Fuels Institute

Literature Review Summary

SUPERCHARGED:
THE ENVIRONMENTAL IMPACT OF ELECTRIC VEHICLES

OCTOBER 2019

Contents

INTRODUCTION 3
IN FAVOR: ELECTRIC VEHICLE BENEFITS 4
UNDER SCRUTINY: ELECTRIC VEHICLE BENEFITS 9
PRODUCTION 11
ABOUT ICES 12
SUMMARY 13
LIST OF SOURCES 14

ABOUT THE LITERATURE REVIEW SUMMARY

Through recommendations made by the Fuels Institute's Board of Advisors and the Institute's independent research, the Fuels Institute reviewed nearly 40 reports, blogs, columns, presentations and news articles addressing the environmental impact of electric vehicles (EV). The following report summarizes the content of those resources.

We provide a bibliography of those resources at the end of this paper.

Disclaimer: Due to the fact that terminology and methodologies used in the reports varied greatly (or were not well described), this summary does not contain specific numbers or details. However, it should provide readers with an overall sense of what is being written with respect to IMO 2020 and the commonalities and trends that exist in the literature. It is important to remember that none of the statements presented below are purported to be true or accurate. Furthermore, none of the statements made below are those of the Fuels Institute. The content is presented as a summary and overview of the literature reviewed.

Introduction

The Environmental Impact of Electric Vehicles

Anyone standing next to two idling cars—one powered by an internal combustion engine (ICE) and the other by a battery—might assume it would be easy to identify the one producing the more damaging environmental impact. But can they?

While the tailpipe emissions from the two vehicles can be easily compared, this method of assessment captures just a snapshot of the complete environmental impact produced by the vehicles, some researchers maintain. While the EV and its faint, slot car-like hum has earned it mass public perception of its eco-friendliness, one must assess the entire lifecycle of the EV to gain a more precise view of its environmental impact. That's a view that captures its manufacture, distribution, use, longevity, disposal and even use location, to name just a few, during which both greenhouse gasses (GHG) and local pollutants are emitted. The literature offers differing views of the environmental impact of EVs. In this literature review, we will **summarize** those that seem to present a more positive evaluation of EVs and their benefits first, followed by those that seem less optimistic about the impact of EVs. Finally, we will look at recent studies of ICEs and their environmental impact.

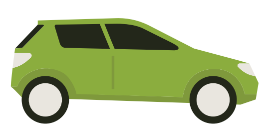
FULL ENVIRONMENTAL IMPACT: THE LIFECYCLE OF THE EV

MANUFACTURING VS. TOTAL LIFETIME

Greenhouse gas (GHG) emissions during the production stage of EVs range from **1.3 to 2 times higher** than for ICEs. The mid-size EV emits **51% less** GHG than its gas-powered version while the full-size emits **53% less** over lifetime of each car.

UP TO **2X** HIGHER GHG EMISSIONS IN **PRODUCTION**

51% LESS **LIFETIME** GHG EMISSIONS THAN ICEs



MEASURING EV IMPACT...

Careful review of the EV's lifecycle: manufacture, distribution, use (including location), longevity, and disposal is critial.

PRODUCTION

Nearly **half of an EV's lifetime global warming potential (GWP)** is due to to the energy requirements for raw material extraction and processing as well as the manufacture of its batteries.

USE LOCATION

Driving an EV shifts pollution from the road to the electricity generation station. **91% of the resulting pollution shifts to a state other than where the EV car operates**. Only 18% of the pollution emitted from ICEs discharges in other states.

DISPOSAL

Recovering cathode materials in EV batteries during the recycling process will further reduce the environmental impact. One study concluded that these will lead to a "huge reduction potential of CO_2 emissions in China."

In Favor:

Electric Vehicle Benefits

GLOBAL WARMING IMPACT

Despite no tailpipe emissions, an EV still produces significant global warming emissions that depend on two factors: the vehicle's efficiency and the source of electricity charging the battery. For the former, a less efficient EV draws on more electricity from the electric grid, which emits pollution; and for the latter, electricity that relies on coal power rather than renewable energy, for instance, will emit more pollution (more below).

Using mid- and full-size EVs as testing vehicles, the U.S. average fuel efficiency that gasoline-powered vehicles need to achieve to equal the emissions from their EV counterparts ranges from 35 mpg in the Central region to 112 mpg in northern Alaska — or an average of 68 mpg across all regions.

When powered by the present mix of electricity in Europe, EVs deliver a 10% to 24% decrease in GWP compared to ICEs, assuming an average lifetime of 93,200 miles.

As grids tap more renewable sources of energy —moving away from coal and towards wind and solar — EVs will grow even cleaner. When renewables comprise 80% of a grid's electricity, emissions from EVs will drop 25% during manufacturing and 84% during driving compared to current emissions. These reductions will produce measurable improvements that affect air quality, climate change and fossil fuel preservation.

MANUFACTURING VS. TOTAL LIFETIME

Generally, GHG emissions during the production stage of EVs range from 1.3-2 times higher than for ICEs, mainly attributed to the manufacture of the EV's lithium-ion battery. During this phase, a mid-size EV adds more than 1-15% more tons to the environment than its ICE counterpart, while a full-size EV adds six tons of emissions, or 68% more. Overall, the mid-size EV overcomes its manufacturing emission "deficit" in just 4,900 miles (and the full-size in 19,000 miles) before achieving lower total lifetime emissions than its gas-powered counterpart. When evaluating the lifetime of each car, the mid-size EV emits 51% less than its gas-powered version while the full-size emits 53% less GHG.

Other studies quantify the return on investment at two years of average usage, or 1.5 years if charging the EV from renewable energy, with grid decarbonization further reducing the break-even timeframe.

ABOUT BATTERIES

One study of the lifetime impact of lithium-ion batteries concluded that while production has the greatest impact on GHG emissions, the total depends on the materials and techniques used. "[B]attery composition will influence overall battery mass, which in turn affects cradle-to-grave energy and emissions associated with battery production." (See Source No. 16, pg. 74)

As production techniques evolve and reduce the mass of cathode and anode materials, the environmental impact of EV batteries will also decrease. Furthermore, recovering cathode materials during the recycling process will further reduce the environmental impact.

One study concluded that these will lead to a "huge reduction potential of CO_2 emissions in China." (See Source No. 26)

Overall, the mid-size EV overcomes its manufacturing emission "deficit" in just 4,900 miles...the mid-size EV emits 51% less GHG than its gas-powered version.

CARBON FOOTPRINT

At least one European study concluded that EVs emit less GHG than ICEs, no matter the source of electricity at the power plant. For instance, even when considering the most carbon-intensive electricity, an EV emits less GHG than a diesel-powered vehicle. As regions move to more renewable sources of electricity — and as battery technology improves — the environmental performance of EVs will increase and add greater environmental benefits.

TRENDING CLEANER

Adding to the environmental value proposition of EVs is their trend of increased efficiency. Between 2003 -2013, EVs achieved marked decreases in numerous emissions, including CO_2 (-15%), SO_2 (-70%) and NOx (-50%). While these numbers vary across regions, reductions are occurring throughout the U.S. and will continue as renewable sources of energy displace coal in the generation of electricity, resulting in even greater environmental benefits of EVs.

While higher fuel economy requirements are producing a commensurate decrease of emissions from ICEs, technological advances in EV efficiency are keeping pace (if not running ahead). For instance, between 2015 and 2025, one study estimates that GWP will drop 22% for ICEs and 26% for EVs. (See Source No. 4)

GOVERNMENT INTERVENTION

Government policy can stimulate additional environmental benefits associated with EVs. At least one study pointed out numerous areas where government intervention would produce greater EV adoption and thus environmental benefits (See Source No. 2):

- **INCREASE RENEWABLE ELECTRICITY GENERATION AND LOWER POWER PLANT EMISSIONS:** As noted above, transitioning the generation of electricity from coal to renewables would produce dramatic reductions in global warming emissions from EVs. If this renewable mix reaches 80% of the power supply by 2050, the resulting emissions from EVs would drop 60% from today's levels, comparable to an ICE that achieves more than 300 mpg. The EPA's Clean Power Plan includes a goal of lowering carbon emissions from electricity generation by 32%between 2005-2030.
- **INVEST IN BATTERY TECHNOLOGY:** With EV batteries producing the most profound environmental impacts, congressional funding of battery research programs yields significant environmental improvements, as evidenced by several previous programs that helped reduce battery costs from $1,000 per kWh in 2007 to $300 per kWh by 2014.
- **IMPROVE EV ACCESSIBILITY:** One study urged Congress to preserve the $7,500 federal EV tax credit for EV purchases while reinstating a previous tax incentive that funded EV infrastructure development, including funding partnerships for more charging stations. (See Source No. 2) Such efforts spur adoption and reduce carbon emissions.

GRID IMPACT

EVs provide ancillary benefits to the grid, including voltage and frequency regulation, as well as peak power leveraging and reactive power support that enhances operational efficiency, secures the electric grid and reduces power system operating costs.

Under scrutiny:

Electric Vehicle Benefits

There is much uncertainty in assessing the environmental benefits and impact of EVs. **Even beyond the lifecycle stages—production, driving, disposal, recycling—myriad factors impact GHG emissions, including:**

1. **The size of the EV**
2. **Lifetime mileage of the EV**
3. **Electricity generation mix**
4. **Type of ICE (gasoline vs diesel)**

While GHG emissions tied to the production of EVs are 1.3-2 times higher than for ICEs, the figure can rise even higher and depends on driving efficiency and the electricity generation source.

SHIFTING POLLUTANTS

Much of the literature noted that EVs emit far less CO2 than their ICE counterparts, a phenomenon irrespective of the electricity source. However, the makeup of the electric grid plays a role in the release of other gaseous pollutants and particulates. For instance, in China, even with an electric grid mostly powered by coal, EVs decrease CO_2 emissions by 20% compared to ICEs. However, in the same study, emissions of PM10, PM2.5+, NOx, and SO_2 emissions increased 360%, 250%, 120% and 370%, respectively. (See Source No. 19)

As noted above, geography plays a critical role in assessing the environmental impact of EVs, as traffic-related air pollution shifts from the road (generally densely populated, urban areas) to electricity generation stations (generally in rural areas). And the source of electricity in these stations plays an additional role.

When viewed in the context of the current electricity mix in the U.S., the use of EVs in regions where electricity is generated by coal, lignite or heavy oil combustion is "counterproductive." (See Source No. 6, pg. 9, Par. 1 line 4) (Note: The use of coal and natural gas dominate the current U.S. mix, comprising nearly 70%). In these cases, increasing the fuel efficiency of ICEs could produce a more significant reduction in greenhouse gas emissions.

REEXAMINING EMISSIONS

As the lifecycle phases of an EV exhibit highly divergent emission patterns, it's imprecise to merely cite the driving phase when it comes to GHG emission reductions. As noted, during this phase, pollution shifts from the road to electricity generation station, which are often distant from where the vehicles operate.

In fact, 91% of the resulting pollution shifts to a state other than where the EV operates, whereas only 18% of the pollution emitted from ICEs discharges in other states.

(See Source No. 2, pg. 19)

Additionally, while the electricity mix plays a role in emissions, the time of day when one charges an EV also impacts emissions. A Belgian study revealed that daytime charging, when demand is highest, "has a significant impact" producing increased emissions. (See Source No. 9, pg. 3443)

ENVIRONMENTAL IMPACT

"[T]he ultimate environmental … reality of electric vehicles is far more complicated than their promise," one study concluded. (See Source No. 4, pg. 1) One must look at location to gain an accurate view of the comparable environmental impact of EVs vs ICEs.

For instance, in Los Angeles, the carbon emissions from ICEs is much larger than that for EVS, a result of the dense population and electricity generated from the Western power grid. However, the reverse occurs in the Midwest, where lower population densities incur fewer overall ICE-related damages, and coal-fired electricity generation produces greater EV damages. In the latter case, the environmental benefit of an EV is negative and is almost equal to the damages from a comparable ICE. Furthermore, in New York and Chicago, where the environmental damage from gasoline vehicles is heavy, the environmental benefits from EVs remain minimal or even negative, due to the source of electricity generation.

"The bottom line is that the economic and environmental rationales for subsidizing [EV]s do not withstand scrutiny," one study concluded, noting that while EVs emit less CO_2 than ICEs, the amount is below 1% of the total forecast of U.S. CO_2 emissions, and that when one considers the resulting increased emission of air pollutants — SOx, NOx and particulates — with the current mix of electric generation, EVs "will have no measurable impact on climate and hence, no economic value." (See Source No. 7, pg. 26)

HEALTH

One study looked at the current European electricity mix and concluded that while EVs offer a 10% to 24% reduction in GWP compared to ICEs assuming a lifetime of 93,000 miles, supply chains involved in EV production "exhibit the potential for significant increases in human toxicity, freshwater eco-toxicity, firewater eutrophication, and metal depletion impacts …" (See Source No. 6, pg. 1)

The increases are in part attributed to the toxic emissions that occur during the extraction of copper and nickel and their associated sulphidic mine tailings. Additionally, where electricity relies on coal, coal mining impacts human toxicity.

SUBSIDIES

While governmental intervention can enhance the efficiency of EVs, one study argued that EV subsidies are discriminatory. (See Source No. 7) Citing 38 states, the District of Columbia, and the federal government as offering either direct or indirect EV subsidies, the study said that such efforts benefit the rich at the expense of the poor, who are unable to afford purchasing EVs but still must assume costs that support its infrastructure. That same study found a negligible economic benefit for EVs, further concluding that "there is no economic basis for the billions of dollars spent subsidizing their adoption."

Production

As noted above, environmental emissions for EVs during the production phase are up to twice that for comparable ICEs. This section delves into a deeper discussion of that disparity, especially focusing on battery production.

Production is responsible for nearly half of an EV's lifetime GWP, owing to the energy requirements for raw material extraction and processing as well as the manufacture of its batteries.

The environmental impact of battery production depends on location and the electricity used. For instance, Li-ion battery production primarily occurs in China, South Korea and Japan, whose electricity mix is generally carbon-intensive. Transitioning to lower carbon energy during this phase would lower GHG emissions.

In one study looking at the production of lithium-ion batteries in China, the GHG emissions were roughly 30% higher than those for comparable ICEs. (See Source No. 27) The main factors for these emissions derive from the production of cathode materials and rough aluminum, collectively making up nearly 75% of total emissions. Cathode production in particular requires significant energy to manufacture, due to impacts associated with materials extraction and processing, along with energy use. The study concluded that improving cathode production offered the greatest opportunities for decreasing GHG emissions.

Other studies estimate that battery production is responsible for between 10% to 70% of GHG emissions, with cell manufacturing and battery assembly accounting for between 3% and 80% of total battery emissions during the production phase.

The key phases of battery production that emit the most GHG are electrode drying and the operation of drying rooms during cell manufacture.

Finally, battery materials impact the environment in different ways. Batteries that use large amounts of aluminum $LiMnO2$ and $LiFePO4$, for instance, have a greater impact on ozone depletion.

About ICEs

Some of the literature shifted their focus to ICEs, assessing those factors that would produce the desired economic benefit.

One study maintained that in light of "stringent emissions standards" and low-sulfur gasoline, ICEs "emit very little pollution, and they will emit even less in the future." (See Source No. 7, pg. 26) By 2035, another study concluded, advanced powertrains, coupled with low carbon intensity of future fuels (assuming that the U.S. continued developing clean fuels) could contribute to a substantial reduction in GHG emissions
for ICEs.

Hypothetically, a densely populated urban area would see an improvement in air quality if EVs replaced all existing ICEs, but similar air quality improvements could be realized by replacing existing ICEs with new ICEs, whose efficiencies emit less pollution than older vehicles.

And depending on where electric-generating plants discharge pollution, the air quality in urban areas could actually decrease by introducing additional EVs.

Summary

The recurring theme in much of the literature focused on variables — that is, EVs can benefit the environment if x, y and z are present. But then, only if a, b and c are not. And so on.

Understanding these complex relationships, there was no consensus break-even set of conditions that need to occur in order to realize the environmental benefits that the public attributes to the adoption of EVs.

If there were widespread adoption of EVs and a built out EV infrastructure and electricity generated from renewables and so on … then assuredly, EVs would deliver significant environmental benefits. But the reality is far more complex, with innumerable variables that impact carbon emissions. As such, it seems that any accurate analysis is a snapshot in both time and place, whose unique circumstances may not offer any more widespread implications.

Sources

1. Rachael Nealer, David Reichmuth & Don Anair, "Cleaner Cars from Cradle to Grave." *Union of Concerned Scientists* (November 2015.)
2. Stephen Holland, Erin Mansur, Nicholas Muller & Andrew Yates, "Environmental Benefits from Driving Electric Vehicles?" NBER (June 2015).
3. Tien Nguyen, Jake Ward & Kristen Johnson, "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles." *Office of Bionergy Technologies, Fuel Cell Technologies & Vehicle Technologies* (May 2013).
4. Arthur D Little, "Battery Electric Vehicles vs. Internal Combustion Engine Vehicles." *Arthur D Little* (November 29, 2016).
5. M. Alexander, "Environmental Assessment of a Full Electric Transportation Portfolio." *Electric Power Research Institute* (September 2015).
6. Troy R. Hawkins, et. al., "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles." *Journal of Industrial Ecology* (October 2012).
7. Jonathan A. Lesser, "Short Circuit: The High Cost of Electric Vehicle Subsidies." *Manhattan Institute* (May 2018).
8. Dale Hall and Nic Lutsey, "Effects of Battery Manufacturing on Electric Vehicle Life-cycle Greenhouse Gas Emissions." *ResearchGate* (February 2018).
9. Joeri Van Mierloa,"Comparative Environmental Assessment of Alternative Fueled Vehicles Using a Life Cycle Assessment." Sciencedirect.com (June 2017).
10. Transport & Environment, "Electric Vehicle Life Cycle Analysis and Raw Material Availability." Transportenvironment.org (October 2017).
11. EPA's Office of Pollution Prevention and Toxics and EPA's Office of Research and Development, "Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles." United States Environmental Protection Agency (April 2013).
12. Jana Patterson, "Understanding the Life Cycle GHG Emissions for Different Vehicle Types and Powertrain Technologies." *Low Carbon Vehicle Partnership* (August 2018).
13. Amgad Elgowainy et. al., "Cost of Ownership and Well-to-Wheels Carbon Emissions/ Oil Use of Alternative Fuels and Advanced Light-duty Vehicle Technologies." Sciencedirect.com (October 5, 2013).

14. Amgad Elgowainy et. al., “Current and Future United States Light-Duty Vehicle Pathways: Cradle-to-Grave Lifecycle Greenhouse Gas Emissions and Economic Assessment.” *Environmental Science & Technology* (2018).

15. Amgad Elgowainy et. al., “Cradle-to-Grave Lifecycle Analysis of U.S. Light Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025-2030) Technologies.” *Argonne National Laboratory* (2016).

16. Jennifer B. Dunn, Linda Gaines, Jarod C. Kelly & Kevin G. Gallagher, “Life Cycle Analysis Summary for Automotive Lithium-Ion Battery Product.” *The Minerals, Metals & Materials Society* (2016).

17. J. B. Dunn et. al., “The Significance of Li-ion Batteries in Electric Vehicle Life-cycle Energy and Emissions and Recycling's Role in its Reduction.” *RSC Publishing* (December 17, 2014).

18. European Environment Agency, “Electric Vehicles From Life Cycle and Circular Economy Perspectives.” *European Environment Agency* (November 9, 2018).

19. Weeberb J.Requia et. al., “How Clean Are Electric Vehicles? Evidence-based Review of the Effects of Electric Mobility on Air Pollutants, Greenhouse Gas Emissions and Human Health.” *Elsevier* (May 1, 2018).

20. L. Gaines and J. Sullivan, “How Green is Battery Recycling?” Argonne National Laboratory (undated).

21. Max Grünig, Marc Witte, Dominic Marcellino et. al. “An Overview of Electric Vehicles on the Market and in Development.” *Ecologic Institute* (April 2011).

22. Linda Gaines and Jennifer Dunn, “Lithium-ion Battery Production and Recycling Materials Issues.” *Argonne National Laboratory* (June 9, 2015).

23. Ingrid Malmgren, “Quantifying the Societal Benefits of Electric Vehicles.” MDPI (December 30, 2016).

24. Francis Mwasilu et. al., “Electric Vehicles and Smart Grid Interaction: A Review on Vehicle to Grid and Renewable Energy Sources Interaction.” *Elsevier* (April 3, 2014).

25. Salman Habib, Muhammad Kamran & Umar Rashid, “Impact Analysis of Vehicle-to-Grid Technology and Charging Strategies of Electric Vehicles on Distribution Networks - A Review.” *Journal of Power Sources* (December 4, 2014).

26. Qinyu Qiao et. al., “Comparative Study on Life Cycle CO2 Emissions from the Production of Electric and Conventional Vehicles in China.” *MDPI* (June 2017).

27. Han Hao et. al., “GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China.” *MDPI* (April 4, 2017).

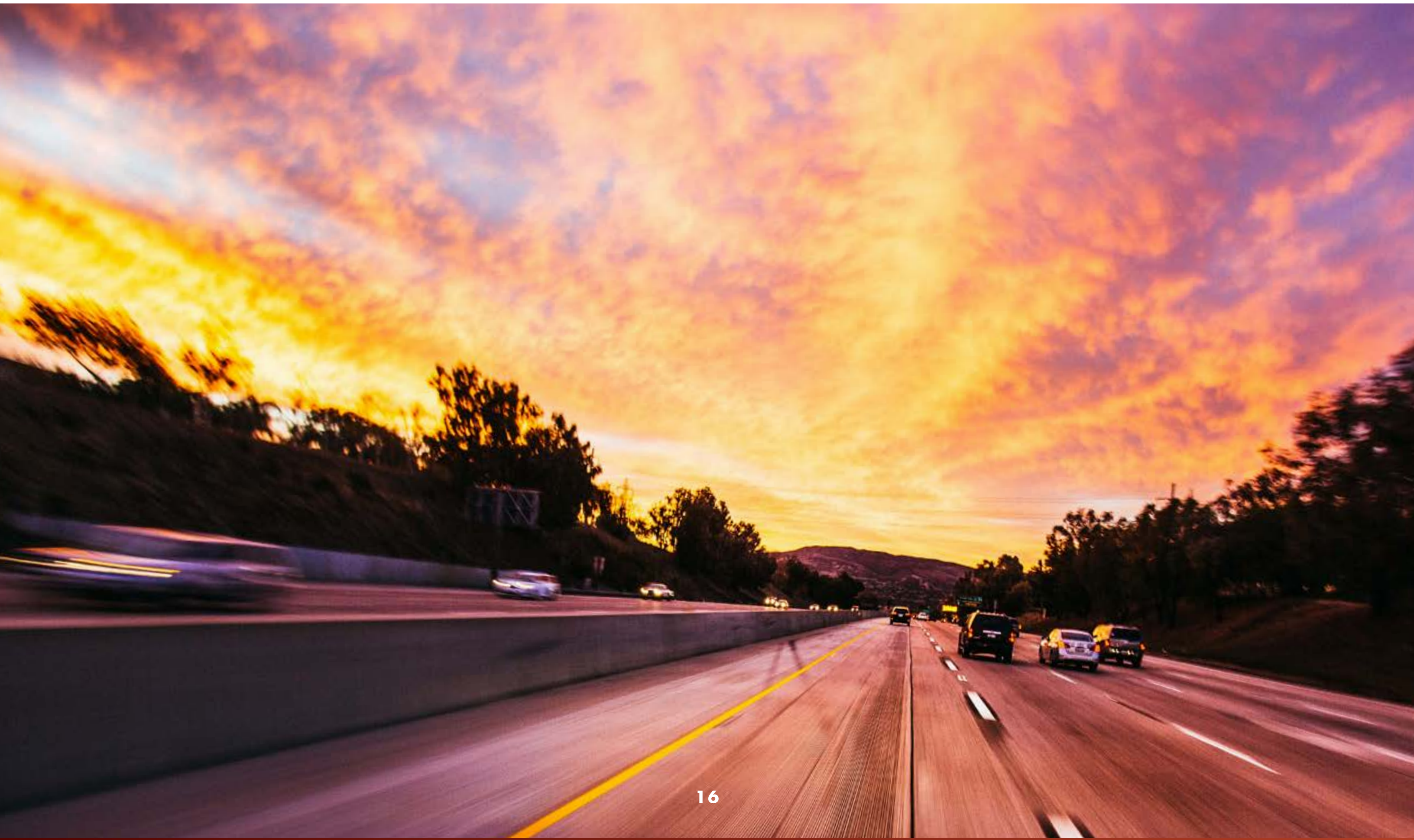
28. John Kingston, “Hydrogen, Not Batteries, Seen as the Fuel for Carbon-free Trucking in the Long Run.” Amp.freightwaves.com (March 12, 2019).

29. Jonathan A. Lesser, “Short Circuit: The High Cost of Electric Vehicle Subsidies.” *Manhattan Institute* (May 14, 2018).

30. Linda Ellingsen & Christine Hung, Christine, “Research for TRAN Committee - Battery-Powered Electric Vehicles: Market Development and Lifecycle Emissions.” *European Parliament, Policy Department for Structural and Cohesion Policies*, Brussels (2018).

31. Linda Ager-Wick Ellingsen, “The Size and Range Effect: Lifecycle Greenhouse Gas Emissions of Electric Vehicles.” *IOP Publishing Ltd.* (May 6, 2016).

32. Jack Stewart, “Look Here: Even More Evidence That Electric Cars Could Save the Planet.” *WIRED* (March 15, 2018).



About the Fuels Institute

The Fuels Institute, founded by NACS in 2013, is a 501(c)(4) non-profit research-oriented think tank dedicated to evaluating the market issues related to vehicles and the fuels that power them. By bringing together diverse stakeholders of the transportation and fuels markets, the Institute helps to identify opportunities and challenges associated with new technologies and to facilitate industry coordination to help ensure that consumers derive the greatest benefit.

The Fuels Institute commissions and publishes comprehensive, fact-based research projects that address the interests of the affected stakeholders. Such publications will help to inform both business owners considering long-term investment decisions and policymakers considering legislation and regulations affecting the market. Research is independent and unbiased, designed to answer questions, not advocate a specific outcome. Participants in the Fuels Institute are dedicated to promoting facts and providing decision makers with the most credible information possible, so that the market can deliver the best in vehicle and fueling options to the consumer.

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NACS

The Fuels Institute was founded in 2013 by NACS, the international association that advances convenience and fuel retailing. Through recurring financial contributions and daily operational support, NACS helps the Fuels Institute to invest in and carry out its work to foster collaboration among the various stakeholders with interests in the transportation energy market and to promote a comprehensive and objective evaluation of issues affecting that market and its customers both today and in the future.

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