SUPPORTING INFORMATION FOR:

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Summary

This supporting information provides the energy and material data from the GREET model, which are used in the Sankey Diagrams and the 2040 scenario analyses for conventional U.S. ICEVs and BEVs. The life cycle primary energy data is depicted by source and stage for both powertrains. The material data show the mass distribution of virgin and recycled materials used in conventional U.S. ICEV and BEV sedans. Additionally, the document includes a figure showing the material composition of U.S. BEVs and the end-of-life management of associated materials. Finally, it presents details of Ford's circular economy strategies. The underlying data for figures 2-4 in the main article and supporting information are also included in this file.

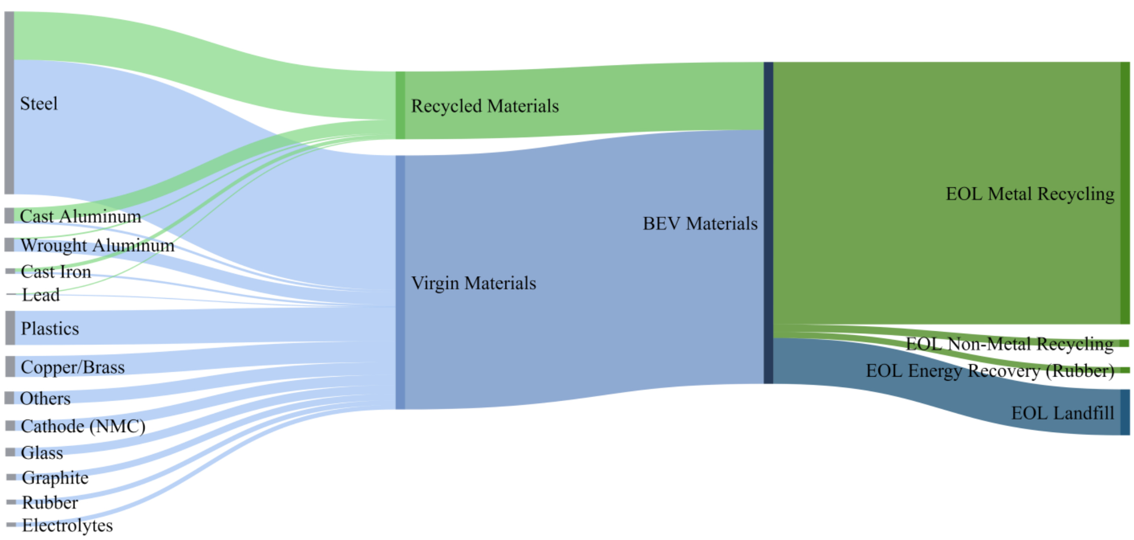

Figure S1-1. Composition of U.S. BEVs (by share of total mass, including batteries) and the end-of-life management of associated materials. Data are sourced from the GREET model (Argonne National Laboratory, 2018). Recycled materials (shown in green) inherently contribute to circularity, while virgin and non-recycled materials (shown in blue) do not.

Table S1-1. 2040 simulation: Life cycle primary energy (in MJ) by source and stage for conventional U.S. ICEVs (Argonne National Laboratory, 2018). Shares of total life cycle primary energy are denoted in parentheses. Note that the use phase also includes energy requirements for fuel processing; vehicle operations alone account for ~70% of total life cycle primary energy.

	MM (MJ)	**Use (MJ)**	**EOL (MJ)**	**Total (MJ)**
Fossil	76,682	643,607	2,273	722,563
	(9.86%)	(82.77%)	(0.29%)	(92.92%)
Renewable	4,432	43,224	428	48,084
	(0.57%)	(5.56%)	(0.06%)	(6.18%)
Nuclear	2,594	4,134	251	6,979
	(0.33%)	(0.53%)	(0.03%)	(0.90%)
Total	83,708	690,965	2,952	777,626
	(10.76%)	(88.86%)	(0.38%)	(100.00%)

Table S1-2. 2040 Simulation: Life cycle primary energy (in MJ) by source and stage for U.S. BEVs (Argonne National Laboratory, 2018). Shares of total life cycle primary energy are denoted in parentheses. Note that the use phase also includes energy requirements for electricity production; vehicle operations alone account for ~36% of total life cycle primary energy.

	MM (MJ)	Use (MJ)	EOL (MJ)	Total (MJ)
Fossil	87,957 (27.73%)	165,671 (52.22%)	2,273 (0.72%)	255,901 (80.66%)
Renewable	7,074 (2.23%)	31,191 (9.83%)	428 (0.13%)	38,694 (12.20%)
Nuclear	4,142 (1.31%)	18,260 (5.76%)	251 (0.08%)	22,652 (7.14%)
Total	99,173 (31.26%)	215,123 (67.81%)	2,952 (0.93%)	317,248 (100.00%)

Table S1-3 (Data from Figure 2 in manuscript). Life cycle primary energy (in MJ) by source and stage for conventional U.S. ICEVs (Argonne National Laboratory, 2018). Shares of total life cycle primary energy are denoted in parentheses. Note that the use phase also includes energy requirements for fuel processing; vehicle operations alone account for ~72% of total life cycle primary energy.

	MM (MJ)	Use (MJ)	EOL (MJ)	Total (MJ)
Fossil	79,562 (7.25%)	937,563 (85.46%)	2,646 (0.24%)	1,019,772 (92.96%)
Renewable	3,003 (0.27%)	60,374 (5.50%)	284 (0.03%)	63,661 (5.80%)
Nuclear	3,646 (0.33%)	9,635 (0.88%)	345 (0.03%)	13,626 (1.24%)
Total	86,211 (7.86%)	1,007,573 (91.84%)	3,274 (0.30%)	1,097,058 (100.00%)

Table S1-4 (Data from Figure 3 in manuscript). Life cycle primary energy (in MJ) by source and stage for U.S. BEVs (Argonne National Laboratory, 2018). Shares of total life cycle primary energy are denoted in parentheses. Note that the use phase also includes energy requirements for electricity production; vehicle operations alone account for ~36% of total life cycle primary energy.

	MM (MJ)	Use (MJ)	EOL (MJ)	Total (MJ)
Fossil	92,053 (22.10%)	250,971 (60.25%)	2,646 (0.64%)	345,670 (82.98%)
Renewable	4,839 (1.16%)	26,900 (6.46%)	284 (0.07%)	32,023 (7.96%)
Nuclear	5,875 (1.41%)	32,660 (7.84%)	345 (0.08%)	38,880 (9.33%)
Total	102,767 (24.67%)	310,532 (74.54%)	3,274 (0.79%)	416,573 (100.00%)

Table S1-5 (Data from Figure 4 in manuscript). Mass distribution of virgin and recycled materials used in conventional U.S. ICEV sedans (Argonne National Laboratory, 2018). Shares of total vehicle mass are denoted in parentheses.

	Virgin Material (kg)	Recycled Material (kg)	Total (kg)
Steel	642 (45.79%)	230 (16.43%)	872 (62.22%)
Cast Iron	51 (3.67%)	91 (6.50%)	143 (10.17%)
Cast Aluminum	9 (0.66%)	53 (3.75%)	62 (4.41%)
Lead	3 (0.22%)	8 (0.59%)	11 (0.80%)
Wrought Aluminum	23 (1.67%)	3 (0.21%)	26 (1.86%)
Plastics	158 (11.28%)	-	158 (11.28%)
Glass	42 (2.97%)	-	42 (2.97%)
Rubber	30 (2.16%)	-	30 (2.16%)
Others	32 (2.26%)	-	32 (2.26%)
Copper/Brass	26 (1.86%)	-	26 (1.86%)
Total	1,017 (72.53%)	385 (27.47%)	1,402 (100.00%)

Table S1-6 (Data from Figure S1-1 in Supporting Information S1). Mass distribution of virgin and recycled material used in U.S. BEV sedans (Argonne National Laboratory, 2018). Shares of total vehicle mass are denoted in parentheses.

	Virgin Material (kg)	Recycled Material (kg)	Total (kg)
Steel	620 (41.80%)	222 (14.99%)	842 (56.79%)
Cast Aluminum	11 (0.73%)	62 (4.16%)	73 (4.89%)
Wrought Aluminum	57 (3.84%)	7 (0.47%)	64 (4.32%)
Cast Iron	9 (0.62%)	16 (1.10%)	26 (1.73%)
Lead	2 (0.13%)	5 (0.34%)	7 (0.47%)
Plastics	157 (10.60%)	-	157 (10.60%)
Copper/Brass	97 (6.51%)	-	97 (6.51%)
Others	59 (3.97%)	-	59 (3.97%)
Cathode (NMC)	47 (3.20%)	-	47 (3.20%)
Glass	40 (2.67%)	-	40 (2.67%)
Graphite	30 (2.00%)	-	30 (2.00%)
Rubber	22 (1.50%)	-	22 (1.50%)
Electrolytes	20 (1.35%)	-	20 (1.35%)
Total	1,170 (78.93%)	312 (21.07%)	1,482 (100.00%)

CIRCULAR ECONOMY AT FORD MOTOR COMPANY

Materials Manufacturing

Ford has numerous strategies aimed at reducing material consumption and environmental impacts associated with procuring materials. Ford integrates plant-based and renewable feedstocks in production vehicles, which are obtained from farming byproducts and residues, and consequently reduces their dependence on petroleum (Ford Motor Company, 2019c). Examples of materials being explored for various car parts include castor, soy, rice hulls, coconut fibers, cellulose, wheat straw and hibiscus (Ford Motor Company, 2019c).

At some factories, Ford conducts closed-loop aluminum recycling, wherein aluminum scraps used to stamp truck body parts are returned to suppliers to create new sheets that go into the body frames of four lines of North American Ford trucks. Ford was the first automotive original equipment manufacturer (OEM) to mass-produce a vehicle with aluminum alloy body (Ford Motor Company, 2019a).

Beyond aluminum, Ford incorporates several other recycled materials in their vehicles. Steel is returned to Ford's stamping plants as part of Ford's Core Recovery Program, where dealers send back select damaged or worn steel parts to be recycled (Ford Motor Company, 2018b). Ford also uses recycled materials from nylon carpets, plastic bottles, and cotton. Further, Ford is engaged in reducing the quantities of critical materials (including rare earth metals) and is developing research projects to accomplish that objective (Ford Motor Company, 2019c).

Product and Parts Manufacturing

Ford leverages their extended operational control during the Products and Parts Manufacturing phase by deploying a broad base of circular economy practices, pertinent to material, energy, waste, and water flows. On a per-vehicle basis, Ford has achieved a 61% reduction in waste-to- landfill between 2013 and 2017 (Ford Motor Company, 2018b). Ford currently has 88 zero waste-to-landfill sites facilities (Ford Motor Company, 2019c). For attaining zero waste to landfill status, Ford requires that no manufacturing waste from a facility gets landfilled (Ford Motor Company, 2019c). To achieve this goal, Ford implements numerous waste-reduction initiatives including investment in new technologies and programs, such as standardizing waste tracking and sorting, identifying major sources of waste at each facility, and working with suppliers to increase sustainable packaging (Ford Motor Company, 2019c). Through Ford's recycling program, they avoid the landfilling of 3 million lbs. of grinding swarf (metallic particles, abrasives and oils) each year (Ford Motor Company, 2018b).

Packaging is a key part of the automotive supply chain. Ford's packaging guidelines require supplier-provided packaging to have a neutral or positive environmental footprint, achieved through zero waste to landfill and the use of 100% recycled, renewable, or recyclable materials (Ford Motor Company, 2019c). Note that 'neutral' corresponds to zero waste, while 'positive' corresponds to waste avoided via recycling. Using standardized containers makes packaging more transferable between suppliers and across programs (Ford Motor Company, 2019c). In many locations, Ford has contracts with packaging providers to collect and store the packaging for their suppliers (Ford Motor Company, 2019c).

Ford reduced facility energy consumption (on a per vehicle basis) by 6.8% between 2014 and 2017 (Ford Motor Company, 2018b). The company is also working on expanding their use of renewable energy. For instance, Ford installed 5.9 MW of wind turbines and 1.2 MW of solar photovoltaics in two of their European facilities (Ford Motor Company, 2019b). In 2019, Ford announced the procurement of 500,000 MW of Michigan wind power (Ford Motor Company, 2019c). Finally, Ford is also working on switching to less carbon-intensive fuels in some of their facilities.

Water is critical to any OEMs' business, including Ford's; parts of their operations, such as paint shops, are particularly water-intensive (Ford Motor Company, 2018b). Their long-term water strategy lays emphasis on region-specific solutions, focusing on reducing freshwater use through a combination of lower consumption, on-site treatment, utilization of non-water-based technologies (i.e. minimum quantity lubrication, dry-booth, alternative cooling), and tapping into alternative sources of water, such as effluent from other companies (Ford Motor Company, 2019c). Ford targets reducing water use per vehicle produced by 30% from 2015 to 2020 (Ford Motor Company, 2019c).

Ford also has strategies to reduce the impact from their buildings. Ford currently operates 26 LEED-certified buildings around the world (Ford Motor Company, 2019c). Features of these buildings include renewable energy, green roofs, permeable parking lots, on-site electric vehicle charging and LED light fixtures (Ford Motor Company, 2018b).

Distribution

As part of their corporate policies, the company deploys specific logistics management strategies to reduce environmental impacts from the distribution phase (Ford Motor Company, 2019b). Freight fuel usage is decreased by deploying more fuel-efficient vehicles (through aerodynamic and/or powertrain improvements), optimizing network design, and increasing utilization rates of existing routes (Ford Motor Company, 2019b). Further, where possible, Ford is exploring the use of both alternative fuels and lubricants (with lower environmental impacts) in their freight vehicles (Ford Motor Company, 2019b). Finally, the company is targeting improvements beyond those of a technical nature, specifically by offering eco-driver behavioral training programs (Ford Motor Company, 2019b).

Dealership and Servicing

Ford has two main types of sustainability initiatives at the dealership level: building efficiency and parts reuse. In Ford's Go Green Dealership Program, each participating dealership receives an assessment identifying where improvements can be made regarding lighting efficiency, HVAC systems efficiency, building envelope improvements, water consumption reduction, and applications for renewable energy (Ford Motor Company, 2019b). About half of the dealership network participates, resulting in roughly 40,000 metric tonnes CO_2e avoided annually (Ford Motor Company, 2019b).

Ford remanufactures transmissions, engines, alternators, and clutches by repairing them and using them in a different vehicle than the original one, thus extending the life of these parts. Bumpers, headlights, windshield wiper motors, and other parts that do not require remanufacturing can be removed during servicing and either reused or recycled depending on their condition (Ford Motor Company, 2019c).

Use

Through vehicle lightweighting and more efficient engine design, the fuel economy of Ford's fleet improves annually. Many Ford models also use alternative fuels as a means to reduce greenhouse gas emissions. All of Ford's gasoline vehicles can operate on E10 gasoline, while their flex-fuel vehicles can operate on E85. Additionally, Ford also produces hybrid electric vehicles (3% of 2017 U.S. production), plug-in hybrid electric vehicles battery electric vehicles (1% of 2017 U.S. production), and a BEV (0.1% of 2017 U.S. production) (Ford Motor Company, 2019b). Going forward, Ford intends to increase their offering of electrified vehicles that will further enhance the sustainability of their product portfolio. Ford has committed to spend $11 billion on electrified vehicles by 2022 (Ford Motor Company, 2019c).

By offering shared mobility services, Ford reduces the need for manufacturing more products to satisfy personal ownership. With the addition of Spin, Ford now offers an electrified scooter service that can help reduce urban traffic congestion, parking limitation, and air pollution (Ford Motor Company, 2018a).

End-of-Life

Through material selection and sharing information about the properties of the materials with dismantlers, Ford targets achieving a high degree of recyclability at the end of their vehicles' lives (Ford Motor Company, 2019c). Materials such as tires, metal ingots, and lithium ion batteries can be used in other industries in a second life. Damaged, worn, or failed auto parts (e.g. bumpers, headlamp assemblies, engines, and transmissions) are recovered and recycled because of their high value and potential to reduce environmental impacts (Ford Motor Company, 2019c). Some of the materials that are commonly recycled for creating new materials are iron, steel, aluminum, lead-acid battery materials, rubber. Plastic, foam, and some other nonmetallic materials can be diverted from landfill and used for energy recovery (Ford Motor Company, 2018b). Ford participates in the EU end of life vehicle directive where they collect vehicles at the end of their life from owners (Ford Motor Company, 2019c). Ford then performs a structured end-of-life evaluation to determine which parts are suitable for recycling or remanufacturing (Ford Motor Company, 2018b).

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