Life Cycle Analysis Comparison: Understanding the Research

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About the Fuels Institute

Founded in 2013 by NACS.

• A **not-for-profit, non-advocacy research organization** studying transportation energy.

• Considers “fuel” to be any type of **energy** being used to power a vehicle.

• Publishes **peer-reviewed, fact-based research designed to answer questions, not advocate any specific outcome**.

• An extremely **diverse organization in the fuels and vehicles markets**, ensuring broad perspective guides our research.

• Our partners are dedicated to promoting facts and providing decision makers with the most credible information possible, so the market can deliver the best vehicle and fuel options to consumers. This **collaborative, non-advocacy approach ensures our products are both objective and reliable**.
Disclaimer: The opinions and views expressed herein do not necessarily state or reflect those of the individuals on the Fuels Institute Board of Directors and the Fuels Institute Board of Advisors, or any contributing organization to the Fuels Institute. They are exclusively those of the speaker.
Overview:

The Fuels Institute commissioned Ricardo Strategic Consulting to evaluate and compare the lifecycle environmental impact of electric (EV) and internal combustion engine vehicles (ICEV), the energy sources that power them and the economic impact of each on consumers.

The purpose was to inform stakeholders about opportunities to improve the environmental performance of both vehicle systems while delivering to end users the most cost-effective means of transportation.
100+ years of delivering excellence to help our clients define the future

A global, multi-industry, multi-discipline consultancy and niche manufacture of high performance products.

The objective throughout our history has been to maximize efficiency and eliminate waste in everything we do.
Products and services

Technical Consulting
- Automotive systems
- Rail consulting
- Environmental consulting
- Strategic consulting
- Independent assurance

Performance Products
- Niche manufacturing
- Computer-aided engineering software
- Software simulation
Cross sector and cross functional performance enhancement

Assurance and certification
Energy consulting
Engines
Environmental consulting

Hybrid & electrical vehicles
Knowledge and training
Niche manufacturing
Software

Strategic consulting
Testing
Transmissions & drivelines
Vehicle engineering
Even ambitious EV forecasts have slow effect

Even if PEVs reach 60% sales in 2040, they will only represent 27% of LDVs on the road. IHSMarkit predicts 18.1 million PEVs in operation by 2030, which is only 5.9% of the 307 million vehicles on the road in 2030.
The Components of the Life Cycle Analysis

Study evaluates every component of the life cycle of a vehicle and its respective fuel/energy.

Vehicle Life Cycle

- **Well-to-Wheel (WTW) Analysis**: Analysis on the production of fuels and electricity, and operational emissions.
- **Vehicle cycle “Embedded” emissions**: Result from vehicle manufacturing, maintenance and end-of-life (EoL) disposal.
- **Fuel & Electricity Production**: Assessment of (Well-to-Tank [WT]) environmental impact of producing the energy vector(s) from a primary energy source, generation plants, through to distribution point.
- **Vehicle Production**: Assessment of “Cradle-to-Gate” environmental impact of producing the vehicle, including extract of raw materials, processing, component manufacture, logistics, vehicle assembly and painting.
- **Use/Operation**: Environmental impact of driving (Tank-to-Wheels [TTW] emissions) and impact from maintenance and servicing.
- **End-of-Life**: Adds assessment of environmental impact of “end of life” scenario (i.e., “to-Grave”). Can include: re-using or re-purposing components, recycling materials, energy recovery and disposal to landfill.

The whole vehicle life cycle includes embedded emissions from vehicle production, maintenance and servicing, and end-of-life activities, and WTW (WT + TT) emissions from fuels and electricity.
Literature Review - Methodology

Literature review to determine common assumptions to be validated through the Argonne GREET Model

Understanding LCA Studies – “Guidance Framework” Overview

1. Study Subject & Functional Unit
   - What product system was studied?
   - What was the functional unit?

2. System Boundary
   - What was included in the analysis? And what was excluded?

3. Study Type (e.g. Academic / Policy / EPD)

4. Approaches
   - Vehicle Production: Assessment of environmental impact producing the vehicle (burning source to distribution)
   - Use: Tailpipe CO₂, main driving impact from maintenance and servicing
   - End-of-Life: Assessment of environmental impact “end of life” scenarios, recycling, end of life)

5. Geography
   - Inputs, Assumptions & Outputs

6. Inputs Data
   - Primary vs. Secondary data
   - Who provided the input data? What was provided?

Key Assumptions
- Vehicle duty cycle
- Lifetime Mileage [km]
- Electricity carbon intensity [kgCO₂/kWh]
- Battery embedded carbon factor [kgCO₂/kWh or kgCO₂/kg], etc.

LCA Datasets
- Life Cycle Inventories (LCI)

Environmental Impact Factors
- Global Warming Potential (GWP) [tCO₂e]
- Human Toxicity, etc.

Time Horizon
- Model Year (current / historic / future)
- Vehicle Lifetime
- Allowance for temporal effects, etc.

Rest of World – 15 papers
Some papers considered >1 geographical region

Literature Review Dashboard
- 130+ papers & reports identified
- 15+ Literature Searches completed
- In addition 30 News Articles and ~20 OEM and Supplier Sustainability & Environmental reports also identified
LCA - Methodology

Leveraged the open source, highly credible GREET Model to run the life cycle analyses. Used literature review to determine common assumptions and create the sensitivity scenarios to model.

• Material Extraction
• Manufacturing and Assembly
• Operation Cycle
• Vehicle After Life Management
• Sensitivity Analysis:
  • Lifetime miles
  • Grid carbon intensity
  • Ambient temperature
  • Driver behavior
  • Vehicle weight
  • Battery chemistry
  • Battery density
  • Biofuels blends
High Level Summary – LCA Comparison

Mileage and carbon intensity of grid influence LCA, but in most cases BEVs emit less carbon

-28.8%

-40.9%

Sensitivities Studied
- Lifetime miles
- Grid carbon intensity
- Ambient temperature
- Driver behavior
- Vehicle weight
- Battery chemistry
- Battery density
- Biofuels blends

Cradle to Grave Definitions
- Vehicle Production: Material Sourcing + Manufacture
- Well to Tank: Energy Production
- Tank to Wheel: Use of Energy
- End of Life: Disposal/Recycling

Tons of greenhouse gas emissions

200,000 miles
(average USA electricity mix)
All vehicles are subject to external factors.

Impact of External Variables on Life Time Carbon Emissions

- 100,000 Miles
- Low Carbon Grid
- High Carbon Grid
- Extremely High Carbon Grid
- 10 Degrees Colder
- 20 Degrees Colder
- Aggressive Driving
- Very Aggressive Driving

Source: Ricardo Consulting
Emissions come from different stages of life

Reducing carbon from EVs and ICEVs requires different points of focus

- 73% of emissions from vehicle operation
- 72% of emissions from electricity generation
- Emissions from material sourcing and manufacture for EVs is 2x that of ICEVs

**200,000 miles**
(average USA electricity mix)
Focus on electricity generation

Reducing carbon from EVs and ICEVs requires different points of focus

73% of emissions from vehicle operation

72% of emissions from electricity generation

Emissions from material sourcing and manufacture for EVs is 2x that of ICEVs

200,000 miles
(average USA electricity mix)
Electric Grid Sensitivities

Current Electricity Mix in the USA (%)

<table>
<thead>
<tr>
<th></th>
<th>US National Average</th>
<th>Michigan</th>
<th>Maine</th>
<th>West Virginia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>40</td>
<td>33</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>Nuclear</td>
<td>20</td>
<td>29</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Coal</td>
<td>19</td>
<td>27</td>
<td>1</td>
<td>89</td>
</tr>
<tr>
<td>Wind</td>
<td>8</td>
<td>7</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>Hydro</td>
<td>7</td>
<td>-</td>
<td>34</td>
<td>3</td>
</tr>
<tr>
<td>Solar</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Biomass</td>
<td>1</td>
<td>2</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Oil</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>1</td>
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<tr>
<td>Geothermal</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Other Fossil</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>
How do we strategically deploy solutions?

Not all markets are created equal – deployment of decarbonization strategies should take into consideration regional, market and duty-cycle variations to maximize carbon reduction as quickly and affordably as possible.

Life Cycle Emissions
(Grid Carbon Intensity Scenarios)

-37%
Focus on decarbonizing liquid fuels

73% of emissions from vehicle operation

72% of emissions from electricity generation

Emissions from material sourcing and manufacture for EVs is 2x that of ICEVs

200,000 miles
(average USA electricity mix)
How to reduce carbon intensity of fuels?

Biofuels offer great opportunity to provide lower carbon fuel options for ICEVs

Estimated Carbon Intensity
(grams of CO2 per mega Joule of energy produced)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>2020</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA Gasoline</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>CNG</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Starch Ethanol</td>
<td>71</td>
<td>45</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>CNG/LNG from Landfill</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Biomass-Based Diesel</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cellulosic Ethanol</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Electricity</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

Source: Ricardo Consulting
Biofuel blend levels create a challenge

Life cycle impact of low-CI fuels is modest due to blend ratio and because fuel consumption represents only part of the cradle to grave emissions of a vehicle.

Effect of Biofuels on ICEV Life Cycle Emissions

- E10: 65 tons, 48% to Wheels, 12% Well to Tank, 4% Manufacture, 4% Material Sourcing
- E15: 64 tons, 47% to Wheels, 12% Well to Tank, 4% Manufacture, 4% Material Sourcing
- E15 Cellulosic: 58 tons, 42% to Wheels, 11% Well to Tank, 4% Manufacture, 4% Material Sourcing
- Diesel: 69 tons, 54% to Wheels, 10% Well to Tank, 4% Manufacture, 4% Material Sourcing
- B20: 59 tons, 42% to Wheels, 12% Well to Tank, 4% Manufacture, 4% Material Sourcing
- RD100: 41 tons, 29% to Wheels, 7% Well to Tank, 4% Manufacture, 4% Material Sourcing

Source: Ricardo Consulting
How we drive affects affordability

- Degradation is often not included in LCA models
- OEMs typically assume replacement of battery below 70% capacity
  - 30% degradation after 1,700 – 2,100 charging cycles
  - Contemporary BEVs require 800 to 1,000 charge cycles for a 200,000-mile (based upon estimated vehicle range)
- Ricardo estimates 1 – 2.4 sets of battery packs over vehicle lifetime

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Lithium Manganese Oxide 24kWhr</th>
<th>Lithium Iron Phosphate 24kWhr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumption Wh/km</td>
<td>Light 105</td>
<td>Moderate 178</td>
</tr>
<tr>
<td></td>
<td>Light 114</td>
<td>Moderate 187</td>
</tr>
<tr>
<td>Driving Range (new battery)</td>
<td>Light 229</td>
<td>Moderate 135</td>
</tr>
<tr>
<td></td>
<td>Light 211</td>
<td>Moderate 128</td>
</tr>
<tr>
<td>Driving Range (EOL battery – 70% capacity)</td>
<td>Light 160</td>
<td>Moderate 94</td>
</tr>
<tr>
<td></td>
<td>Light 147</td>
<td>Moderate 90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Lithium Manganese Oxide</th>
<th>Lithium Iron Phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Energy Transferred (kWhr)</td>
<td>Light 18.905</td>
<td>Moderate 17.896</td>
</tr>
<tr>
<td></td>
<td>Light 24.572</td>
<td>Moderate 23.260</td>
</tr>
<tr>
<td>Total Distance Traveled (km)</td>
<td>Light 180,047</td>
<td>Moderate 100,541</td>
</tr>
<tr>
<td></td>
<td>Light 214,703</td>
<td>Moderate 124,086</td>
</tr>
<tr>
<td>Use Cycles</td>
<td>Light 1555</td>
<td>Moderate 1472</td>
</tr>
<tr>
<td></td>
<td>Light 2022</td>
<td>Moderate 1914</td>
</tr>
</tbody>
</table>

Number of batteries required (for 200k km life): 1.1, 2, 2.4, 1, 1.6, 2.
Even without tax credits, BEVs estimated to deliver lower total cost of ownership.

### 10-year TCO

<table>
<thead>
<tr>
<th></th>
<th>ICE Vehicle</th>
<th>HEV</th>
<th>BEV</th>
</tr>
</thead>
</table>
| **Capital Cost** | 27,044      | 31,232 | 35,758 | **Without tax credits/incentives**
| **Insurance Costs** | 13,434    | 14,653 | 15,971 |
| **Fuel Costs**    | 19,643      | 9,240 | 5,198 |
| **Maintenance & Repairs** | 21,459  | 19,618 | 18,229 |
| **Total**         | 81,581      | 74,743 | 75,157 |

The BEV TCO presented here represents a worst case scenario – no tax credits plus expense of battery replacement.
Key takeaways

- BEVs on average are less carbon intense, but exhibit more variability based upon different conditions
  - Recognizing optimal geographic deployment will enhance BEVs contributions to carbon mitigation
  - Ensuring consumers understand the impact of external factors on range and battery durability is essential
- The battery component of BEVs makes them much more carbon intense when they come off the line, but ICEVs lose their advantage when consuming energy
  - This means reducing the carbon intensity of liquid fuel can help bridge the gap between the technologies
- HEVs can contribute significantly to emissions reduction:
  - HEVs on average emit 29% less carbon than ICEV, but 17% more than BEVs
  - HEVs would benefit from lower carbon liquid fuels also
  - HEVs offer TCO advantage over ICE and BEVs when battery replacement is factored in.
- BEVs represent a lower total cost of ownership, even when factoring in battery replacement
  - Will consumers make that calculation? When cost parity at point of purchase is achieved, will consumers opt for the new tech?
- Driving behavior can significantly shorten expected useful life of a BEV battery
  - A very aggressive driver can lose 50% range per full charge and have to replace the BEV battery 2x during a 200,000 lifetime
Questions and Discussion

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