Dovetail Partners Consuming Responsibly Report No. 6

Environmental Assessment of Conventional vs. Hybrid vs. Battery electric Vehicles

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Environmental Assessment of Conventional vs. Hybrid vs. Battery electric Vehicles

Executive Summary

Over the past decade, initiatives to reduce U.S. greenhouse gas emissions have gained momentum, with conversion of both electric generation and transportation fuels away from fossil fuels toward renewable forms of energy. At the same time, there has been considerable development of vehicle alternatives, and electric-drive vehicles in particular.

Which of these new technologies yields the greatest environmental benefits is not straightforward. The answer depends largely on the extent to which electricity used in recharging vehicle batteries is produced using fossil fuels. Average commute distances, and time-of-day when recharging batteries also affect electric vehicle environmental efficiency.

In general, hybrid-electric vehicles (i.e., vehicles that combine internal combustion engines with battery power) that don't have plug-in capability reduce vehicle lifetime emissions by 25-30% compared to internal combustion vehicles. Hybrids with plug-in capability and battery electric (all-electric) vehicles are even more effective in reducing emissions, with a 30-50% advantage over internal combustion vehicles. As electricity generation becomes increasingly free of fossil fuels, emissions differences between standard and electric vehicles are likely to increase because achievable emissions reductions are strongly influenced by the greenhouse gas (GHG) intensity of the electricity used to charge vehicle batteries.

A global challenge posed by ongoing electric vehicle development is the corresponding sharp increase in consumption of critical metals in the batteries. Assuring adequate supplies of needed metals, addressing environmental impacts of increased minerals mining and processing activity, and development of substitute materials will all require concerted attention.

Growing Interest in Electric Vehicles Then and Now

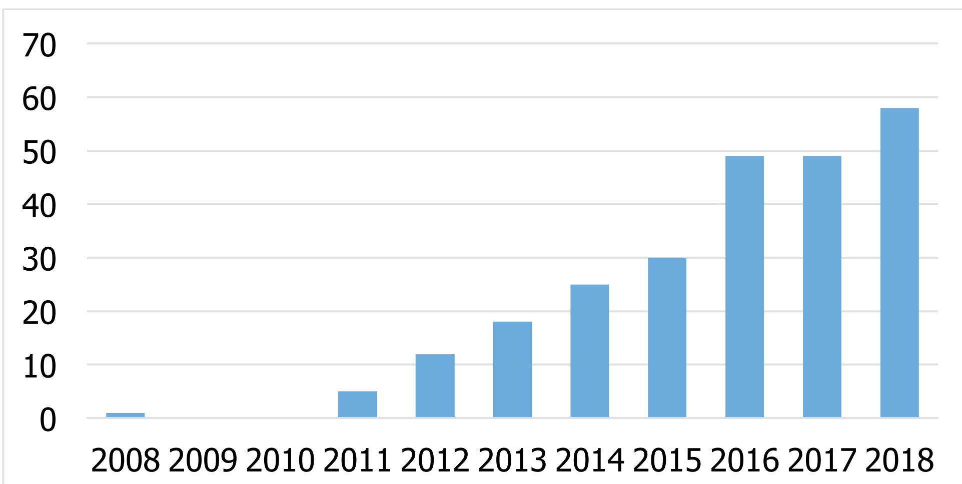
As explained in several fascinating histories of electric cars[1], interest in battery-powered vehicles began almost 200 years ago. The first commercially successful electric powered vehicle was introduced in 1890. Less than 10 years later, Ferdinand Porsche, who would later found the legendary Porsche sports car company, developed both a new model of an electric car and the world's first hybrid electric car. But the 1908 introduction of the Model 'T', which was far less expensive than electric cars, brought a quick end to the electric car market.

[1] See U.S. Department of Energy (2014) (https://www.energy.gov/articles/history-electric-car), and Fialka (2015) Car Wars: The Rise, the Fall, and the Resurgence of the Electric Car. Thomas Dunne Books.

Fast forward to the late 1960s and 1970s. High oil prices, shortages of gasoline brought on by oil embargos by OPEC[2], and concerns about diminishing petroleum reserves rekindled interest in electric powered vehicles, and triggered development efforts by major car manufacturers. In 2019, it is concern about carbon emissions, and realization that gasoline and diesel-fueled vehicles are a significant source of greenhouse gases (GHG), that is driving worldwide interest in alternative transportation fuels, and electric and hybrid-electric vehicles in particular.

Within the United States, the fact that production of electricity and transportation each account for 28% of the nation's GHG emissions have made electric power production and alternative transportation fuels a major focus of emissions reduction efforts. A key strategy is to reduce as quickly as possible the use of fossil fuels in electricity generation and to convert the ground transportation fleet from internal combustion to electric drive vehicles. It is an effort that is beginning to gain momentum. In 2018, for example, there were 59 plug-in electric hybrid and battery electric auto brands and models available on the U.S. market, up from just 1 in 2008 (Figure 1).

Figure 1
Number of Plug-in Hybrid and Battery Electric Passenger Car Models on the U.S. Market 2008-2018



Source: US Department of Energy/US Environmental Protection Agency. 2018.

This report examines the environmental performance of hybrid-electric and battery electric vehicles vs. those powered solely by internal combustion engines. Based on an extensive review of research, comparison of vehicle types involves assessment through complete life cycles – from resource extraction and processing, through vehicle manufacturing, use, and end of life disposal.

[2] OPEC - Organization of Petroleum Exporting Countries

Electric Power – Better Environmental Performance?

Various technology options are currently available in the electric car market. Hybrid-electric vehicles (referred to simply as HEVs in this report) are the most common today, with plug-in hybrids (PHEVs) also widely available. Both of these make use of battery power in combination with internal combustion engines.[3] Emissions linked to operating these vehicles come from the tailpipe (when the internal combustion engine is in operation), and for plug-in hybrids emissions also occur at the electric power plant to the extent that fossil fuels are used as a source of energy. Battery-electric vehicles (referred to herein as BEVs) are also commercially available; these vehicles rely solely on rechargeable battery packs, and have no internal combustion engine to provide backup power when batteries run low. BEVs produce zero emissions while operating, but are responsible for emissions at the power plant, again to the extent that fossil fuels are used in generating electricity.

A variation of the BEV is the extended range electric vehicle which makes use of an auxiliary power unit containing additional rechargeable batteries. The auxiliary unit is sometimes contained within a small trailer.

Electric drive car buyers are today motivated by the promise of reduced fossil fuel consumption and lower greenhouse gas emissions. A 2014 U.S. survey found that those who felt most strongly about reducing transportation energy consumption and cutting GHG emissions were 71 and 44 times more likely, respectively, to indicate that they would consider purchasing a compact PHEV than those who felt least strongly about these issues.[4]

Types of Alternative Vehicles

HEV: Hybrid-electric vehicle

PHEV: Plug-in Hybrid – electric vehicle

BEV: Battery-electric vehicle

So how much better are PHEVs from an environmental point of view than conventional vehicles? What about BEVs and HEVs? And, are there factors other than on-the-road emissions that need to be considered in judging environmental impact? Numerous studies have examined these questions.

Summarized findings of reports reviewed indicate that:

- HEVs, PHEVs, and BEVs play a critical role in reducing global greenhouse gas emissions.
- Vehicle life cycle emissions reductions of 80%+ are technically possible through replacement of internal combustion vehicles with functionally equivalent BEVs.

[3] Hybrid electric vehicles switch seamlessly between electric and combustion engine drive, automatically switching to electric power when the vehicle is stopped in traffic or steady moderate speed driving; the combustion engine is engaged when accelerating, traveling up a slope, or when intensively heating or cooling the car interior. Hybrids without plug-in capability have batteries with less storage capacity than those which do have this feature, and consequently must engage the internal combustion engine more often to maintain the battery charge.

[4] Krupa et el. (2014)

- PHEVS and BEVs have the greatest advantage over internal combustion vehicles in urban settings where distances driven daily are relatively short, and travel often involves stop and go driving.
- Achievable emissions reductions are strongly influenced by the GHG intensity of the electricity used to charge vehicle batteries.
- Considering U.S. average electricity GHG intensity, HEVs and PHEVs achieve essentially the same level of over-the-road GHG emissions reduction (27-32%).
- When low carbon intensity electricity is used as a charging source, PHEVs are 30-47% more efficient than HEVs, and 51-63% more efficient than internal combustion vehicles. However, when PHEVs are charged using a high carbon intense energy source, emissions can be as much as 9-18% ***higher*** than HEVs.
- Considerable progress has been made over the past decade in shifting U.S. electricity production from fossil fuels to renewables, reducing GHG intensity of electricity generation.
- Only when electricity production is essentially free from emissions of fossil carbon, can PHEVs and BEVs reach their full potential in mitigating GHG emissions.
- Energy consumption and GHG emissions can be minimized by driving electric vehicles (or any type of vehicle) at lower speeds (e.g., urban driving at 55 mph (~90 kph) rather than 70 mph (~110 kph), and by minimizing rapid acceleration.
- A heavily loaded vehicle (including one loaded with accessories) will consume more energy and have greater emissions than one that is more lightly loaded.
- The manufacture of HEVs, PHEVs, and BEVs requires consumption of greater quantities of strategic metals than non-electric vehicles, creating urgency around development of improved vehicle designs and new recycling strategies.

What Life Cycle Assessment Reveals

On-the Road Performance not the Only Consideration

The manufacture of HEVs, PHEVs, and BEVs results in greater GHG emissions than manufacture of functionally equivalent internal combustion vehicles largely due to the GHG emissions associated with the manufacture of batteries and other electric drive components, as well as end-of-life disposal. High emissions linked to manufacturing of batteries and electric motors are in large part due to extraction and processing of critical metallic elements. Manufacturing related GHG emissions in some cases constitute a significant portion of overall vehicle life cycle emissions. The difference in manufacturing emissions influences the degree to which new technologies can reduce vehicle lifetime GHG emissions in comparison to traditional internal combustion vehicles.

Increased use of critical metals in electric vehicles increases impacts beyond emissions. Landscape impacts associated with mining (not consistently quantifiable within a life cycle assessment) can also be substantial.

Ongoing efforts focused on battery recycling will help to reduce emissions and other impacts from production and disposal of electric vehicles. Potential replacement of active components of lithium-ion batteries with nanomaterials may increase battery manufacturing emissions, but shows promise for reducing critical metals use and increasing battery performance, which will ultimately decrease vehicle life cycle emissions.

Hybrid Vehicles

HEVs and PHEVs, which utilize battery power in combination with internal combustion engines, reduce operating emissions by switching to battery power when power demand is low. As long as the sources of power used in electric generation result in lower emissions than production and utilization of gasoline or diesel fuels, hybrid vehicles can deliver lower emissions than conventional internal combustion vehicles.

Because of continued reliance on internal combustion engines, hybrid technology is widely viewed as a bridge to lower emission BEVs. For now, however, hybrid electric vehicles are essential to realizing some of the advantages of electric power in long distance travel.

Hybrid Electric Vehicles

Several studies during the period 2009-2012[5] found that HEVs reduce over-the-road emissions 27-35% compared to internal combustion vehicles. Reductions of as much as 63% were reported as possible.

In general, HEVs deliver less emissions reduction than PHEVs, although the potential advantage of PHEVs is almost totally dependent upon the GHG intensity of the electricity used in recharging batteries. The greatest advantage of PHEVs is realized when the contribution of fossil fuels to electricity generation is minimal.

Plug-in Hybrid Electric Vehicles

A 2009 examination of the potential of PHEVs,[6] which assumed that electricity from the grid would power 47% of long distance travel and 76% of short distance travel, found that:

- Assuming availability of low GHG intensity electricity, PHEVs are 30-47% more efficient than hybrids without plug-in capability, and 51-63% more efficient than conventional internal combustion vehicles.

[5] Boureima et al. (2009), Helmers and Marx (2012), Samaras and Meisterling (2008), Sioshanshi and Denholm (2009)

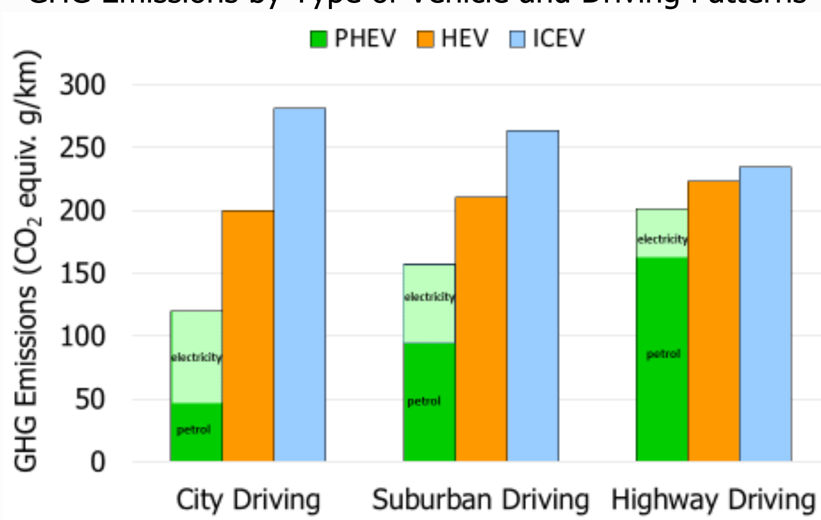
[6] Sioshanshi and Denholm (2009)

- Assuming use of high GHG intensity electricity for battery recharging, emissions from PHEVs over a vehicle life cycle would be much *greater* than for HEVs, and even greater (9-18% greater) than for internal combustion vehicles.

This same study found that at (then 2009) average U.S. GHG intensity of electricity, PHEVs reduced use-phase GHG emissions by 38-41% compared to internal combustion vehicles, and 7-12% compared to HEVs. When manufacturing of batteries was included in calculations, the emissions reduction advantage of PHEVs relative to internal combustion vehicles narrowed to about 32%, with the performance difference between HEVs becoming negligible.

Several studies have highlighted the effect of regional electricity GHG intensity and driving patterns on the efficiency of PHEVs relative to HEVs and conventional internal combustion vehicles.[7] Figure 2 is typical of findings of these studies. Shown in this figure are results of an analysis for the city of Toronto where the daily round-trip commute time is 40 minutes. City driving is characterized by a daily driving distance of 12-18 miles (20-29 km), average speeds of 18-25 mph (29-40 km/h), and frequent starts and stops. Suburban driving involved longer distances of 21-33 miles (33-53 km), speeds in the 29-45 mph (46-73 km/h) range, and infrequent stopping. Highway driving allowed greater average speeds (53-58 mph, 85-94 km/h) and greater distances (40-42 miles, 64-68 km). The dark green segment of the PHEV bars represents the portion of travel powered by fossil fuels, the light green segment the portion powered by electricity.

Figure 2
GHG Emissions by Type of Vehicle and Driving Patterns



Plug-in hybrid vehicle (PHEV), Non-plug-in hybrid vehicle (HEV), Internal combustion vehicle (ICEV). Each category represents a 40-minute round-trip commute

Source: Adapted from Raykin (2012) as presented by Nordelöf et al. (2014)

[7] Raykin (2012)

In city driving, PHEVs have the lowest emissions, as the bulk of travel is powered by the battery. As distances become longer and speeds higher, a greater and greater portion of travel is powered by petrol (primarily gasoline) as battery power is depleted; consequently, emissions increase. When the longest distances are traveled, and at the greatest speeds, the emissions advantage of the PHEV relative to HEVs and internal combustion vehicles shrinks. Nonetheless, in the Toronto study, the PHEV had lower emissions in all scenarios. Similar results have been reported for BEVs.[8]

For PHEVs, the extent of emissions reduction achieved is highly dependent upon the GHG intensity of electricity used to recharge batteries, and the degree to which travel occurs using battery power. Consequently, whether purchase of a PHEV is environmentally beneficial depends on the fuel-source used to produce electricity where you live.

Battery electric Vehicles

The potential for emissions reduction through replacement of internal combustion drive vehicles with BEVs has been extensively studied, with much of this work conducted by European scientists. Several of these investigations, which are representative of broader findings, are briefly summarized below.

A Belgian comparative life cycle assessment of electric, hybrid, and gasoline passenger vehicles found BEVs to have 78% lower life cycle GHG emissions than comparable internal combustion gasoline fueled vehicles.[9]

A German study of life cycle GHG emissions reduction potential with battery electric technology involved conversion of a standard Smart Car (Figure 3) to a BEV. Study results revealed a fourfold energy efficiency advantage of the BEV over an identical vehicle powered by an internal combustion engine.[10] Results also showed potential life cycle emissions reduction of over 80% for a BEV vehicle in comparison to a functionally equivalent internal combustion drive vehicle.

Figure 3
Smart Car
A Product of Mercedes-Benz

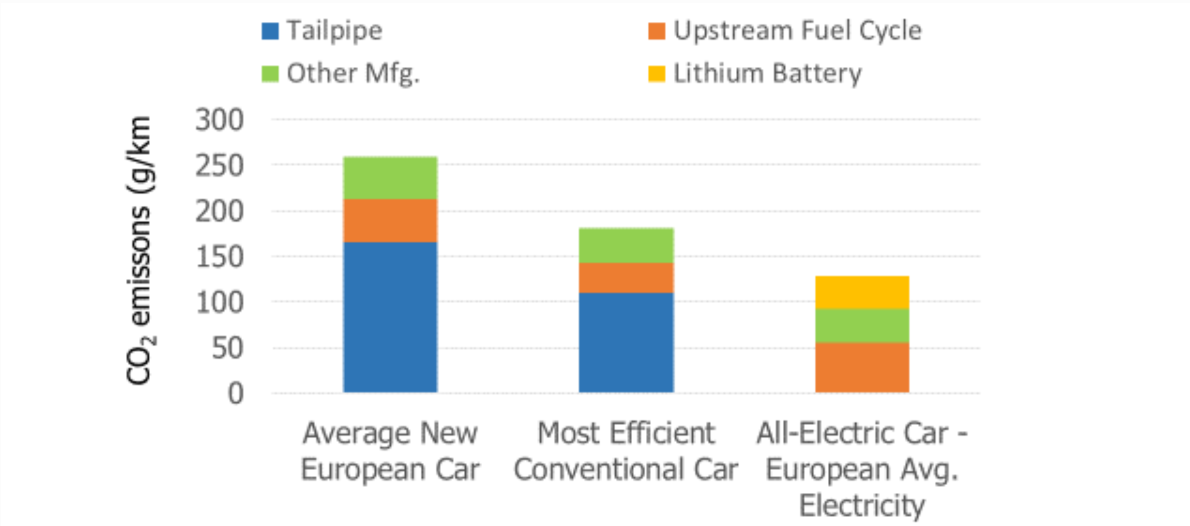
A 2017 US assessment showed pure BEVs to be as much as 5 ½ times more efficient than internal combustion vehicles assuming the availability of near zero GHG intensity electricity.[11]

A 2018 life cycle assessment by European scientists found that a typical BEV charged with average European electricity produces only one-half the operational greenhouse gas

8 Messagie (2014), Tamayao et al. (2015), Yuksel et. Al. (2016)
9 Boureima et al. (2009)
10 Helmers and Marx (2012)
11 Wu and Offer (2017). The analysis did not consider vehicle manufacturing emissions, electricity transmission losses, or other factors.

emissions of an average internal combustion engine European passenger car.[12] Moreover, a BEV using average European electricity was found to have 30% lower GHG emissions over its life cycle compared to *even the most efficient internal combustion engine vehicle on the market* (Figure 4). When findings were extended to include very low-carbon electricity, such as found in Norway or France, it was determined life-cycle emissions of a BEV would be less than one third those of an average combustion-engine vehicle.

Figure 4
Life Cycle GHG Emissions Over 93,200 Miles (150,000) km



Source: Adapted from Hall and Lutsev (2018)

Numerous additional assessments have yielded similar results to those cited above,[13] with variations in findings attributable to the sources of electricity considered, assumed vehicle life, data used as the basis for calculations (laboratory data or actual performance data from over the road travel), and average daily distances driven. Findings have uniformly indicated superior environmental performance of BEVs except in those instances in which energy used to recharge batteries is GHG intensive.[14]

An extensive review of 79 studies of electric vehicle environmental performance[15] found that all of them were in agreement that only if global electricity production is essentially free of fossil carbon emissions, can PHEVs and BEVs reach their full potential in mitigating climate change.

[12] Hall and Lutsev (2018)
[13] Gao and Winfield (2012), Hawkins et al. (2013 a, b), Onat et al. (2015), Tagliaferri et al. (2015)
[14] Ghosh (2014)
[15] Nordelöf et al. (2014)

Vehicle efficiency and emissions are also influenced by vehicle speed and load. As with any type of vehicle, high speeds, rapid acceleration, and high vehicle loads (including loading of a vehicle with accessories) can substantially increase power demand and emissions.[16]

Contribution of Battery Production to Environmental Impacts

The greatest environmental impacts realized in manufacturing electric vehicles result from battery production and, specifically, the extraction and processing of high impact metals (aluminum, copper, cobalt, lithium, manganese, nickel) used in the battery pack.[17] Various studies estimate GHG emissions linked to battery production to account for 2-6%, to as much as 25% of an electric vehicle's lifetime emissions. Over 90% of these emissions are estimated to result from processes involved in obtaining minerals.[18] What has been described as a carbon debt resulting from high emissions in battery manufacturing is "paid off" in about two years, and as little as one and one-half years when an electric vehicle is charged using renewable energy.[19]

Only small quantities of battery components are currently recovered for recycling. Examination of benefits from battery recycling show potential reduction of energy consumption in materials production, and in mineral ore dependency, of 40-60%.[20]

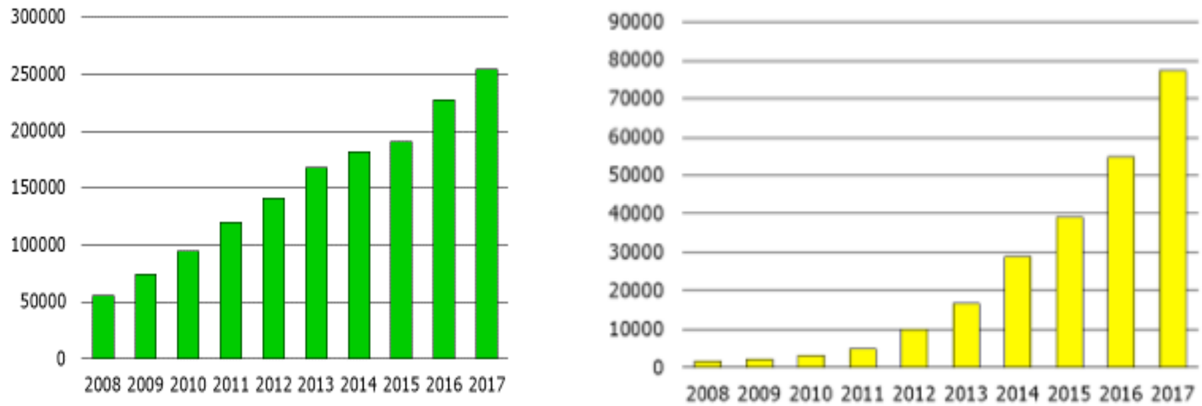
Ongoing research is focused on the battery recycling issue and on finding substitutes for some of the materials used in battery manufacturing. A promising area involves replacement of active materials in lithium ion batteries with various nanomaterials.[21]

Growing Availability of Renewable Electricity

Renewable energy sources provided 17% of US electricity in 2017, with 50% provided by hydropower and combustion of biomass. Only nine years earlier, renewable electricity had accounted for 9% of total U.S. generation and the percentage of electricity provided by hydropower and biomass was 77%. Reduced importance of hydro and biomass in national power generation is due to rapid increases in wind and solar generation (Figure 5).

[16] Ma et al. (2012)
[17] Tagliaferri et al. (2015)
[18] Dunn et al. (2012), Hall and Lutsev (2018), Samaras and Meisterling (2008), Wu and Offer (2017)
[19] Hall and Lutsev (2018)
[20] Dewulf et al. (2010), Kushnir and Sandén (2011), Li et al. (2013)
[21] Kushnir and Sandén (2011), Yazami (2014)

Figure 5
Rising Wind and Solar Electricity Production in the United States (GWh)



Source: Wind energy statistics for 2008-2017, and solar power statistics for 2014-2017 from US Department of Energy, Energy Information Administration (2018). Solar data for 2008-2013 from Weissmann et al. (2018).

The US Department of Energy, Alternative Fuels Data Center reports that the US electricity infrastructure is not operating at its full capacity, with only about 50% of generation capacity used 100% of the time, but close to capacity realized only 5% of the time (about 400 hours per year). It is noted that battery electric and plug-in hybrid vehicles have the potential to create little or no need for additional capacity, as long as they were charged predominantly during off-peak times, such as late at night, when the electric load on the system is at a minimum.[22]

A 2007 study by the Northwest National Laboratory,[23] found that then existing U.S. electricity infrastructure had sufficient capacity to meet about 73% of the energy needs of the country's light-duty vehicles. Distributed capacity, such as provided by rooftop solar panels, would add to this capacity. A cautionary note is provided by a 2015 study which found that delayed charging (i.e. after midnight) leads to higher emissions across much of the US due largely to increase use of coal in marginal generation at night.[24] The effect can be much the same as when the GHG intensity of regional electricity is high in general.[25]

[22] US Department of Energy, Alternative Fuels Data Center (2018)
[23] Kintner-Meyer et al. (2007)
[24] Tamayao et al. (2015)
[25] Regional and state-by-state information regarding GHG emissions from electricity generation, including peak vs. non-peak emissions, are available via EPAs e-Grid database. The website can be accessed via (https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid), with access to summary tables here: (https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf).

Resource Issues

A challenge to rapid conversion of the global vehicle fleet from internal combustion to electric drive vehicles is the substantial impact on metals consumption. Significant increases of consumption of aluminum, copper, cobalt, graphite, lithium, nickel, and titanium are expected to result from increasing electric vehicle production.

For example, conventional internal combustion vehicles contain about 40 lb (20 kg) of copper, HEVs about 88 lb (40 kg), and PHEVs about 132 lb (60 kg). An average BEV contains over 176 lb (80 kg) of copper, or four times that of a conventional vehicle.[26] Shifting only 8 percent of the global vehicle fleet to electric power is estimated to result in an increase in world copper consumption of more than one third.

Consumption of cobalt and lithium for use in electric vehicles has risen sharply since 2015, with greater increases expected within the next several decades. The situation for cobalt is especially interesting. At the beginning of 2017, the price per metric ton (2200 pounds) of cobalt was $32,500, while only a year later that number had risen to $81,000. Lithium-based batteries used more than 50% of all cobalt produced in the world in 2017, and by 2025 consumption of cobalt for this purpose is forecast to be more than 25% greater than current world production. Lithium consumption is also expected to soar. Demand is likely to increase by a factor of 3-4 times by 2025, with the vast majority of the growth driven by production of BEVs.[27]

Attention to resource issues is clearly needed as part of the effort to increase the electric vehicle fleet. Major investment is needed to increase minerals exploration activity, recycling rates, efficiencies of metals use, develop substitute materials, and to reduce environmental impacts of minerals extraction.

Consumer Tips

Consumers who seek to make environmentally beneficial vehicle choices need to be aware of options and those factors that reduce impacts of transportation. We suggest that:

- Serious consideration be given to buying electric with your next vehicle purchase. The Department of Energy maintains a website which provides information for all alternative fuel vehicles and allows side-by-side comparison of various models. (https://www.fueleconomy.gov/feg/alternatives.shtml)[28]
- You look into the mix of fuels used to generate your electricity (see link under Renewable Energy heading, footnote #25).

[26] McKay (2016)
[27] Halpin et al. (2018)
[28] Also see the US Environmental Protection Agencies (EPA) Certified SmartWay program for identifying vehicles that emit less GHG and smog-forming tailpipe emissions, https://www.fueleconomy.gov/feg/SmartWay.do

    - If the proportion of fossil fuels (and particularly coal) is high, contact state and community leaders to urge timely transition to renewables.
    - Consider HVE vehicle purchase rather than PHEV or BEV if coal is dominant in generating electricity.
- When purchasing a vehicle, select a model that is no larger than absolutely necessary.
- Moderate driving habits

Summary

A shift toward electric-powered vehicles is gaining momentum in the United States and worldwide. The degree to which this change is effective in reducing greenhouse gas emissions depends heavily on how rapidly the use of fossil fuels can be reduced or eliminated in generating electricity.

Which vehicle a consumer should choose – hybrid electric, plug-in hybrid electric, or battery electric vehicle – in order to minimize emissions is currently largely dependent on the greenhouse gas intensity of electricity generated in a particular region. Long commute distances favor non-plug-in hybrid vehicles, while plug-in hybrids and battery electric vehicles deliver the greatest advantage in short-distance city driving conditions.

In general, electric vehicles offer significant emissions reduction compared to internal combustion drive vehicles. The magnitude of emissions reduction offered by electric vehicles is likely to increase with progress in reducing emissions from electricity generation.

Resource issues loom large in future electric vehicle development, and will have to be addressed within the near future. Development of substitute materials for battery production will also be important.

Sources of Information

Boureima, F., Messagie, M., Matheys. J., Wynen, V., Sergeant, N., Van Mierlo, J., De Vos. M. and De Caevel. B. 2009. Comparative LCA of Electric, Hybrid, LPG and Gasoline Cars in Belgian Context. World Electr Veh 3(1):1–8. (https://www.researchgate.net/publication/234162892_Comparative_LCA_of_electric_hybrid_LPG_and_gasoline_cars_in_Belgian_context)

Dewulf, J., Van der Vorst, G., Denturck, K., Van Langenhove, H., Ghyoot, W., Tytgat, J. and Vandeputte, K. 2010. Recycling Rechargeable Lithium Ion Batteries: Critical Analysis of Natural Resource Savings. Resour Conserv Recycl 54(4):229–234. (https://www.infona.pl/resource/bwmeta1.element.elsevier-baa141f5-1d69-39e8-a7b7-627e2de209ba)

Dunn, J., Gaines, L., Sullivan, J. and Wang, M. 2012. Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-ion Batteries. Environ Sci Technol 46(22):12704–12710.

Fialka, J. 2015. Car Wars: The Rise, the Fall, and the Resurgence of the Electric Car. New York: Thomas Dunne Books.

Gaines L., Sullivan, J., Burnham, A., and Belharouak, I. 2011. Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries. Transp Res Rec J Transp Res. Board 2252:57–65. (https://www.researchgate.net/publication/265158823_Paper_No_11-3891_Life-Cycle_Analysis_for_Lithium-Ion_Battery_Production_and_Recycling)

Gao, L. and Winfield, Z. 2012. Life Cycle Assessment of Environmental and Economic Impacts of Advanced Vehicles. Energies 5(3):605–620. (https://www.mdpi.com/1996-1073/5/3/605/htm)

Ghosh, T. 2014. Economic and Environmental Impacts of Plug-in Hybrids and Battery Electric Vehicles: A Comparative Analysis. University of San Francisco, Masters Projects and Capstones. (https://repository.usfca.edu/cgi/viewcontent.cgi?article=1012&context=capstone)

Grant, K. 2017. BHP Sees Copper as 'Metal of the Future' as Electric Car Demand Booms. The Street.com, Sept. 26. (https://www.thestreet.com/story/14319949/1/bhp-tipping-point-electric-vehicles-copper.html).

Hall, D. and Lutsev, N. 2018. Effects of Battery Manufacturing on Electric Vehicle Life-Cycle Greenhouse Gas Emissions. International Council on Clean Transportation, Feb. (https://www.theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf)

Halpin, L., Spalton, R. and D'Arcy, C. 2018. Lithium: Does Rising Demand Mean Rising Prices? Edinburgh Partners. (https://www.edinburghpartners.com/wp-content/uploads/2018/07/Lithium-Does-Rising-Demand-Mean-Rising-Prices-May-2018.pdf)

Hawkins, T., Singh, B., Majeau-Bettez, G. and Strømman, A. 2013a. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J Ind Ecol 17(1):53–64. (https://onlinelibrary.wiley.com/doi/full/10.1111/j.1530-9290.2012.00532.x)

Hawkins, T., Singh, B., Majeau-Bettez, G. and Strømman, A. 2013b. Corrigendum to: Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman. 2012. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J Ind Ecol 17(1):158–160. (https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12011)

Helmers, E. and Marx, P. 2012. Electric Cars: Technical Characteristics and Environmental Impacts. Environ Sci Eur 24(4):1–15.

Kintner-Meyer, M., Schneider, K. and Pratt, R. 2007. Impact Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids, Part 1: Technical analysis. November, 2007. Pacific Northwest National Laboratory, USA. (https://www.ferc.gov/about/com-mem/5-24-07-technical-analy-wellinghoff.pdf)

International Copper Association. 2017. The Electric Vehicle Market and Copper Demand.(https://copperalliance.org/wordpress/wp-content/uploads/2017/06/2017.06-E-Mobility-Factsheet-1.pdf)

King, A. 2018. Battery Builders Get the Cobalt Blues. Chemistry World, March 12. (https://www.chemistryworld.com/news/battery-builders-get-the-cobalt-blues/3008738.article)

Krupa, J., Rizzo, D., Eppstein, M., Lanute, D.B., Gaalema, D., Lakkaraju, K. and Warrender, C.. 2014**.** Analysis of a consumer survey on plug-in hybrid electric vehicles. Transportation Research Part A: Policy and Practice Volume 64, June 2014, pp. 14-31. (https://www.sciencedirect.com/science/article/pii/S0965856414000500)

Kushnir, D. and Sandén, B. 2011. Multi-level Energy Analysis of Emerging Technologies: a Case Study in New Materials for Lithium Ion Batteries. J. Clean Prod 19(13):1405–1416.

Li, L., Dunn, J., Zhang, X., Gaines, L., Chen, R., Wu, F. and Amine, K. 2013. Recovery of Metals from Spent Lithium-ion Batteries with Organic Acids as Leaching Reagents and Environmental Assessment. J Power Sources 233:180–189.

Ma, H., Balthasar, F., Tait, N., Riera-Palou, X. and Harrison, A. 2012. A New Comparison between the Life Cycle Greenhouse Gas Emissions of Battery Electric Vehicles and Internal Combustion Vehicles. Energy Pol 44:160–173.

McKay, H. 2016. Electric Cars Will Influence Demand for Metals More than Oil. Financial Times, Oct. 31. (https://www.ft.com/content/84b3fa1c-9ee8-11e6-891e-abe238dee8e2)

Messagie, M. 2014. Life Cycle Analysis of the Climate Impact of Electric Vehicles. Transport and Environment Research Group, Vrije Universiteit, Brussels. (https://www.transportenvironment.org/sites/te/files/publications/TE%20-%20draft%20report%20v04.pdf)

Nordelöf, A., Messagie, M., Tillman, A-M., Söderman, M. and Mierlo, J. 2014. Environmental Impacts of Hybrid, Plug-in Hybrid, and Battery Electric Vehicles – What Can We Learn from Life Cycle Assessment? The International Journal of Life Cycle Assessment 19(11): 1866-1890. (https://core.ac.uk/download/pdf/81517338.pdf)

Onat, N., Kucukvar, M. and Tatari, O. 2015. Conventional, Hybrid, Plug-in Hybrid or Electric Vehicles? State-Based Comparative Carbon and Energy Footprint Analysis in the United States. Applied Energy 150 (2015): 36-49. (https://www.academia.edu/12004927/Conventional_Hybrid_Plug-in_Hybrid_or_Electric_Vehicles_State-based_Comparative_Carbon_and_Energy_Footprint_Analysis_in_the_United_States?auto=download)

Raykin, L. 2011. Implications of Driving Patterns on Well-to-Wheel Performance of Plug-in Hybrid Electric Vehicles. MS Thesis, Department of Civil Engineering, University of Toronto. (https://tspace.library.utoronto.ca/bitstream/1807/42882/1/Raykin_Leonid_201111_MASc_thesis.pdf)

Samaras, C. and Meisterling, K. 2008. Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. Environmental Science and Technology 42(9): 3170-3176. (https://pubs.acs.org/doi/10.1021/es702178s)

Sioshansi, R. and Denholm, P. 2009. Emissions Impacts and Benefits of Plug-in Hybrid Electric Vehicles and Vehicle-to-Grid Services. Environ Sci Technol 43(4):1199–1204.

Tagliaferri, C., Evangelisti, S., Acconcia, F., Domenech, T., Elkins, P., Barletta, D. and Lettieri, P. 2015. Life Cycle Assessment of Future Electric and Hybrid Vehicles: A Cradle-to-Grave Systems Engineering Approach. Chemical Engineering Research & Design 112(8): 298-309. (http://discovery.ucl.ac.uk/1503806/1/Tagliaferri%20Life%20cycle%20assessment%20of%20future%20electric%20and%20hybrid%20vehicles.pdf)

Tamayao, M-A., Michalek, J., Hendrickson, C. and Azevedo, I. 2015. Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO_2 Emissions across the United States. Environ. Sci. Technol., 2015, 49(14):8844–8855. (https://pubs.acs.org/doi/abs/10.1021/acs.est.5b00815?src=recsys&journalCode=esthag)

U.S. Department of Energy. 2014. History of the Electric Car. (https://www.energy.gov/articles/history-electric-car)

US Department of Energy, Alternative Fuels Data Center. 2018. Electricity Production and Distribution. (https://afdc.energy.gov/fuels/electricity_production.html)

US Department of Energy, Energy Information Administration. 2018. Electricity Data, Table 1.1.A.: Net Generation from Renewable Sources: Total (All Sectors) 2008-Sept. 2018. (https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01_a)

US Department of Energy. 2018. Alternative Vehicle Calculator. Office of Energy Efficiency and Renewable Energy. (https://www.fueleconomy.gov/feg/alternatives.shtml)

US Department of Energy/US Environmental Protection Agency. 2018. Beyond Tailpipe Emissions: Greenhouse Gas Emissions for Electric and Plug-In Hybrid Electric Vehicles. (https://www.fueleconomy.gov/feg/Find.do?zipCode=55127&year=2018&vehicleId=39871&action=bt3)

US Environmental Protection Agency. 2018. Emissions & Generation Resource Integrated Database (eGRID). (https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid)

US Environmental Protection Agency. 2018. Fast Facts on Transportation Greenhouse Gas Emissions. (https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions)

Weissman, G., Sargent, R. and Fanshaw, B. 2018. Renewables on the Rise 2018: A Decade of Progress Toward a Clean Energy Future. Environment America Research and Policy Group. (https://environmentamerica.org/sites/environment/files/reports/AME_Renewables-on-the-Rise_Jul18-Web.pdf)

Wu, B. and Offer, G. 2017. Environmental Impact of Hybrid and Electric Vehicles. In: Harrison, R. and Hester, R. Environmental Impacts of Road Vehicles: Past, Present and Future. Royal Society of Chemistry, pp. 133-156.

Yazami, R. (ed.) 2014. Nanomaterials for Lithium-Ion Batteries: Fundamentals and Applications. Pan Stanford Publishing Ltd.
(see summary at https://www.technology.matthey.com/article/59/1/26-29/)

Yuksel, T., Tamayao, M-A., Hendrickson, C., Azevedo, M. and Michalek, J. 2016. Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States. Environ. Res. Lett. 11 (2016) 044007. (http://iopscience.iop.org/article/10.1088/1748-9326/11/4/044007/pdf)