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RESEARCH AND ANALYSIS

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Circular economy framework for automobiles

Closing energy and material loops

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Abstract

Corporations, including automotive manufacturers, are increasingly exploring extended circular economy strategies as a means to enhance the sustainability of their products. The circular economy paradigm focuses on reducing nonrenewable materials and energy, promoting renewable feedstocks and energy, and keeping products/materials in use across the life cycle of a system. As such, life cycle environmental burdens associated with vehicle manufacturing, use, and disposal could potentially be reduced through circular economy strategies; however, no such comprehensive circular economy framework currently exists for the automotive industry. We develop the first circular economy schematic of automobiles, derived from the Ellen MacArthur Foundation's framework. Further, we characterize the current automotive circular economy using metrics of renewable energy and recycled materials. Specifically, for current U.S. average sedans, we find that internal combustion engine vehicles (ICEVs) use ~6% renewable life cycle primary energy and 27% recycled materials; for battery electric vehicles (BEVs), these measures are ~8% and 21%, respectively. On a vehicle-miles-traveled basis, BEVs use ~47% less nonrenewable life cycle primary energy than ICEVs, highlighting the importance of electrification as a strategy for automotive manufacturers to reduce environmental burdens. Our proposed circular economy framework is then applied to Ford Motor Company's sustainability programs and initiatives as an example. This schematic aims to provide a starting point for the automotive industry to operationalize circular economy strategies, the application of which could advance its overall sustainability performance.

KEYWORDS
automobiles, circular economy, energy, industrial ecology, materials, sustainability

1 | INTRODUCTION

With the projected growth of transportation in the coming decades, it is imperative to develop robust strategies that reduce material and energy-resource requirements across the entire mobility ecosystem (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013). Future transportation demand should be met by a portfolio of alternatives—including personal vehicles, public transit, ridesharing, and telework—and as such, it is important to identify what roles each of these modes could play in contributing to a sustainable mobility system (Keoleian, Kar, & Manion, 1997).

Light-duty vehicles dominate the current share of automotive fleets and transportation energy demand, accounting for ~15% of global energy consumption (International Energy Agency, 2019; Sims et al., 2014). Manufacturing vehicles is also inherently resource intensive; for example, automotive steel and aluminum, two large contributors to a vehicle's mass, are responsible for ~12% and 27% of respective global use for each material (Galevsky, Rudneva, & Aleksandrov, 2018; World Steel Assoication, 2018). The environmental burdens associated with an automobile extend both across its life cycle and also into other business sectors (Orsato & Wells, 2007).

The circular economy paradigm, which aims to close the loop on material and energy flows across the life cycle of a system and extend the useful life of a product, is increasingly being presented as a means to enhance sustainability (Blomsma & Brennan, 2017). By leveraging renewable energy and recycled materials, circular economy strategies could potentially help reduce life cycle greenhouse gas (GHG) emissions and resource consumption. The analytical foundation for the circular economy concept is embedded in cyclical (Type III) systems, first proposed by Graedel, Allenby, and Linhart (1993), wherein renewable flows are inherently circular, while nonrenewable flows (of exhaustible resources) are linear (Graedel et al., 1993). Currently, no industry-level circular economy framework exists for qualifying automotive energy and material flows. Although automotive original equipment manufacturers (OEMs) have several sustainability strategies, framing them in a broader circular economy lens can capture multiple life cycles, alternative business models, feedback loops within a system (closed-loop), and flows between systems (open-loop) (Contreras, 2015). A circular economy perspective can highlight energy and material flows in and out of a given system, both upstream and downstream. In doing so, it can help create broader and more holistic corporate sustainability strategies.

While circular economy offers a high-level perspective of energy and material flows within and between industries, quantitative methods such as life cycle assessments (LCAs) must be used in tandem as the underlying tool to measure these flows and inform decision-making (Sassanelli, Rosa, Rocca, & Terzi, 2019). Sassanelli et al. (2019) found that LCA-based methods are the most common quantitative tools used to assess circular economy performance. Although LCAs are commonly applied by OEMs, with circular economy, they can expand its use beyond quantifying environmental impacts of their products and processes, and ultimately devise robust enterprise-level sustainability paradigms.

As automotive OEMs extend their responsibility across the value-chain and broaden into the realm of mobility services, it is crucial to expand their view of sustainability from a technology (or vehicle) level to an enterprise level for capturing different product use-cases (Jittrapirom et al., 2017; Zheng, Xu, & Feng, 2017). Wells and Orsato (2005) propose an alternative business model for automotive OEMs; De los Rios and Charnley (2017) analyze Audi AG's shared ownership platform ; Saidani, Yannou, Leroy, and Cluzel (2018) investigate the EU's end-of-life vehicle directive). Although these initial studies highlight individual elements of the automotive circular economy, they do not provide a consolidated and comprehensive structure for automotive OEMs and their stakeholders.

To bridge this gap, we present the current state of the automotive industry through a circular economy lens. First, we construct a circular economy framework through individually qualifying the circularity of each of the vehicle's life cycle phases. Our schematic is derived from the Ellen MacArthur Foundation's framework, premised on reducing waste and pollution, keeping materials and products in use, and regenerating natural systems (Ellen MacArthur Foundation, 2017b). Further, we identify potential strategies that could enhance automotive value-chain sustainability. Second, we develop Sankey diagrams that quantify the extent of renewable energy and recycled materials used across the lifetime of generic U.S. internal combustion engine and battery electric sedans. These two metrics, highlighted by the Ellen MacArthur Foundation, are means for OEMs to potentially reduce GHG emissions and minimize resource depletion. While not always an accurate proxy for end-point sustainability objectives, OEMs tend to have greater control over these levers. Third, we apply our proposed framework to Ford Motor Company, thereby developing their current circular economy as an example. Our schematic could be an approachable and practical starting point for automotive OEMs and their stakeholders to operationalize a circular economy by quantifying circular material and renewable energy flows.

2 | CIRCULAR ECONOMY FRAMEWORK FOR AUTOMOBILES

Our framework for circular economy of automobiles is premised on the Ellen MacArthur Foundation's principles, and designed through a product life cycle lens (Figure 1). Specifically, vehicle life cycle stages are classified as materials and manufacturing, use, and end-of-life. Specific material and energy flows through (and between) these life cycle stages are depicted using loops and arrows. Further, essential components of a circular economy, including renewable energy and biomaterial flows, alongside recycling, repurposing, and remanufacturing loops are identified. Automotive OEMs can apply this framework to their specific strategies and business operations (see the Circular Economy at Ford Motor Company section for an example).

Data for characterizing the circular economy performance across a generic automobile's life cycle was primarily taken from the 2018 GREET model and the 2019 Transportation Energy Data Book (Argonne National Laboratory, 2018; Boundy, 2019). Although these databases may not always capture regional variability in data and immediate developments in technology, they are commonly used in practice, owing to their transparency and consistency in reporting methodologies. Hence, they provide a useful starting point—one which OEMs can build upon using their own data.

For a conventional gasoline internal combustion engine vehicle (ICEV) in the United States, life cycle primary energy consumption is dominated by the use phase (~92%), with materials and manufacturing accounting for ~8%, and end-of-life having

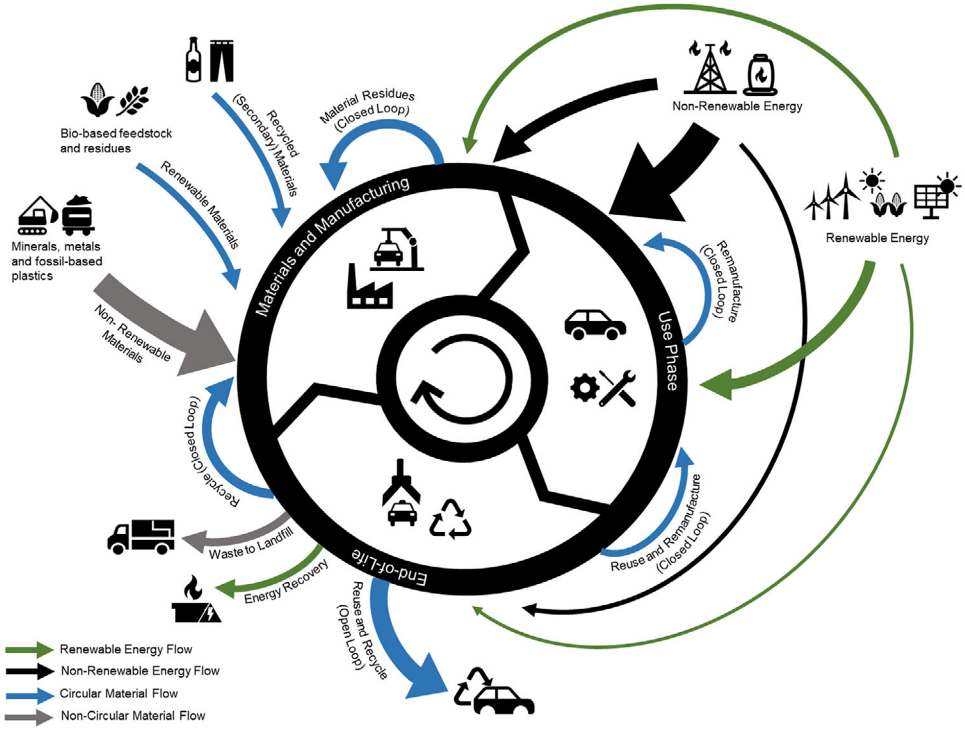

FIGURE 1 Current circular economy framework for automobiles. Arrow widths are roughly indicative of the relative magnitudes of flows, but do not represent specific values. Energy and material flows are not on a uniform scale (e.g., mass basis) and should not be conflated (please see subsequent Figures 2–4 for their quantification). Evidently, noncircular flows dominate across the vehicle life cycle. It should be noted that all materials and energy sources (including renewable energy) use some fossil energy upstream. Additionally, each processed material has differing inherent compositions of primary and nonrenewable sources

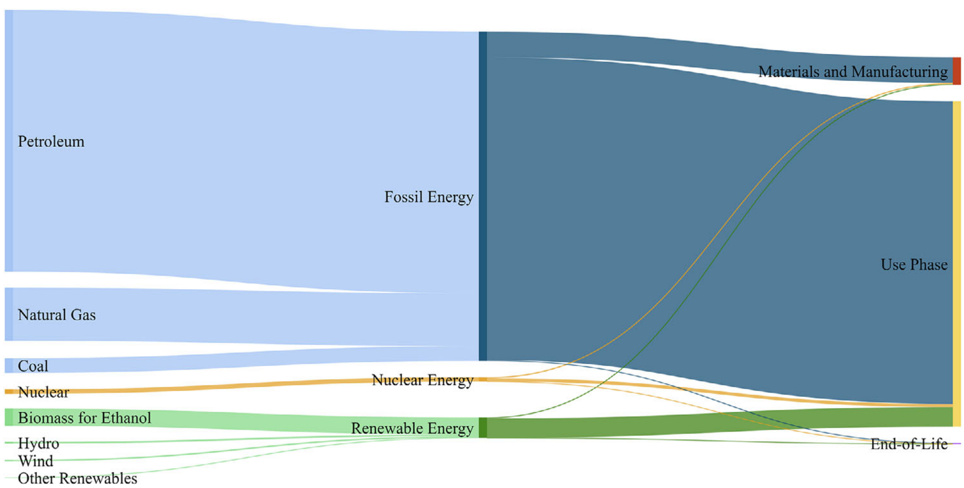

FIGURE 2 Life cycle primary energy flows for conventional U.S. ICEVs using E10 fuel. The width of flow is directly proportional to total primary life cycle energy distribution. Data are sourced from the GREET model (Argonne National Laboratory, 2018). Unlike fossil and nuclear sources (shown in blue and orange respectively), renewable energy sources (shown in green) inherently enhance automotive circularity. Underlying data used to create this figure can be found in the Supporting Information S1 and Supporting Information S2 files

negligible impacts (Figure 2). Renewable sources account for ~6% (64 GJ/vehicle) of total vehicle and fuel cycle primary energy for ICEVs.

The distribution is less-skewed towards the use phase for a U.S. battery electric vehicle (BEV), with materials and manufacturing contributing to a greater share (~25%) of life cycle primary energy consumption, use being ~75%, and end-of-life again having a small energy footprint (Figure 3). Renewable sources account for ~8% (32 GJ/vehicle) of total vehicle and fuel cycle primary energy for BEVs charged by the U.S. average grid, although this changes with regional electric grids (driven by the use phase).

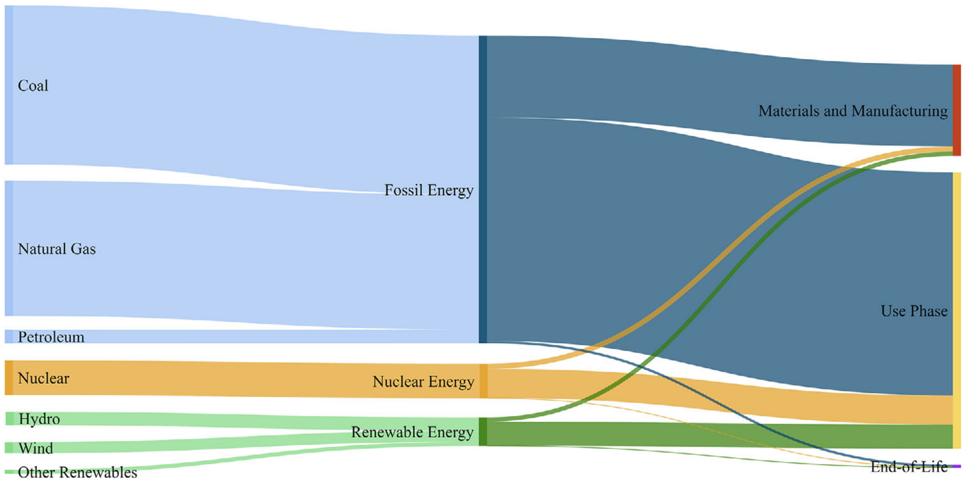

FIGURE 3 Life cycle primary energy flows for BEVs operating on 2019 U.S. average electric grid. The width of flow is directly proportional to total life cycle energy. Data are adapted from the GREET model (Argonne National Laboratory, 2018). Unlike fossil and nuclear sources (shown in blue and orange respectively), renewable energy sources (shown in green) inherently enhance automotive circularity. Underlying data used to create this figure can be found in the Supporting Information S1 and Supporting Information S2 files

2.1 | Scenario analyses

The U.S. Billion-Ton Report identified the potential of replacing 30% of 2005 petroleum consumption with biomass (Langholtz, Stokes, & Eaton, 2016). If 30% of fuels consumed by ICEVs were ethanol (vs. the current standard of 10%), their total life cycle fossil fuel consumption would drop from 93% to 81%, while primary life cycle renewable energy consumption would increase from 6% to 16%. However, the historical proliferation and efficacy of flex-fuel vehicles, designed to operate using greater shares of ethanol, has been somewhat limited.

Were current BEVs to be charged on a cleaner grid such as Washington's, the renewables share of total life cycle primary energy would be 55%; however, if powered by more fossil fuel-intensive grids like those in Florida, the renewables fraction would be under 2% (U.S. Energy Information Administration, 2012, 2020). Note that while the fraction of renewables is indicative of a grid's circularity—and is used as a lever in most statewide renewable portfolio standards—it does not necessarily correlate perfectly with relative GHG profiles, given differences in carbon intensities of underlying resources (e.g., coal vs. gas).

Finally, to gauge the energy distribution of future automobiles, we simulated U.S. average ICEVs and BEVs using 2040 GREET data (see Tables S1-1 and S1-2 in Supporting Information S1 for details). Reflecting anticipated technology improvements, ICEVs were found to have 29% lower life cycle primary energy in 2040 relative to 2019; the total fraction of renewables, however, was still relatively similar (~6%). BEVs had the added benefit of a cleaner grid-mix and were found to have 24% lower life cycle primary energy in 2040 relative to 2019, with renewables accounting for 12% (vs. 8% in the base case).

3 | CHARACTERIZING MATERIALS AND MANUFACTURING CIRCULARITY

The first stage of an automobile's life cycle—and the one where OEMs have most direct control over their products—is the materials and manufacturing phase. Decisions about material sourcing, product design, process selection, and associated logistics management have important consequences for the life cycle environmental performance of a vehicle and the overall value-chain sustainability of an OEM.

3.1 | Materials manufacturing

Materials manufacturing includes the mining/extraction, refining, transportation, and processing of substances into materials of a desired quality required for subsequent products and parts manufacturing. Despite increasing shares of plastics and aluminum, the material composition of conventional light-duty vehicles has remained relatively similar over the previous decades. Sankey diagrams in Figure 4 for conventional ICEVs and Figure S1-1 in the Supporting Information S1 for BEVs show that the steel family dominates the share of total vehicle mass (40–60%) (Keoleian & Sullivan, 2012). Almost three-quarters of steel used in an automobile is virgin (primary) steel, while recycled (secondary) steel accounts for the rest. The typical processing of virgin steel using coke in blast and basic oxygen furnaces inherently limits its sustainability; on average, nonfossil energy

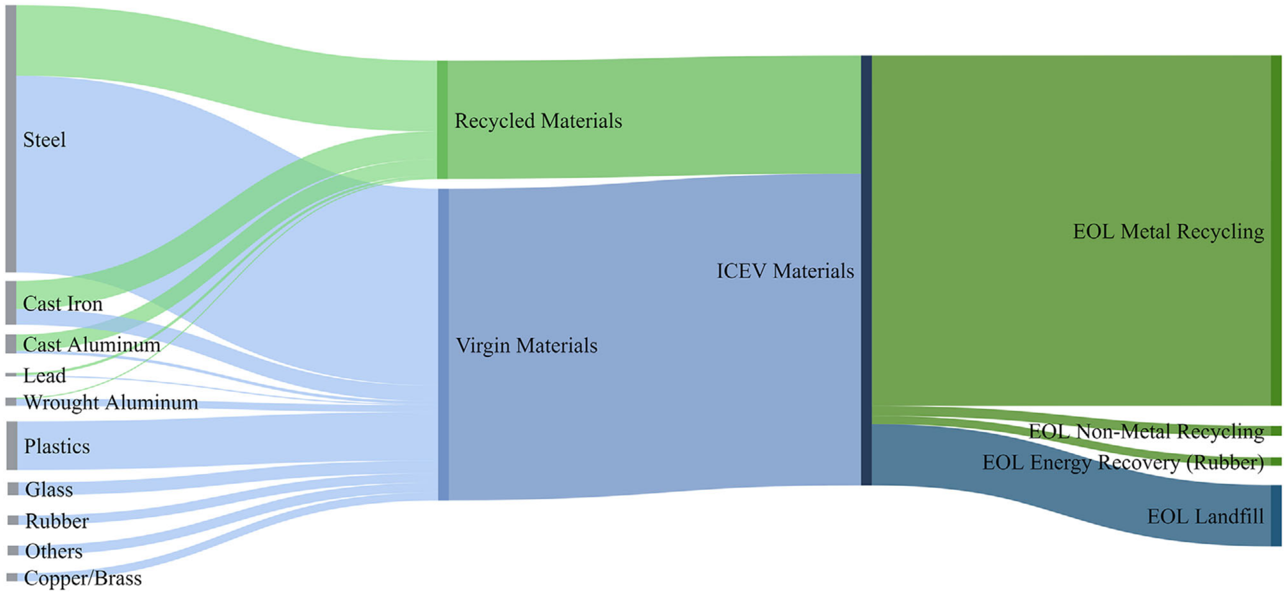

FIGURE 4 Composition of conventional U.S. ICEVs (by share of total mass, including batteries) and the end-of-life management of associated materials. Data are sourced from the GREET model (Argonne National Laboratory, 2018). Recycled materials (shown in green) inherently contribute to circularity, while virgin and non-recycled materials (shown in blue) do not. Underlying data used to create this figure can be found in the Supporting Information S1 and Supporting Information S2 files

contributes only 8% toward producing virgin steel. Recycled steel is processed in an electric arc furnace (EAF), however, and has 54% lower GHG emissions per unit mass relative to virgin steel. EAFs use both less energy and operate on a greater share of nonfossil energy (15%). Thus, using renewable electricity in the steel manufacturing process—alongside incorporating measures for increasing both energy and mass efficiency—could be levers for increasing automotive sustainability. Although steel is the most recycled material globally (by mass), a large fraction of automotive steel is open-loop recycled, i.e., used in nonautomotive applications like reinforcing bars (rebar) (Ellen MacArthur Foundation, 2017c; Walker, Coleman, Hodgson, Collins, & Brimacombe, 2018). Furthermore, despite steel being considered a fairly circular material (albeit through flows into alternate systems/applications), the production of virgin steel imposes several environmental burdens, such as slag, sludge, and dust. As such, where feasible, OEMs should work toward using a greater share of recycled (EAF) steel. Additionally, there is an opportunity for OEMs to collaborate with suppliers to enhance steel circular economy practices like by product use and switching to cleaner energy sources for production.

An important trend in automotive manufacturing is the increasing role of aluminum, often as a substitute for iron or steel. A key tradeoff needs to be evaluated regarding the high upstream impacts of primary aluminum production vs. its potential downstream (usephase) lightweighting benefits (relative to steel) (Hertwich et al., 2019; Kim, McMillan, Keoleian, & Skerlos, 2010). While aluminum weighs less than steel, thereby enabling a higher use phase fuel economy, it can be significantly more energy and GHG-intensive to manufacture than steel (Hertwich et al., 2019; Luk, Kim, De Kleine, Wallington, & MacLean, 2017). The emissions of high global-warming potential gases like perfluorocarbons incurred during aluminum smelting contribute to increased overall GHGs (Elgowainy et al., 2016). However, aluminum substitutions can also theoretically reduce vehicle weight by 11–25% (Kim et al., 2010). Hence, OEMs should analyze the environmental costs associated with aluminum in this life cycle stage while considering its usephase benefits.

GREET assumes a North American aluminum smelter powered predominantly by hydro (81%) and coal (14%), which results in an overall cradle-to-gate nonfossil energy input of ~37%. It should be noted that not all primary aluminum is created equal; regional electric grids can have a notable impact on the relative environmental footprint of the metal (McMillan & Keoleian, 2009). For example, American aluminum tends to be less carbon-intensive than that from Asia. Thus, automotive OEMs should carefully consider where in their global supply chains the aluminum is being sourced from.

On a vehicle level, two variants of aluminum are commonly used: cast and wrought. Automotive cast aluminum typically has a greater recycled content than does wrought aluminum (except for wheel rims and hubs, and cylinder heads). Cast aluminum is used for powertrain applications like transmission-housings, pistons, and engine blocks, while wrought aluminum is used for fabricating body-frames (owing to its greater tensile strength) (Filho, 2016). Both materials use ~37% nonfossil energy to produce in an average North American smelter; however, automotive wrought aluminum has far less recycled material than does automotive cast aluminum—11% vs. 85% respectively—for ensuring desirable material performance and properties. This is an important distinction—both the recycled forms emit fewer GHGs than their primary forms, since recycling aluminum avoids energy-intensive primary production processes such as bauxite refining and alumina smelting. For enhancing circularity, OEMs could work with material suppliers and end-of-life vehicle managers on closing the wrought aluminum loop for sheets and extrusions.

The third important group of automotive materials is plastics, whose share in automobile composition has been gradually increasing over the decades owing to mass and performance-related benefits. Plastic production and transformation processes are often enabled by fossil fuel feedstocks that are inherently noncircular. Another issue posed by plastics is their limited recyclability at end-of-life (Keoleian & Sullivan, 2012).

Lightweighting is also accomplished through alternative glazing, seat, and engine materials and designs (Skszek, Conklin, Wagner, & Zaluzec, 2015). Although materials like carbon fiber reinforced plastics (composites) and magnesium could play a role in automotive lightweighting in the future, similar to aluminum, their usephase benefits must be weighed against their GHG/energy-intensive production (Elgowainy et al., 2016; Kim & Wallington, 2013). Incorporating greater shares of bio-based alternatives like cellulose, kenaf, and soy could retain lightweighting benefits, displace finite resources, and promote naturally occurring, renewable feedstocks (Boland et al., 2016; Hall, 2009). It should be noted here that existing biomaterials are not completely circular, in that they require some nonrenewable/fossil-based inputs; LCAs can help compare their impacts relative to nonrenewable alternatives. The current penetration of biomaterials (by mass) in vehicles, however, remains low. Additionally, note that lightweighting benefits depend on vehicle powertrains; vehicles with efficient powertrains do not benefit as much from lightweighting as do those with less-efficient powertrains (Luk et al., 2017).

An essential facet of material selection from a circular economy lens is eliminating, substituting, or reducing the use of scarce/finite, nonrenewable, and toxic elements (Ellen MacArthur Foundation, 2013). A salient example in the automotive industry is the use of critical and rare earth elements like cobalt, neodymium, and platinum. Small quantities of critical materials are found in internal combustion engines, motors and generators, exhaust control systems (catalytic converters), batteries for electric vehicles (EVs), and other vehicle components. These materials often have significant burdens (environmental, social, and economic) associated with their extraction and processing; hence, it is crucial to reduce their consumption through increasing material-use efficiency, material substitution, or promoting end-of-life recovery for closed-loop recycling. One noteworthy metal with a relatively circular flow is lead, commonly used in automotive lead-acid batteries; secondary forms account for about three-quarters of lead use in cars.

3.2 | Product design

A common theme for achieving morecircular automobiles is creating optimal design strategies that improve a vehicle's life cycle environmental performance. Sustainability outcomes are contingent on the weight an OEM ascribes to various design objectives (such as performance and cost), since inherent tradeoffs may exist (Mayyas, Qattawi, Omar, & Shan, 2012). From a materials standpoint, some strategies for achieving these outcomes could include dematerialization, where the same level of product functionality or service is offered while using fewer materials; reduced material intensity, where parts are downgauged while maintaining vehicle durability; increased material efficiency, where a greater share of feedstocks are converted into finished products (reduced wastage); and material selection, wherein alternative materials with lower burdens are reused or recycled from a previous application. Note that while an OEM would want to use material efficiency as a lever for ultimately reducing costs, minimizing waste, and maximizing performance, they ought to also consider other undesired outcomes, such as increased energy use (e.g., additive manufacturing).

The importance of the design stage on product sustainability is evidenced by Figure 4 and Figure S1-1 in the Supporting Information S1, which show that BEVs have lower shares of recycled materials than ICEVs. As such, designing for recyclability must consider the diversity and characteristics of constituent materials, alongside the design complexity of parts.

There is also potential to increase circularity by designing vehicles for greater longevity (i.e., increased lifetime miles traveled) (Kim, Keoleian, Grande, & Bean, 2003). Designing for optimal longevity entails extending automobile lives by using more durable, adaptable, and reliable materials and parts that can be easily serviced, remanufactured, or reused (Kim et al., 2003). Note that automotive OEMs need to consider issuing warranties for reused parts. The need for product longevity becomes particularly salient with the advent of transportation-as-a-service business models, shared-use mobility platforms, and connected/automated fleets (Nyström, 2019). Specifically, manufacturing moredurable components like alternators, door hinges, and switches could enable an increased useful life for vehicles. The industry has done reasonably well by designing automobiles for end-of-life management through adopting design approaches focused on ease of disassembly, material identification, and simplification (modularity) and parts consolidation. Closed-loop recycling can be further promoted in the design phase by selecting materials of similar grades for extended parts and model years, and also such that end-of-life cross-contamination is minimized.

3.3 | Automotive manufacturing

On a process level, material flows can be expanded to include effluent and waste. Circular economy strategies include process substitution like switching to cleaner-burning fuels or lower-waste additive manufacturing techniques; energy efficiency measures like upgrading incandescents/sodium lamps/metal-halide lights to LEDs that reduce electricity overhead; using (on-site generated/procured) renewable utilities; reducing water-use through on-site treatment or recycling; controlling material flows for minimizing effluents and waste; avoiding waste diversion for treatment or landfilling through by product utilization; inventory control and material-handling practices like maximizing utilization of pallets and promoting renewable or recyclable packaging materials; and process/facilities layout planning to minimize footprint and losses (Nunes & Bennett, 2010).

3.4 | Logistics

OEMs now consider burdens from logistical channels for distribution that originate both up and downstream of their facilities. Upstream, inbound materials and/or components are delivered to vehicle assembly plants. Downstream (post-assembly), outbound (sales-ready) vehicles are sent to OEM dealerships and franchises. Despite not always having complete control of distribution management, automotive companies can work with channel partners for enhancing logistical circularity. This can be done by implementing distribution-oriented strategies such as freight fuel economy improvements, deploying alternatively fueled vehicles for reducing GHG emissions, and utilizing freight carriers and networks more efficiently (Piecyk, Browne, Whiteing, & McKinnon, 2015). The U.S. EPA's Smartway program is one example of a means for OEMs to reduce logistics-related burdens (U.S. Environmental Protection Agency, 2019).

4 | CHARACTERIZING USEPHASE CIRCULARITY

The vast majority of automobile life cycle primary energy is consumed during the use phase; ~92% for U.S. ICEVs and 75% for U.S. BEVs (Argonne National Laboratory, 2018). The use phase includes the operation of the vehicle (including upstream fuel processing/electricity production) along with the required service. Usephase circularity is heavily influenced by vehicle design, fuel type, nature of operation/business model, and powertrain selection.

4.1 | Fuel economy

Fuel economy is an important factor in determining usephase circularity. Fuel economy improvements are mainly achieved in three ways: using lightweight materials for manufacturing; aerodynamic vehicle designs; and developing more efficient powertrains. There are various global standards that ensure fleet fuel economy steadily improves, and environmental impacts consequently decrease. Although designing a vehicle for longevity can avoid environmental burdens associated with materials manufacturing, product and parts manufacturing, and distribution, it may delay the adoption of more efficient vehicles (Kim et al., 2003). Thus, it is important to consider the tradeoff between longer vehicle use and fuel economy improvements/powertrain advancements in newer models (Kim et al., 2003). There is an optimal point of vehicle replacement wherein the environmental (fuel economy) benefits from switching to a newer variant outweigh the impacts from producing a new car (Kim et al., 2003).

4.2 | Fuel type and powertrain

Environmental burdens from combustible fuels come from two sources: in-use consumption, and upstream extraction and processing. The vast majority (92%) of global transport energy demands are met by petroleum, with small proportions met by biofuels (2.9%) and electricity (1.4%) (U.S. Energy Information Administration, 2016). It is important that OEMs consider the total fuel cycle when evaluating use phase impacts, as it provides a more comprehensive measure of usephase sustainability performance. Most U.S. light-duty vehicles operate on E10 gasoline, which contains 10% ethanol by volume. Flex-fuel vehicles can run on blends containing up to 85% ethanol. Because of the lower total fuel cycle impacts associated with ethanol relative to gasoline, fuels containing higher shares of ethanol can decrease fossil fuel consumption. However, it should be noted that about 30% of the total feedstock and fuel cycle energy inputs for ethanol come from fossil-based sources, and also that ethanol has a lower heating value than petroleum (Argonne National Laboratory, 2018). Other alternative fuels, such as compressed natural gas and hydrogen, can also potentially decrease GHGs (Elgowainy et al., 2016).

A vehicle's powertrain and its associated fuel type significantly influence its sustainability performance. OEMs are increasingly investing in electrified powertrains. Hybrid electric vehicles and plug-in hybrid electric vehicles use a combination of an internal combustion engine and an electric motor, improving their fuel economies relative to ICEVs. Plug-in hybrid electric vehicles can run on pure electric mode for a modest distance, generally 20–50 miles. BEVs are powered solely by electric powertrains and do not produce tailpipe GHGs. The total fuel cycle is particularly important when considering BEVs. Although they do not produce any emissions from combustion of fuel, they do have associated GHG emissions from electricity generation. In most grids, however, upstream GHG emissions from electricity generation are lower than those from gasoline combustion (MacPherson, Keoleian, & Kelly, 2012). An additional benefit of EVs is that they can use an inverter to discharge electricity back to the grid during periods of high demand. By using EVs as flexible capacity, OEMs have an opportunity to work with electric utilities for increasing renewables on the grid (Rabobank, 2014). Despite this grid service, such a use-case has tradeoffs, as there are consequences to battery health and EVs represent additional load on the power system.

Although electrified vehicles have relative environmental benefits, they accounted for only 4.2% of U.S. new automobile sales in 2018 (Boundy, 2019). This is largely due to the fact that electrified vehicles, currently in a nascent deployment stage, have higher purchase prices relative to comparable ICEV models. However, it is expected that battery costs will continue declining, making EVs more affordable. Additional tailwinds for EV penetration include consumer demand and decarbonization mandates.

4.3 | Servicing

The servicing of a vehicle includes refueling, cleaning, maintenance, repair, and remanufacturing. Burdens from servicing are relatively small, with emissions from vehicle operations being about 100-times greater (Keoleian & Sullivan, 2012). Remanufacturing, a prevalent practice overseen by OEMs (e.g., Ford Core Recovery Program, GM Core Return Program) is a strategy for enhancing the automotive circular economy. Remanufacturing can prevent used parts from entering landfills and also avoid burdens from new parts that would otherwise be manufactured as replacements (Smith & Keoleian, 2004). This process can be favorable from both economic and resource-use perspectives (Smith & Keoleian, 2004). Note that remanufactured auto-parts have to be rigorously tested so that their performance and reliability is comparable to factory products. In the automotive industry, almost 80% of vehicle components can be remanufactured (typically including clutches, water pumps, engines, starters, transmissions, brake systems, and alternators) (Jody, Daniels, Duranceau, Pomykala, & Spangenberger, 2011; Keoleian et al., 1997; Ramoni & Zhang, 2013). Certain parts that do not require remanufacturing, such as bumpers, headlights, and windshield wiper motors can be reused from cars that have reached their end-of-life, provided that they are undamaged. If parts cannot be reused in any capacity, they can then be recycled (if economical).

4.4 | Shared mobility

Shared mobility encompasses several modes of transportation that do not require individual vehicle ownership, including carsharing, personal vehicle sharing, bikesharing, ridesharing, and on-demand ride-services (Machado, de Salles Hue, Berssaneti, & Quintanilha, 2018). Increased usage of shared mobility services could result in decreased life cycle environmental burdens per passenger mile traveled (Greenblatt & Shaheen, 2015; Nijland & van Meerkerk, 2017). Better utilization of vehicles that match trip activities through a sharing service can result in fuel savings. Furthermore, vehicles in shared services are used more often, so there is quicker fleet turnover, which means newer vehicles with higher fuel economies can make up a greater portion of the on-road fleet (Fagnant & Kockelman, 2014). Ridesharing means fewer vehicles will need to be produced to meet transportation demand, thus reducing the amount of automotive materials that need to be manufactured (Greenblatt & Shaheen, 2015; Nijland & van Meerkerk, 2017). By offering ridesharing and on-demand mobility services, OEMs and mobility companies can potentially increase their sustainability in the use phase relative to personal vehicle ownership. Although shared mobility platforms could result in fewer GHG emissions per passengers, some studies find that solo ride-sourcing will increase traffic and GHG emissions due to empty miles driven to pick up passengers (Anair, Martin, Pinto de Moura, & Goldman, 2020). Moreover, ride-hailing trips often replace public transit rather than personal vehicle trips, which will increase vehicle miles traveled (Anair et al., 2020). Thus, increasing occupancy rates and decreasing empty miles are important strategies for reducing ride-sourcing GHGs.

5 | CHARACTERIZING END-OF-LIFE CIRCULARITY

Despite having the lowest energy footprint for ICEVs and BEVs (~1%), the end-of-life phase has key materials-related considerations associated with it. Vehicles typically reach this phase due to deterioration or heavy damage following an accident (Jody et al., 2011). Around 10–15 million vehicles are retired from service annually in the United States (Jody et al., 2011). Being a product with a considerably large materials footprint, strategies around vehicle resource-recovery processes (remanufacture, reuse, and recycle) should be promoted by OEMs.

In the United States, around 95% of end-of-life vehicles enter the recycling infrastructure. Due to their high metallic content (~75% of light-duty vehicle weight), automobiles are amongst the most recycled products today (Jody et al., 2011). For example, automotive lead-acid batteries have recycling rates of ~95% in some countries. About 80% of lead needed for their production comes from secondary sources (Garche, Moseley, & Karden, 2015).

Even if the non-recycled fraction is small, its environmental impact should not be overlooked. The recovery of nonmetallic components such as plastics, rubber, and textiles represents an opportunity for improving circularity performance.

5.1 | End-of-life management processes

At its end-of-life, a vehicle arrives to authorized treatment facilities for dismantling (Sakai et al., 2014; Vermeulen, Van Caneghem, Block, Baeyens, & Vandecasteele, 2011). First, batteries, fluids, lubricants, brake fluids, and other hazardous substances are collected and generally recycled/reused. Then, recyclables and valuable materials for secondary use are collected (depending on the age of the vehicle when disposed), with special attention on components with high market value or containing valuable materials. Post-dismantling, residual vehicle hulks are shredded. Subsequently, ferrous and nonferrous metals, including copper and aluminum, are separated by a series of mechanical and magnetic separation processes. The by product of this process is called automotive shredder residue, which consists of light (nonmetallic) and heavy (nonferrous metallic) fractions. The light fraction is composed of plastics, rubber, foam, residual metal pieces, paper, fabric, glass, sand, and other low-density materials, usually sent to landfills.

5.2 | Current end-of-life circularity strategies

Resource-recovery processes are essential to close the loop and achieve morecircular automobiles. The success of these recovery strategies is dependent on both economic markets for valuable materials and vehicle design-aspects like component durability and reliability, ease of disassembly and reassembly, ease of cleaning, inspection, and maintenance. The first strategy entails directly reusing auto parts with potential resale value; if they cannot be reused directly, they have to go through a remanufacture, reprocess, or upgrade before returning as usable components. Although some remanufacturing does occur at a vehicle's end-of-life, the majority of remanufacturing occurs in the use phase, with damaged parts from on-road vehicles (Kim, Raichur, & Skerlos, 2008).

Another strategy is the recycling of auto parts, which involves materials being processed out of one form and remade into a new product. For example, shredders in the United States supply 12–18 million short tons of ferrous and nonferrous scrap from end-of-life vehicles for use in the metals industry for other products (Boundy, 2019; Jody et al., 2011). The scrap industry recycles ~10 million short tons of shredded iron and steel annually, resulting in considerable energy savings (Jody et al., 2011). With the introduction of lightweight materials, including aluminum and plastics, recycling strategies would have to be further improved to achieve greater energy and cost savings. The final strategy is the recovery of waste for useful purposes such as energy generation, road surfacing, etc.

5.3 | Opportunities for enhancing end-of-life circularity

Automotive OEMs could consider additional strategies to reduce and eliminate solid waste (mainly automotive shredder residue) that currently go to landfill. At their end-of-life, there is an opportunity to manage plastics and foams through techniques like mechanical separation, energy/heat recovery (using thermochemical processes such as pyrolysis or gasification), and reprocessing the fines fraction for use as filler in asphalt, concrete, or other composites (Sakai et al., 2014; Vermeulen et al., 2011). However, financial incentives and profitable business cases need to be developed first, since market economics are currently not favorable. Creating economies of scale around end-of-life management could potentially promote sustainability.

Other recycling processes currently in practice could also be improved to ensure high quality of secondary products made from recycled materials. For example, there is an opportunity to use more sophisticated processes to separate wrought from cast aluminum in end-of-life vehicles, and in the long term, utilizing automatic alloy sorting technologies and reducing the need for magnesium removal in refining (Kelly & Apelian, 2018; Løvik, Modaresi, & Müller, 2014).

As BEV penetration increases, recycling and remanufacturing strategies for spent traction batteries should be promoted among automotive OEMs and battery manufacturers, recyclers, and remanufacturers. Degraded batteries removed from BEVs still retain ~80% of their initial capacity, indicating that the cell materials in the battery are active, albeit insufficient to power a vehicle (Ramoni & Zhang, 2013). The direct recycling of materials in lithium-ion batteries can reduce both energy consumption during material production and also global demand for extraction of materials contained in them (Dunn, Gaines, Sullivan, & Wang, 2012; Keoleian & Sullivan, 2012). However, recycling of rare earths in permanent magnets and batteries is presently not economical, with only the metallic contents recovered for their value (Keoleian & Sullivan, 2012). Most lithium ion batteries are cobalt-based, which tends to be the most rare and expensive material in them (Ramoni & Zhang, 2013). Recovery of cobalt has been identified as the main economic driver for recycling lithium ion batteries, although the technologies for its recovery are limited. Given the challenges associated with recycling BEV batteries, other strategies can be considered for their high economic value, such as remanufacturing batteries for reuse in lower performance applications (Ramoni & Zhang, 2013).

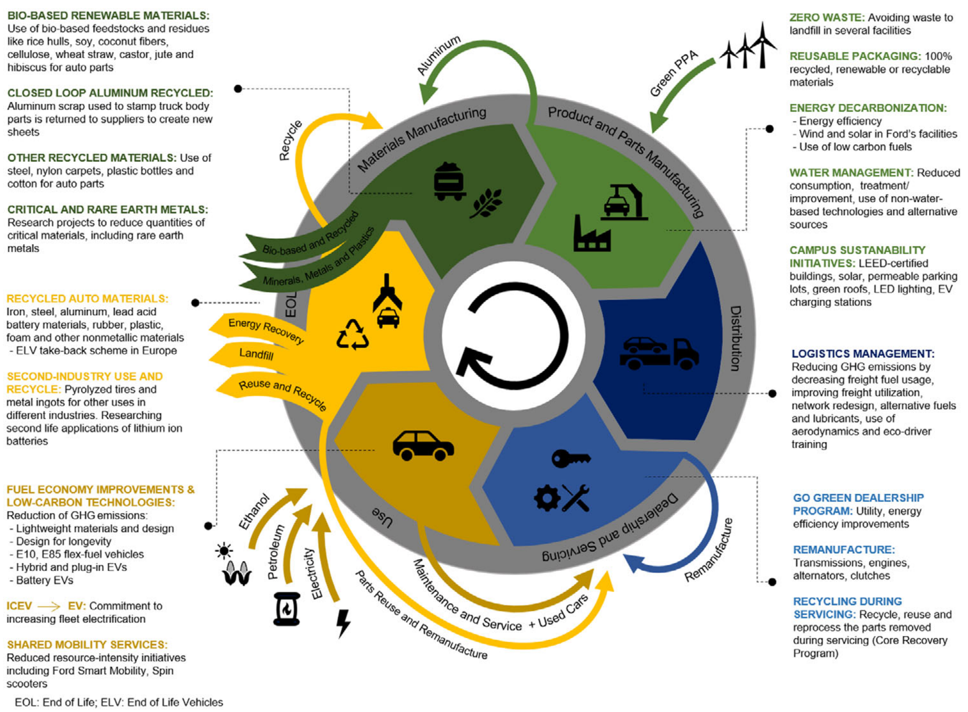

FIGURE 5 Circular Economy at Ford Motor Company. Material and energy flows are depicted by arrows, with Ford's specific sustainability initiatives displayed on either side

6 | CIRCULAR ECONOMY AT FORD MOTOR COMPANY

Figure 5 depicting the circular economy at Ford Motor Company was designed using the framework shown in Figure 1. Ford's specific initiatives and strategies are presented on either side of the diagram. Figure 5 displays six life cycle stages (rather than three) to characterize Ford's sustainability initiatives with greater granularity. Refer to the corresponding Supporting Information S2 for associated details about these initiatives. Note that Sankey diagrams could not be developed specific to Ford owing to a lack of available data regarding the magnitude of their specific energy and material flows.

7 | DISCUSSION

We develop an initial framework for qualifying the current state of the automotive circular economy and demonstrate its application with a case-study of Ford Motor Company. Renewable energy, renewable/recycled materials, and closed-loop flows form the basis of our schematic. A life cycle perspective helps characterize existing automotive circularity for OEMs to build upon. We observe that nonrenewable and fossil-based flows dominate the life cycle for current ICEVs and BEVs. From our study, three key insights about existing automotive circular economy practices and opportunities for improvement can be drawn.

First, renewable energy sources, proxies for automotive circularity, account for a relatively small proportion of current ICEV and BEV life cycle primary energy, about 6% and 8% respectively. Despite both variants using some renewable energy sources (ethanol/electricity), upstream fossil-based contributions in the total fuel cycle have a noticeable impact on sustainability performance. The increasing penetration of renewable electricity can greatly improve the overall circularity of BEVs, and partially that of ICEVs. For BEVs, these benefits are realized in all life cycle stages; for ICEVs, renewables can be leveraged primarily during manufacturing and fuel processing. Currently, ~29% of non-usephase energy for both powertrains comes from electricity, which could be procured from renewables. It should be noted here that owing to their higher fuel economies, BEVs are at an advantage relative to ICEVs on an absolute basis, using about a third of the fossil energy of ICEVs in their life cycle, considering the current U.S. average grid (Tables S1-3 and S1-4 in Supporting Information S1). Normalizing for expected vehicle-miles-traveled, BEVs use ~47% less nonrenewable life cycle primary energy than do ICEVs. While both ICEVs and BEVs stand to benefit as automobiles get more efficient over time, OEMs seeking to reduce their value-chain environmental burdens should prioritize increasing the share of EVs in the on-road fleet.

Second, despite materials circularity being low from a bio-based/renewable feedstocks basis, it is relatively higher when considering recycled materials. Current ICEVs are made using 27.5% recycled materials (primarily metals), while for BEVs this share is ~21% (Tables S1-5 and S1-6 in

Supporting Information S1). As the penetration of aluminum increases, OEMs should be wary of both where it is sourced from, and work on closing the loop for its wrought form. For petroleum-based plastics, options include recycling and substitution with bio-based feedstocks and renewable materials, while critical and rare earth elements should be either be eliminated, substituted, or recycled. LCAs can be used to choose between alternatives.

Third, our findings, used to represent an average of the current space, will differ both between OEMs and vehicle models. To gauge the degree of circularity of their respective businesses, automotive OEMs could create Sankey diagrams to understand their respective energy and material flows. Generic sources such as GREET would need to be supplemented with primary data sourced from across the value-chain. Although automotive OEMs mention several circular/sustainability initiatives in their corporate communications, insofar no manufacturer has a comprehensive, overarching paradigm for representing their circular economy strategies (Ford Motor Company, 2019; General Motors, 2019; Groupe Renault, 2019). The Ford case-study (Figure 5) is just one example of how OEMs can tailor our proposed framework (Figure 1) to their operations for enhancing circular economy performance. Creating a schematic is beneficial for framing their sustainability efforts through a broader circular economy lens, qualifying energy and material flows to focus their efforts on high-impact strategies, and communicating diverse sustainability programs with internal and external stakeholders. There may be an additional opportunity for the transportation industry to benchmark cross-sectorally, potentially analyzing apparel and consumer electronics businesses for their circular economy implementation (Ellen MacArthur Foundation, 2017a; Meloni, Souchet, & Sturges, 2018).

Note that the benefits of circular economy strategies may not always be realized in practice. There are quality, safety, and cost constraints that limit the viability of recycling/reusing materials in perpetuity (Korhonen, Honkasalo, & Seppälä, 2018). Further, Zink and Geyer (2017) found that circular economy strategies such as repairing, remanufacturing, and recycling may not necessarily replace primary production under prevailing economic and policy conditions. Thus, for circular economy to produce an environmental benefit, it is important that mechanisms exist for secondary products to effectively displace primary products (Zink & Geyer, 2017).

Attaining circularity, however, is also contingent on avoiding unintended consequences like increased vehicle miles traveled from rebound effects of convenient mobility services. As such, the applicability of circular economy strategies should be evaluated using LCA tools on a case-by-case basis. Future work should take a more focused approach to determine which circular economy strategies yield the greatest reductions in GHG emissions and resource depletion. Further analysis on material efficiency, reusing and recycling parts, vehicle design, shared mobility, and low-carbon technologies are critical for developing targeted circular economy strategies. Moreover, studies should also consider the time-rates of attaining circularity; the consequences of more circular automobiles on system-wide decarbonization; and the impacts of disruptive technologies such as self-driving and flying cars (Gawron, Keoleian, De Kleine, Wallington, & Kim, 2018; Kasliwal et al., 2019). Only by considering the full range of possibilities can the automotive industry move toward a more sustainable and circular future.

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CONFLICT OF INTEREST

Hyung Chul Kim works for Ford Motor Company and acknowledges conflict of interest for section 6.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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