collaboration as an ecosystem**

Levers of strategic advantage	Levers too big for individual players for differentiation	Levers outside direct control but led by other industries
Lead	**Share**	**Follow**
Be in the driver's seat and take active role and investment to take decarbonization lead in value chain	Share knowledge and collaborate to coordinate decarbonization of customers, suppliers and value chain	Passively wait for industry to embark on decarbonization pathway to implement new technologies
Example: steel		
Secondary steel. Use limited by specification and not cost Use opportunity to work with key suppliers to differentiate	Closed-loop recycling. Limited by controlled access to high-quality volumes H2-based DRI and EAF. Limited by development and ramp-up time of H2 Use a shared strategy to orchestrate ecosystem and transition to DRI-EAF	CCS. Limited by capture rate, costs and long-term environmental risks Use a follow-up strategy making sure to implement when maturity achieved

Lead: OEMs and materials manufacturers should lead in areas where their investment and active leadership can drive decarbonization in the value chain and create a competitive advantage. For example, activities that increase the recycling share of materials through the optimization of materials specifications present such an opportunity.

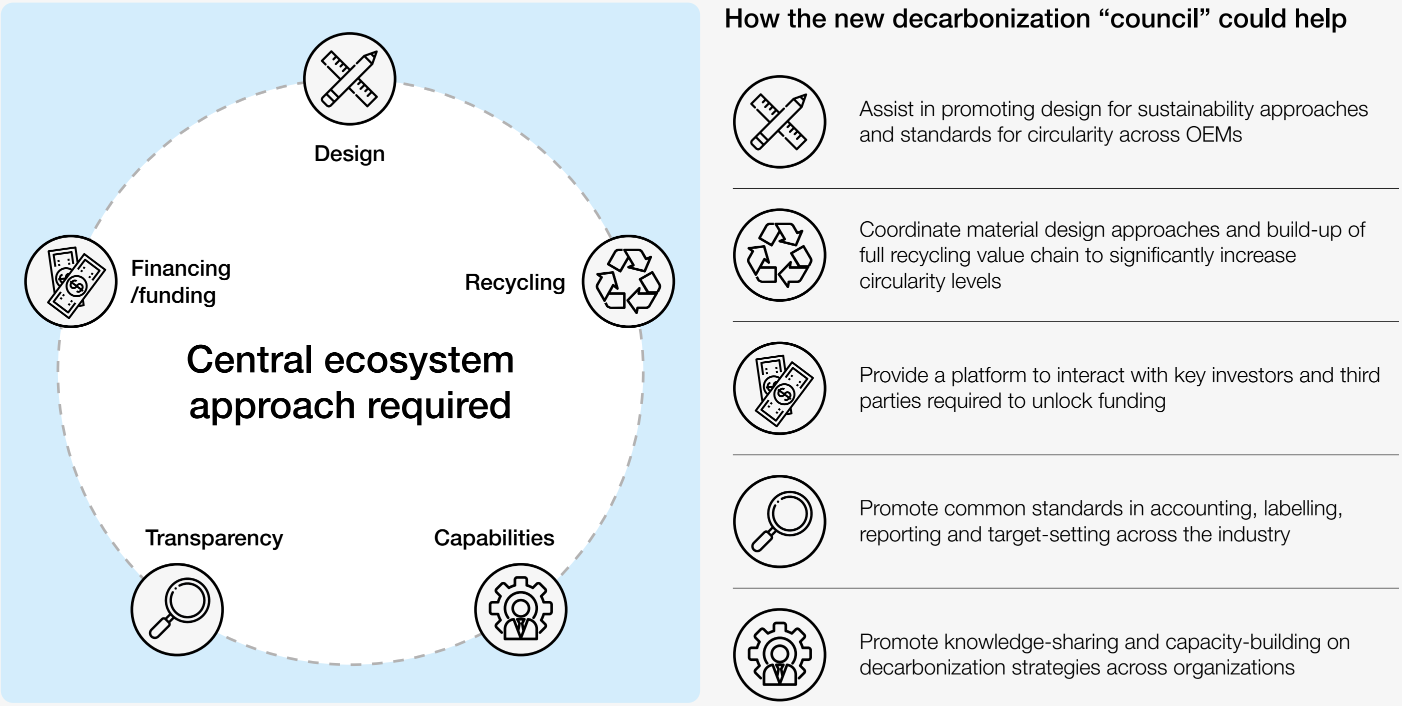
Share: Industry participants should share knowledge and collaborate when levers may be too large for one player to implement on their own or when the actions are effective only at scale. For these levers, the ecosystem must take a collective approach to decarbonization. For example, building the infrastructure for recycling end-of-life (EOL) automotive materials back into new cars or building a hydrogen supply chain with key suppliers and peers could accelerate materials decarbonization for the whole ecosystem.

Follow: OEMs and manufacturers follow where solutions are already on course for development and deployment in other industries, and their realization depends primarily on advances in other industries – e.g. pyrolysis for plastics recycling.

3.2 Collaboration on five key areas

Many materials decarbonization efforts require a new level of non-competitive collaboration between multiple industry players. Based on a series of workshops and expert discussions within the Circular Cars Initiative (CCI),[4] we recommend five areas for industry collaboration: vehicle design, recycling, financing, transparency and capability-building (Figure 14).

FIGURE 14 **Five key enablers for ecosystem materials decarbonization towards the zero-carbon car**



Source: World Economic Forum – CCI – cluster interviews and summer workshop

Vehicle design: A revised approach to vehicle design may be required for high-quality automotive components and materials to be recycled or reused at the end of a vehicle's life. Design for disassembly for easier access to materials or design for reduced complexity of material composition can facilitate reuse, remanufacturing and recycling. For batteries in particular, participants could consider paying close attention to the ease of recycling during the design phase. More standardized solutions across OEMs could also revolutionize second-life applications and allow automotive batteries to support the renewables-dependent grid of the future.

Recycling: Because automotive materials are usually of the highest grade, downcycling materials at the end of each vehicle's life should be avoided. Adjustments to existing material specifications so that a higher scrap intake is possible is a strategy that could be implemented more extensively today. More flexible alloy and materials composition could also facilitate higher recycling rates.

Stakeholders should develop better collection and sorting of process scrap and EOL material. Alliances within the automotive ecosystem can ensure that quality scrap is returned to material suppliers without contamination and available for reuse. At the same time, investments in enhanced scrap treatment facilities can make the increased volume – and diversity – of scrap manageable.

Financing: While some decarbonization efforts will pay for themselves, others may lead to increased material costs. Most of the decarbonization levers, such as hydrogen-based steelmaking, will require substantial initial financing and co-investment. Finding the appropriate financing and funding solutions will therefore be crucial. Third-party investors and public funds could play a critical role in this transition by financing large-scale capital projects or funding research into promising technologies.

Transparency: The automotive ecosystem could benefit from consistent, reliable supply chain greenhouse gas emissions transparency and data to facilitate fact-based decision-making with regard to decarbonization. Component specifications could also include carbon footprint measurements

and standardized reporting on metrics such as recycling share. More transparency for end users can also accelerate materials decarbonization since consumers tend to prefer more sustainable products and can exert both financial and political pressure for decarbonization.

Capability-building: The automotive industry places a focus on optimizing processes for quality, cost and time. Sustainability is expected to become an important part of this equation. The industry will need to develop the capabilities to strategically consider issues of sustainability – and reorient operations towards decarbonization in particular. Developing consistent decarbonization targets would be an important first step in embedding them into existing incentive systems. These targets and incentives should be combined with capacity-building programmes and knowledge exchange.

3.3 A consortium of automotive ecosystem players

“ Most of the decarbonization levers, such as hydrogen-based steelmaking, will require substantial initial financing and co-investment.

To shape the ecosystem-wide collaboration required to realize this “lead, share, follow” approach, the World Economic Forum with the members of the Circular Cars Initiative intends to establish an Automotive Circularity Board (ACB) (working title), a consortium of global players in the automotive value chain focused on achieving net-zero emissions. The ACB would not only support necessary collaboration across the automobility ecosystem, it would establish a platform for taking action on specific projects and initiatives.

The ACB would comprise relevant value-chain stakeholders and support greater alignment across the ecosystem, knowledge-sharing and the development of industry recommendations for materials decarbonization and circularity.

The work of the ACB would be focused on action areas including design, recycling, transparency, funding and governance. Examples of potential pre-competitive areas for collaboration include standards in material specifications to achieve higher recycling shares, standardized documentation for bills of materials to provide transparency with respect to GHG emissions, and building industry capacity for EOL vehicle collection and material reuse. In addition to materials decarbonization efforts, the ACB may engage on issues related to sustainable mobility, including infrastructure and fleet financing, emerging markets and municipal policy.

3.4 Possible pilots

Potential pilot projects include:

Design principles for decarbonization: One of the main hurdles for the circular use of components and materials lies in complex and disparate vehicle design. A collaboration to define the technical design principles to facilitate the circular use of components and materials can build a foundation for vehicles that are easier to disassemble or whose components are modular and can be reused. OEMs, Tier-1 suppliers and material suppliers could lead such a pilot.

Materials specifications for circularity: High-quality automotive materials are commonly downcycled at the end of life (EOL), which increases demand for energy-intensive primary materials. Defining requirements for EOL material processing and individual materials' supply chains can help to increase the circular use of automotive materials and reduce downcycling. Companies already focused on EOL material processing should be involved in this pilot.

Financing: Many decarbonization levers require substantial upfront investment and may pay off only in the long term, so optimizing finance for these projects on an industry-wide scale will be critical. The ACB should reccomend innovative finance mechanisms to spread the burden and benefits of decarbonization.

Transparency and traceability: The automotive industry's complex value chain means that neither OEMs nor customers have full and consistent visibility into the sources of the industry's emissions. Developing a comprehensive approach to traceability of material emissions for industry players and customers would greatly facilitate decarbonization for industry players and customers.

Capability-building with education and certification: Collaboration between organizations for the successful implementation of key decarbonization strategies means that standards on carbon considerations are also required. To enact these standards will require industry-wide education and some form of certification for those who have been trained in circularity principles. The ACB and other industry stakeholders should carefully consider existing certification standards and explore opportunities to collaborate with relevant certifying bodies.

Abating material emissions – and building the zero-carbon car – will require significant change in the automotive industry, but it can be accomplished and at a reasonable cost. A focus on high-emissions materials such as steel and batteries, along with extensive industry collaboration and strategic co-investment, will be critical success factors. If the industry acts now, it can build a cleaner, more efficient system for moving people and goods – and help limit the global temperature increase to 1.5°C.

Appendix

Key model assumptions

Lever assumptions: Only specific technology levers are modelled – no general assumptions such as typical yearly efficiency gains in current production technologies are modelled.

Technological baseline: The baseline for the model's analyses is industry average energy and resource consumption from current technologies and processes. Region- and company-specific adjustments can be applied with the current model.

Calculation methodology: For levers, greenfield capital expense (capex) and operating expense (opex) are considered in order to compare like with like. The marginal abatement cost is a comparison between setting up a new facility using the baseline and using new technology considering the projected lifetime for a respective new plant.

Data input: Key input data on commodity prices and emission factors originate mainly from the McKinsey Global Energy Perspective, which projects global energy consumption and prices until 2050. Many other data sources were used to model specific model components (e.g. McKinsey Hydrogen Production Cost Model, McKinsey Battery Cost Model, McKinsey Plastics Recycling Model etc.). Lever-specific data comes from McKinsey decarbonization pathway optimizer assets and internal and external expert interviews, as well as scientific reports and research.

Cost of carbon: As is customary for carbon abatement cost, the regulatory cost of carbon (e.g. European tracking service/ ETS) is not included in the calculation.

The three main categories of carbon abatement: demand reduction, circularity and materials decarbonization

The model's levers can be grouped into three main categories: demand reduction, circularity and materials decarbonization.

- **Demand reduction** focuses on levers that decrease demand for the total amount of material in the vehicle in the first place. Some examples include: reducing the total amount of material used, substituting low-carbon materials for carbon-intensive materials and reducing losses to scrap and other manufacturing processes.

- **Circularity** focuses on all levers that increase the use of recycled materials in the vehicle as well as their long-term circular usage. This includes increased remanufacturing of components, increased intake of open- or closed-loop recycling materials, and the recycling of yield loss.

- **Materials decarbonization** focuses on the emission intensity of the required materials in a vehicle. It includes better energy efficiency in existing processes (such as electrification), the use of alternative fuels or feedstock with lower emission intensity, and structural innovations and specific changes in technologies resulting in lower-carbon footprints.

These approaches to reducing a vehicle's carbon footprint should be considered sequentially. While material demand should be reduced at the beginning of development, the remaining materials should be used in as circular a way as possible. Required material volumes should be produced with technologies and fuels that allow for the most efficient processes with the lowest carbon impact.

Sensitivities of model results

Results of the abatement model and their specific outcomes for different materials and levers are sensitive to certain assumptions. The key sensitivity factors analysed are carbon taxes, ramp-up and maturation times of technologies and commodity prices. The application of sensitivity analyses for steel as an example material show the following results:

- **A carbon tax** – assuming a €100/t CO2 carbon tax by 2030 would affect traditional steelmaking the most, increasing production costs by 53% to $479/t steel. The hydrogen pathway would see only a small increase in cost (~1%) due to emissions linked to hydrogen production. The low-carbon steel pathway would not be affected due to its negative emission and CCS technology. In other words, a tax of €100/t CO2 or greater would eliminate the economic rationale for traditional steelmaking.

- **Technology ramp-up** – delay in technological ramp-up for hydrogen would result in higher hydrogen prices in 2030. Assuming a 20% higher cost of hydrogen-based technologies in 2030 through a delay in maturation of ~5 years would lead to an increase in the cost per ton of steel of $5–10 for hydrogen-based steel (from ~$450/t steel to ~$480/t steel). Nonetheless, under this scenario, the hydrogen pathway would still outcompete the low-carbon traditional steelmaking route in costs.

- **Price of commodities** – all pathways are affected by the price of key commodities:

  - **Scrap steel:** A 20% increase in scrap steel prices would affect the hydrogen pathway the most – increasing cost per ton by 8% to ~$490/t steel. This is due to the assumption that 50% of production would use scrap steel. Low-carbon and traditional steelmaking would be affected, rising 3% and $2 respectively ($540 and $320/t steel). Scrap steel prices would need to shift dramatically to affect the relative economics of each pathway.

  - **Iron ore:** A 20% increase in iron ore prices would affect traditional steelmaking the most, resulting in a 6% price increase ($333/t steel). Hydrogen and low-carbon steelmaking would see a cost increase of 2% and $3 respectively ($460 and $540/t steel). Similar to scrap steel, exposure to iron ore prices exists across the three pathways and is therefore unlikely to dramatically change the economic positioning of the three pathways.

  - **Electricity:** Increases in electricity prices will not change the choice between the current steelmaking route and the two alternative pathways. A $20 increase in electricity prices would lead to a $1–2 increase in steel prices on all routes. This perspective excludes the above-mentioned increase in hydrogen prices as they were modelled separately.

Acronyms

ACB	Automotive Circularity Board
BEV	Battery-electric vehicle
BR	Butadiene rubber
CCI	Circular Cars Initiative
CO2	Carbon dioxide
DRI	Direct reduced iron
EAF	Electric arc furnace
EOL	End of life
ETS	European tracking service
EU	European Union
GHG	Greenhouse gas
GJ	Gigajoule
H2	Hydrogen
ICEV	Internal combustion engine vehicle
kWh	Kilowatt-hour
OEM	Original equipment manufacturer
PA6	Polyamide 6/Nylon 6
PCI	Pulverized coal injection
PP	Polypropylene
PE	Polyethylene
SBR	Styrene-butadiene rubber
t	ton

Contributors

World Economic Forum

Levi Tillemann
Lead, Circular Cars Initiative, World Economic Forum

Christoph Wolff
Global Head of Mobility and Member of the Executive Committee at the World Economic Forum

McKinsey Team Leadership

Eric Hannon (key contact)

Bernd Heid

Tomas Nauclér

Daniel Pacthod

Asutosh Padhi

Anders Suneson (key contact)

Andreas Tschiesner

Yuito Yamada

McKinsey Project Team

Oliver Arndt

Stefan Nekovar

Luc Oster-Pecqueur

Lukas Torscht

Fehmi Yüksel (key contact)

McKinsey Expert Team (selection)

Daniel Cramer

Michel Foucart

Toralf Hagenbruch

Marcin Hajlasz

Anna Orthofer

Patrick Schaufuss

Steven Vercammen

Christof Witte

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EN+ GROUP IPJSC

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WWF International

ZF Friedrichshafen

Endnotes

1. OEMs, tier-1 suppliers, material suppliers, recycling companies, NGOs, consultancies and others.
2. James Eddy, Alexander Pfeiffer and Jasper van de Staaij, "Recharging Economies: The EV-Battery Manufacturing Outlook for Europe", McKinsey and Co., June 2019: https://www.mckinsey.com/industries/oil-and-gas/our-insights/recharging-economies-the-ev-battery-manufacturing-outlook-for-europe (link as of 17/11/20).
3. Among the different battery technologies, an NMC-based (nickel-manganese-cobalt) chemistry and pouch cell type is depicted. The baseline process considers active material and cell production processes in regions with a coal-intensive electricity mix.
4. Over the course of 2020, as part of the CCI, McKinsey has conducted more than 60 industry and expert interviews. The CCI has conducted a series of workshops with more than 80 industry representatives.

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org