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THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

BRIEFING

FEBRUARY 2018

Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions

This briefing reviews recent research regarding greenhouse gas emissions from the manufacturing of lithium-ion batteries for electric vehicles. We analyze this research in the overall context of life-cycle emissions of electric cars as compared to conventional internal combustion vehicles in Europe. Finally, we discuss the primary drivers of battery manufacturing emissions and how these emissions could be further mitigated in the future.

INTRODUCTION

Electric vehicles have attracted widespread interest because of their ability to reduce energy consumption and emissions. Governments and manufacturers continue to make new commitments for electric vehicle sales, and the cost of manufacturing electric vehicles continues to fall, making them more competitive with internal combustion vehicles. Advances in lithium-ion battery technologies have been key to the growing success of electric vehicles, and a continued transition to electric drive will necessitate far greater battery production.

The scientific understanding of the exact environmental impacts of electric vehicles continues to evolve, and the impacts of battery production on electric vehicles' overall emissions is an especially complex topic. Recent studies have investigated the greenhouse gas emissions from battery production, finding a wide range of results and implications. Meanwhile, governments also have begun to consider this issue, and questions have even arisen regarding whether battery life-cycle impacts could be

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integrated into vehicle policy. In this briefing, we review the research literature, analyze the overall life-cycle greenhouse gas emissions impact of electric vehicles, and discuss key related trends into the future.

REVIEW OF LITERATURE AND KEY ASSUMPTIONS

Electric vehicle battery manufacturing emissions have been studied extensively. Table 1 lists several research studies analyzing the emissions related to electric vehicle battery production. These studies vary in scope and methodology, and find a range of values for electric vehicle greenhouse gas emissions attributable to battery production.

As shown in Table 1, the studies indicate that battery production is associated with 56 to 494 kilograms of carbon dioxide per kilowatt-hour of battery capacity (kg CO_2/kWh) for electric vehicles. Several of the studies also provide estimates for the equivalent amount of emissions per kilometer driven over the vehicle lifetimes. These generally find 1–2 g CO_2 per kilometer per kWh of battery capacity. We emphasize that the table simplifies the analytical findings, which in many cases have more scenarios and results than are basically summarized here. The wide range of values found in these studies indicates the degree of uncertainty in assessing life-cycle emissions and the variety of methods and materials used in manufacturing batteries.

The methodology used for a life-cycle assessment (LCA) can greatly influence its conclusions about the carbon intensity of batteries. An LCA can evaluate the environmental impacts of a system using either a bottom-up or top-down approach. A bottom-up approach incorporates the activity data for each stage of each component of a battery and aggregates these different components. In contrast, a top-down analysis first determines the total emissions from a plant and attributes these emissions to different processes. Top-down inventories tend to include more auxiliary energy uses, but they may double-count certain processes and emissions. In this context, top-down inventories typically find higher emissions, often by a factor of two or more.

The methodological and data input factors suggest that these early assessments have a high degree of uncertainty and may not accurately represent the dozens of electric vehicle battery production facilities in use around the world. Most life-cycle analyses rely on only a few primary sources for emissions inventories, indicating the need for more transparent, up-to-date inventories (see note i, Table 1). As many of these studies make clear, the largest share of carbon emissions in the battery production process comes from the electricity used in manufacturing. Therefore, using cleaner electricity in factories can significantly reduce the emissions attributable to battery manufacturing. The type of battery chemistry analyzed also makes a difference, as some chemistries have higher concentrations of energy-intensive metals. These studies also typically do not include battery recycling in their calculations, as there is significant uncertainty about how recycled materials could affect carbon footprints. Additionally, the lithium-ion battery industry is changing quickly, and larger, more efficient factories typically have lower emissions per kWh of battery produced. These developments are assessed further below.

Table 1. Studies on electric vehicle battery production emissions

Authors	Year	Battery production emissions (kg CO$_2$e/kWh)	Additional notes
Messagie[a]	2017	56	Assumes vehicle with 30 kWh battery constructed in the European Union, finding that BEVs will have lower life-cycle emissions than a comparable diesel vehicle when operated in any country in Europe.
Hao et al.[b]	2017	96-127	Uses China grid for battery manufacturing. Finds substantial differences between battery chemistries. Batteries produced in U.S. create 65% less GHGs.
Romare & Dahllöf[c]	2017	150-200	Reviews literature, concluding manufacturing energy contributes at least 50% of battery life-cycle emissions. Assumes battery manufacturing in Asia.
Wolfram & Wiedmann[d]	2017	106	Models life-cycle emissions of various powertrains in Australia. Manufacturing inventories come primarily from ecoinvent database.
Ambrose & Kendal[e]	2016	194-494	Uses top-down simulation to determine GHG emissions for electric vehicle manufacturing and use. Manufacturing process energy represents 80% of battery emissions. Assumes manufacturing grid representative of East Asia.
Dunn et al.[f]	2016	30-50	Uses bottom-up methodology, with U.S. electricity used for manufacturing.
Ellingsen, Singh, & Strømman[g]	2016	157	BEVs of all sizes are cleaner over a lifetime than conventional vehicles, although it may require up to 70,000 km to make up the manufacturing "debt."
Kim et al.[h]	2016	140	Study based on a Ford Focus BEV using real factory data. Total manufacturing of BEV creates 39% more GHGs than a comparable ICE car.
Peters et al.[i]	2016	110 (average)	Reveals significant variety in carbon intensities reported across literature based on methodology and chemistry.
Nealer, Reichmuth, & Anair[j]	2015	73	Finds that BEVs create 50% less GHGs on a per-mile basis than comparable ICEs, and manufacturing (in U.S.) is 8%-12% of life-cycle emissions.
Majeau-Bettez, Hawkins, & Strömman[k]	2011	200-250	Uses combined bottom-up and top-down approach. Different battery chemistries can have significantly different effects.

Note: GHG = greenhouse gas, BEV = battery electric vehicle, ICE = internal combustion engine

a Maarten Messagie, *Life Cycle Analysis of the Climate Impact of Electric Vehicles*, Vrije Universiteit Brussel, Transport & Environment, 2016. https://www.transportenvironment.org/publications/electric-vehicle-life-cycle-analysis-and-raw-material-availability

b Han Hao, Zhexuan Mu, Shuhua Jiang, Zongwei Liu, & Fuquan Zhao, *GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China*, Tsinghua University, 2017. http://www.mdpi.com/2071-1050/9/4/504

c Mia Romare & Lisbeth Dahllöf, *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries*, IVL Swedish Environmental Research Institute, 2017. http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf

d Paul Wolfram & Thomas Wiedmann, "Electrifying Australian transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity," Applied Energy, 2017, 206, 531-540. http://www.sciencedirect.com/science/article/pii/S0306261917312539

e Hanjiro Ambrose & Alissa Kendall, "Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility," Transportation Research Part D: Transport and Environment, 2016, 47, 182-194. http://www.sciencedirect.com/science/article/pii/S1361920915300390

f Jennifer Dunn, Linda Gaines, Jarod Kelly, & Kevin Gallagher, *Life Cycle Analysis Summary for Automotive Lithium-Ion Battery Production and Recycling*, Argonne National Laboratory, 2016. http://www.anl.gov/energy-systems/publication/life-cycle-analysis-summary-automotive-lithium-ion-battery-production-and

g Linda Ager-Wick Ellingsen, Bhawna Singh, & Anders Strømman, "The size and range effect: lifecycle greenhouse gas emissions of electric vehicles," Environmental Research Letters, 2016, 11 (5). http://iopscience.iop.org/article/10.1088/1748-9326/11/5/054010

h Hyung Chul Kim, Timothy Wallington, Renata Arsenault, Chulheung Bae, Suckwon Ahn, & Jaeran Lee, "Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis," Environmental Science & Technology, 2016, 50 (14), 7715-7722. http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00830

i Jens Peters, Manuel Baumann, Benedikt Zimmermann, Jessica Braun, & Marcel Weil, "The environmental impact of Li-Ion batteries and the role of key parameters – A review," Renewable and Sustainable Energy Reviews, 2017, 67, 491-506. http://www.sciencedirect.com/science/article/pii/S1364032116304713

j Rachael Nealer, David Reichmuth, & Don Anair, *Cleaner Cars from Cradle to Grave,* Union of Concerned Scientists, 2015. http://www.ucsusa.org/clean-vehicles/electric-vehicles/life-cycle-ev-emissions#.WWamKdNuJTY

k Guillaume Majeau-Bettez, Troy R. Hawkins, & Anders Hammer Strömman, *Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles,* Norwegian University of Science and Technology (NTNU). *http://pubs.acs.org/doi/abs/10.1021/es103607c*

LIFE-CYCLE EMISSIONS OF ELECTRIC VEHICLES

As a result of the high efficiency of electric motors and the ability to generate electricity from low-carbon sources, electric cars typically have lower emissions in the use phase compared to similar internal combustion engine vehicles.[1] As previously indicated, questions have emerged about the life-cycle greenhouse gas implications of electric vehicles, especially related to early estimates of battery production emissions. We seek to answer this question and compare the life-cycle greenhouse gas emissions of electric and conventional passenger cars in Europe.

Figure 1 shows the life-cycle greenhouse gas emissions of electric and conventional vehicles, detailing the contributions of lithium-ion battery manufacturing, vehicle manufacturing, tailpipe emissions, and upstream fuel cycle emissions. End-of-life emissions impacts are not included here due to the high uncertainty involved; however, this issue is discussed in the Future Outlook section. The figure compares an average new European passenger car,[2] the conventional internal combustion engine vehicle with the lowest CO_2 emissions available in Europe (2017 Peugeot 208 1.6 BlueHDi Active 5dr), and a battery electric vehicle (modeled on a 2017 Nissan Leaf with a 30 kWh battery enabling 107 miles of real-world range) charged using average grid electricity in different regions. Efficiency and emissions for both conventional and electric vehicles are adjusted to reflect real-world driving conditions rather than test-cycle numbers.[3] The carbon intensity of battery production in this figure uses the central estimate from Romare et al. (see note c, Table 1) of 175 kg CO_2e/kWh; this translates to approximately 35 g CO_2e/km over the lifetime of the vehicle. As indicated by the error bars, other studies have found a range of battery production emission values above and below our chosen estimate. The figure shows the results for the electric vehicle use-phase emissions from five countries representing more than three-quarters of European electric vehicle sales through mid-2017.

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[1] See Nic Lutsey, *Integrating electric vehicles within U.S. and European efficiency regulations*, (ICCT: Washington DC, 2017). http://theicct.org/integrating-EVs-vehicle-CO2-regs, and note j in Table 1.

[2] The average new car in 2015 in the EU emitted 120 g/km according to the official test procedure. See Peter Mock (Ed.), *European Vehicle Market Statistics Pocketbook 2016/17* (ICCT: Berlin, 2016). www.theicct.org/european-vehicle-market-statistics-2016-2017

[3] CO_2 emissions (g/km) for internal combustion engine vehicles adjusted upward by 40%, and electric vehicle efficiency (km/kWh) adjusted downward by 30%, relative to the NEDC test cycle. For details, see Uwe Tietge, Sonsoles Díaz, Peter Mock, John German, Anup Bandivadekar, & Norbert Ligterink, *From laboratory to road: A 2016 update* (ICCT: Berlin, 2016). http://www.theicct.org/laboratory-road-2016-update

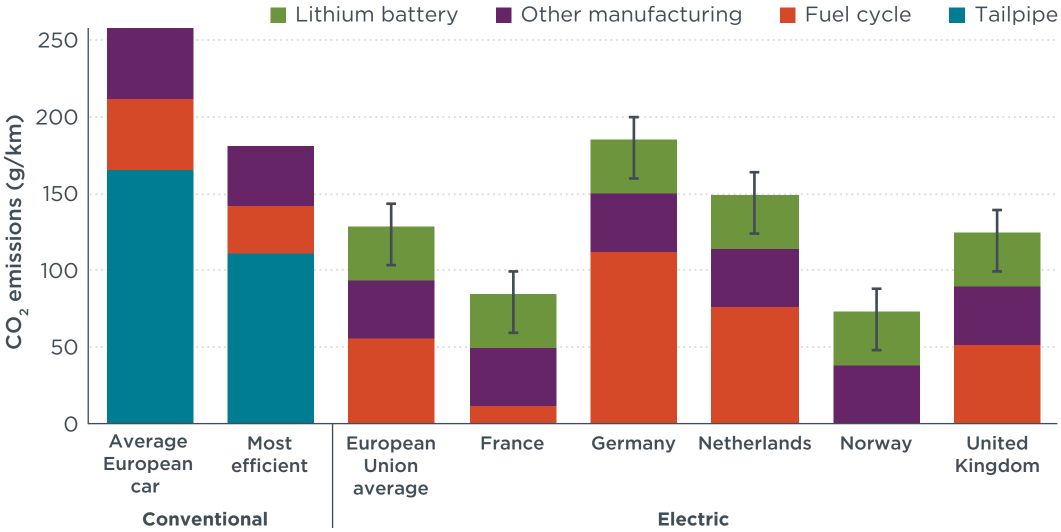

Figure 1. Life-cycle emissions (over 150,000 km) of electric and conventional vehicles in Europe in 2015.

As shown in Figure 1, the life-cycle impact of a vehicle is the sum of the emissions impacts from all the associated vehicle's activities: manufacturing, fuel cycle, and use. Electric vehicle manufacturing requires more energy and produces more emissions than manufacturing a conventional car because of the electric vehicles' batteries. Lithium-ion battery production requires extracting and refining rare earth metals, and is energy intensive because of the high heat and sterile conditions involved. Most lithium-ion batteries in electric vehicles in Europe in 2016 were produced in Japan and South Korea, where approximately 25%–40% of electricity generation is from coal. On the other hand, electric vehicles travel farther with a given amount of energy and account for fewer emissions through the fuel production and vehicle use phases.

Overall, electric vehicles typically have much lower life-cycle greenhouse gas emissions than a typical car in Europe, even when assuming relatively high battery manufacturing emissions. An average electric vehicle in Europe produces 50% less life-cycle greenhouse gases over the first 150,000 kilometers of driving, although the relative benefit varies from 28% to 72%, depending on local electricity production.[4] An electric car's higher manufacturing-phase emissions would be paid back in 2 years of driving with European average grid electricity compared to a typical vehicle. This emissions recovery period is no more than 3 years even in countries with relatively higher-carbon electricity such as in Germany. When comparing to the most efficient internal combustion engine vehicle, a typical electric car in Europe produces 29% less greenhouse gas emissions. We do not account for different driving or charging patterns in different countries; this is a rich area for future work.

We assume that the original battery will last for the lifetime of the car, 150,000 km. This is consistent with available evidence suggesting that electric vehicle battery degradation has not been a widespread problem, even among Tesla vehicles with high

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[4] Electricity grid carbon intensity reflects 2015 data from Eurostat and the European Energy Agency's 2016 report "Overview of electricity production and use in Europe," https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment

travel activity, and there is no evidence to suggest that a replacement is typical within this time frame. Other life-cycle analyses have used similar assumptions for battery lifetime based on available industry data (see notes d and g, Table 1). As seen in the figure, electric vehicles (using EU average electricity) have sufficient greenhouse gas "savings" over a lifetime relative to conventional vehicles that any hypothetical battery replacement rate would not affect our conclusions.

We also considered the life-cycle emissions of plug-in hybrid electric vehicles using this same framework. Figure 2 shows how a plug-in hybrid electric car (modeled after the Chevrolet Volt/Opel Ampera with an 18.4 kWh battery) compares to conventional and battery electric vehicles in terms of life-cycle greenhouse gas emissions in Europe. As with the battery electric vehicle, a plug-in hybrid vehicle has the potential for lower life-cycle greenhouse gas emissions than any internal combustion passenger car in Europe. These emission savings are dependent on the plug-in hybrid car using electricity for short trips, which requires being recharged regularly; in this analysis, we assume that most daily driving is powered by electricity. Some research indicates that plug-in hybrid vehicles are not always charged regularly in some markets.[5] In most regions, a battery electric vehicle has lower life-cycle emissions than a similar plug-in hybrid; the exception is Germany, where the electricity grid has a higher carbon intensity.

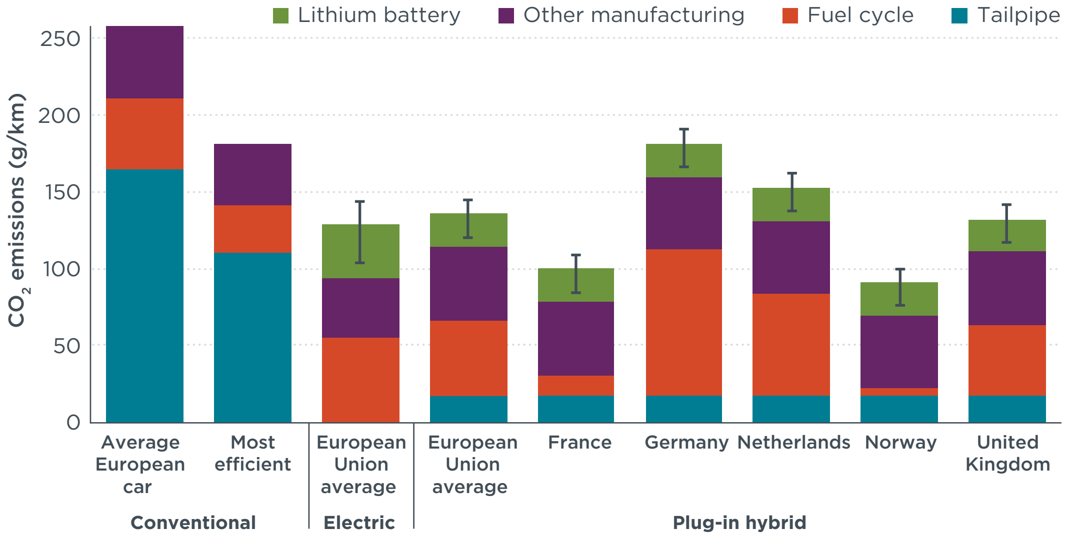

Figure 2. Comparison of life-cycle greenhouse gas emissions in conventional, electric, and plug-in hybrid vehicles in various European markets.

FUTURE OUTLOOK

This brief analysis makes it clear that although the manufacturing of batteries does not outweigh the life-cycle environmental benefits of electric vehicles, these emissions are nonetheless substantial. These emissions could become more substantial as longer-range electric vehicles with larger batteries become more common. However,

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[5] See Patrick Plötz, Simon Árpád Funke, & Patrick Jochem, "Empirical Fuel Consumption and CO_2 Emissions of Plug-In Hybrid Electric Vehicles," *Journal of Industrial Ecology*, 2017. http://onlinelibrary.wiley.com/doi/10.1111/jiec.12623/full

a number of trends point to reduced emissions from battery production in the future, further increasing the greenhouse gas savings offered by electric cars. In this section, we identify trends in this industry and briefly consider their potential for greenhouse gas reductions.

Grid decarbonization. Electricity used in the battery manufacturing process accounts for roughly half of emissions related to battery production, so increased use of renewable energy and more efficient power plants will lead to cleaner batteries. The carbon intensity of electricity is expected to drop by more than 30% by 2030 in most markets that still have relatively high fossil fuel combustion.[6] Decarbonization of electric grids around the world by an average of about 30% will result in approximately 17% lower battery manufacturing emissions by 2030. This does not account for reduced emissions in the fabrication of other vehicle materials—for example, reducing grid emissions will also lower the greenhouse gases associated with the production of metals such as aluminum.

At present, most batteries in European electric cars are produced in Japan and South Korea, where the electric grid is similar to the European average, whereas almost all batteries produced in China are used in the domestic China market. A greater share of electric vehicle batteries could come from China over time, considering the increasing battery production there for its burgeoning electric vehicle market. At the same time, several major new battery production facilities in Europe have been announced to compete with the growing battery production in Asia, and several European countries have launched a new alliance to promote battery manufacturing and research. This analysis represents a snapshot of the landscape as of late 2017, but additional analysis will be needed over time as the market and supply chain develop.

Another key factor is that automakers are pursuing direct links between clean electricity and electric vehicles. For example, Tesla's Gigafactory in the United States, which will produce 35 gigawatt-hours (GWh) of lithium-ion batteries per year, will run completely on renewable energy, most of which will be produced on-site. Of course, grid decarbonization will have a much larger impact on the use phase of electric vehicles, as the carbon intensity of electricity is directly proportional to the emissions per kilometer driven. For this reason, a cleaner grid, both where electric vehicles are produced and charged, will be the largest single driver of electric vehicle life-cycle emissions reduction in the future.

Battery second life. Automotive lithium-ion batteries provide an opportunity for reuse in stationary storage applications after their vehicle use phase. This, in turn, allows the initial battery production footprint to be spread across more use. When batteries are removed from electric vehicles after their first life, they are likely to retain significant capacity, typically 75%–80% of their original capacity. They could, therefore, play an important role in supporting the electric grid, especially as intermittent renewables become more widespread. A report from the National Renewable Energy Laboratory identifies utility-scale peak-shaving as the most promising opportunity for second-life batteries. This market has favorable duty cycles and will likely be large enough to absorb the supply of used batteries for the foreseeable future.[7] A case study outlined

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[6] International Energy Agency, *World Energy Outlook 2015,* (OECD: Paris, 2015).

[7] Jeremy Neubauer, Kandler Smith, Eric Wood, & Ahmed Pesaran. *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries,* (NREL: Boulder, CO, 2015). http://www.nrel.gov/docs/fy15osti/63332.pdf

in this report depicts the second life to be 10 years, using a cycle depth of discharge of 60% of the battery's original capacity. Widespread use of batteries in this application would increase the lifetime use of the battery by 72%, and therefore reduce the battery greenhouse gas emissions attributable to the vehicle on a per-kilometer basis by 42%. Naturally, there is great uncertainty regarding battery second life performance capabilities and business cases; however, a number of utilities and governments are already piloting such programs both for economic and environmental reasons.

Battery recycling. As the electric vehicle industry grows, battery recycling also will become more feasible. Materials production is responsible for approximately half of the greenhouse gas emissions from battery production, and recycled materials typically have a lower carbon footprint than the same materials from virgin sources. For example, production of recycled aluminum creates approximately 95% less greenhouse gas emissions compared to producing aluminum from natural sources. Although one large facility is operated by Umicore in Belgium and others are planned, recycling of lithium-ion batteries is currently relatively undeveloped because of the low number of batteries exiting vehicular use. The recycling process also can be complicated by the structure of the large battery packs. The report from IVL (see note c, Table 1) lists several potential battery recycling pathways that could be implemented in the near future and identifies potential net savings of 1–2.5 kg CO_2 per kg of battery recycled. This would translate to a 7%–17% net reduction in battery life-cycle emissions, or a 4%–10% reduction in battery emissions on a per kilometer basis after accounting for second-use applications. However, as some recycling processes use substantially more energy, the process and location of recycling will affect the total savings in emissions.

Currently, electric vehicle batteries use a variety of structures and cathode materials, making large-scale recycling programs complex. Table 2 lists the breakdown by mass of battery cells in the Chevrolet Bolt (or Opel Ampera-e), which uses the increasingly common nickel-manganese-cobalt (NMC) chemistry. The approximate costs per ton of these materials are also listed. Battery packs typically contain substantial amounts of steel, aluminum, copper, and polymers in addition to these components in the cells. Rare metals in anodes, such as cobalt and nickel, currently present the greatest economic incentive for recycling. However, recycling of aluminum and copper in the battery support structure and management system could significantly reduce greenhouse gas emissions without requiring cells to be opened. Further standardization of battery chemistry, structure, and production, and the creation of regulations on labeling and monitoring batteries, could bolster the commercial viability of recycling as the electric vehicle industry grows.

Table 2. Materials in battery cells of a Chevrolet Bolt and their approximate cost per ton

Material	Percent of battery cell mass	Cost per ton
Aluminum	16%	$1,600
Graphite	14%	$10,000
Steel	13%	$600
Iron	9%	$74
Copper	8%	$6,348
Cobalt	6%	$27,000
Nickel	6%	$10,000
Manganese	5%	$1,700
Polyester	3%	N/A
Lithium	2%	$15,000
Other	18%	N/A

Note: Based on "UBS Evidence Lab Electric Car Teardown – Disruption Ahead?" www.advantagelithium.com/_resources/pdf/UBS-Article.pdf*; Jeff Desjardins, "The Critical Ingredients Needed to Fuel the Battery Boom,"* http://www.visualcapitalist.com/critical-ingredients-fuel-battery-boom*; and "Focus Economics, Base Metals Price Outlook,"* http://www.focus-economics.com/commodities/base-metals

Lithium-ion batteries pose some challenges for large-scale recycling, but they also present substantial opportunity. Recycling is relatively well-developed for components of conventional vehicles. For example, about 99% of lead acid batteries are recycled from vehicles in the United States and other countries, while more than 80% of tires are recycled.[8] Robust recycling industries are already developed for many of the materials in lithium-ion batteries, such as aluminum and copper. Even partial recycling, such as disassembly of packs, may allow recycling of some materials at very low cost, reducing the carbon footprint of manufacturing and supply chain stresses. The European Union has mandated that half of the mass of electric vehicle batteries be recycled, although they have not specified which components are to be recycled.

Battery technology improvements. Lithium-ion batteries and manufacturing techniques continue to improve as the electric vehicle and stationary storage industries grow. Battery energy density, or the energy storage per kilogram of battery, continues to steadily increase at an average rate of approximately 5%–8% per year. Although this does not represent an equivalent reduction in materials or energy, one estimate shows that a 50% increase in battery energy density, which is achievable in 5 to 9 years with this estimated rate of improvement, would lead to a 10%–15% reduction in cumulative energy density (see note i, Table 1). Additionally, other battery characteristics also are expected to improve, with associated environmental benefits. Longer battery lifetimes will allow for longer vehicle lifetimes and fewer replacements, as well as longer or more demanding second lives in stationary applications. Higher charging and discharging efficiencies will lead to lower energy consumption during the use phase of the vehicle battery.

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[8] Linda Gaines, "The future of automotive lithium-ion battery recycling: Charging a sustainable course," *Sustainable Materials and Technologies,* 2014, 1–2, 2-7. http://www.sciencedirect.com/science/article/pii/S2214993714000037

Battery chemistries vary in their carbon intensities, and many automakers currently use energy-intensive chemistries such as lithium nickel cobalt aluminum oxide or lithium-ion phosphate. With battery innovation and scale, less of these materials will be used and they will come from more efficient manufacturing practices; less carbon-intensive chemistries with less cobalt and other rare metals are also becoming more cost-competitive. Eventually, batteries may use sulfur or even air rather than current metal cathodes, which are composed of rare and energy-intensive materials such as cobalt, nickel, and manganese. While these designs could offer significant greenhouse gas savings, these technologies are still years from commercialization, so we do not attempt to quantify these savings here.

Table 3 summarizes how the implementation of these four new technologies and practices could affect battery and electric vehicle emissions. Future electric vehicles will likely include larger lithium-ion battery packs to enable greater range, and we estimate that a 50% larger battery pack will increase life-cycle carbon emissions by 18%. The combination of cleaner electricity, battery recycling, and higher energy density could reduce battery manufacturing emissions per kWh by more than a third. At the vehicle level, these developments combined would reduce the life-cycle greenhouse gases by approximately 47 grams CO_2 per kilometer driven, or by about 36% compared to the reference, both from lower manufacturing and use-phase emissions. Where applicable, we apply estimates for the 2030 time frame and European average grid electricity (see Footnote 5). This assumes that grid electricity will be used for all battery manufacturing, with the geographic distribution of manufacturing similar to the present situation. We emphasize that these values are highly uncertain and depend on economic and technological conditions.

Table 3. Potential reductions in greenhouse gas emissions resulting from improvements in battery manufacturing and use

Development	Percent change in battery manufacturing emissions	Percent change in life-cycle g CO_2e/km
Larger electric vehicle battery	+33% to +66%	+18%
Battery second life	N/A	-22%
Battery recycling	-7% to -17%	-4%
Projected grid decarbonization	-17%	-27%
Greater battery energy density	-10% to -15%	-6%

We also illustrate the same battery trends and their combined impact on overall electric vehicle life-cycle emissions graphically in Figure 3. The reductions achieved through these programs appear sufficient to reduce the life-cycle carbon footprint of electric cars even when using a larger battery, increased to 45 kWh, to support greater range. Decarbonization of the grid is the single largest driver of emission reductions for electric vehicles, both in the manufacturing and use phase. Although the emission reductions from battery recycling and increased energy density appear to be less substantial here, these developments could also play an important role in reducing the costs of batteries and their upstream land and material requirements. This does not include the possibility of breakthroughs in alternative battery technologies, such as solid state or lithium-sulfur, which could result in greater emission reductions, but which are even more uncertain.

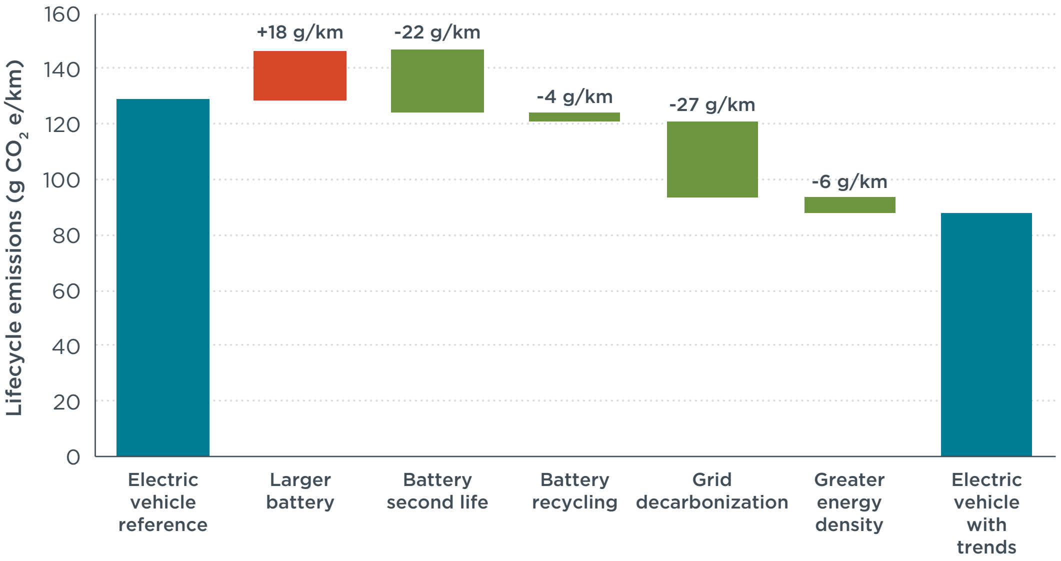

Figure 3. Potential changes in battery manufacturing greenhouse gas emissions (compared to reference 2017 electric vehicle) resulting from increased pack size and improvements in battery manufacturing and use.

CONCLUSIONS

As electric vehicles continue to become more affordable and their sales share continues to grow, it will be increasingly important to understand the life-cycle environmental impacts of the technology. In this briefing, we have examined the effect of lithium-ion battery manufacturing on electric vehicle life-cycle emissions. Although there are still many open questions, we make a number of observations on this topic.

Electric cars are much cleaner than internal combustion engine cars over their lifetime. We find that a typical electric car today produces just half of the greenhouse gas emissions of an average European passenger car. Furthermore, an electric car using average European electricity is almost 30% cleaner over its life cycle compared to even the most efficient internal combustion engine vehicle on the market today. Plug-in hybrid vehicles, when driven on electric power for most trips, have life-cycle emissions similar to battery electric vehicles. In markets with very low-carbon electricity, such as Norway or France, electric vehicles produce less than a third of the life-cycle emissions of an average combustion-engine vehicle. This finding bolsters governments' goals to promote electric cars as part of their decarbonization strategies.

Battery manufacturing life-cycle emissions debt is quickly paid off. An electric vehicle's higher emissions during the manufacturing stage are paid off after only 2 years compared to driving an average conventional vehicle, a time frame that drops to about one and a half years if the car is charged using renewable energy. Approximately half of a battery's emissions come from electricity used in the manufacturing process. Battery manufacturing emissions appear to be of similar magnitude to the manufacturing of an average internal combustion engine vehicle, or approximately a quarter of an electric car's lifetime emissions. However, recent estimates of battery manufacturing emissions vary by a factor of 10, indicating the need for additional research in this field.

Grid decarbonization offers a significant opportunity to reduce the impact of battery manufacturing. The emissions from battery manufacturing are likely to decline significantly in coming decades, especially with the use of cleaner electricity throughout the production cycle. A 30% decrease in grid carbon intensity would reduce emissions from the battery production chain by about 17%, in addition to even greater savings in the use phase. Use of recycled materials and battery chemistries with lower carbon intensity could also reduce emissions in the manufacturing phase. Furthermore, the establishment of a second-life battery market could allow for electric car batteries to support the electric grid for years after their life in the vehicle, which would further reduce the emissions attributable to electric cars. Even as electric vehicles use larger batteries to allow longer electric-range travel, these improvements will allow for lower life-cycle emissions and will further increase electric cars' life-cycle advantage over internal combustion engine vehicles.

Incorporating electric vehicle life-cycle manufacturing emissions into vehicle regulations would be misguided. Scrutiny on electric vehicle battery impacts has been warranted, considering that electric vehicles are central to many government plans to decarbonize the transport sector. However, the benefits of electric vehicles compared to internal combustion vehicles are clear and growing, despite imperfect data availability on the processes of vehicle manufacturing. Following our investigation into the various underlying factors, we see deep problems with introducing aggregated manufacturing emissions data into otherwise well-designed vehicle CO_2 and efficiency regulation. Calculating life-cycle emissions for all vehicle models would be onerous and not at all rigorous. Any such policy would need to include manufacturing emissions for all conventional vehicle components, in addition to batteries, so as not to unfairly penalize electric vehicles. This would also induce great uncertainty in the viability of existing conventional vehicle models that have steel and aluminum parts that originate from various parts of the world with higher and lower carbon intensities. In the 2025–2030 European Union CO_2 regulations, the European Commission considered regulating well-to-wheel or life-cycle emissions, but opted against this approach, concluding that it "would lead to double regulation, and could cause confusion in terms of responsibilities and liabilities, making vehicle manufacturers accountable for emissions occurring outside their sector."[9] Of course, governments can continue to simultaneously reduce upstream and vehicle use emissions with separate policies for recycling, battery second use, grid decarbonization, and vehicle use while promoting higher electric vehicle uptake. Slowing down electric vehicle uptake to wait for a near-zero-emission grid would be incompatible with global goals to decarbonize the transport sector by 2050.

Studies like those summarized in this analysis need to be conducted and re-conducted as the electric vehicle and battery business develop and expand. More rigorous data on material and manufacturing emissions will be essential as lithium-ion battery production expands to serve the growing electric vehicle market, amidst even larger changes in industry and electric power sources around the world. Nonetheless, the drive toward transportation electrification should not be postponed until more and better data are collected. It is clear that electric vehicles already have much lower lifetime emissions than comparable internal combustion engine vehicles, and these savings are likely to increase, creating a significant opportunity for the decarbonization of the transportation sector.

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[9] European Commission. (2017). Q&A on the proposal for post-2020 CO_2 targets for cars and vans. https://ec.europa.eu/clima/policies/transport/vehicles/proposal_en#tab-0-1