Critical Review and Meta-Analysis of Life Cycle Emissions in Automotive LCAs

GRPE Automotive LCA Informal Working Group

20th Session, February 5th 2025

Presented by: Kyle McGaughy, PhD
Co-authors: Andrew Beck, Abby Martell

ERG

Funding Acknowledgement

The U.S. Environmental Protection Agency, through its Office of Transportation and Air Quality (OTAQ), funded and conducted the research described herein under contract 68HE0C18C0001 and 68HERC24F0008. It has been subjected to review by OTAQ and approved for publication. Approval does not signify that the contents reflect the views of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Outline

- Background
- Review Methodology
- Intra-study Comparisons
- Key Methodology Review Findings
- LCA Recommendations
- Questions

Background

Background

- ERG supported EPA by preparing a summary and critical review of recent vehicle LCAs. ERG also outlined best practices for future vehicle LCAs based on the reviewed literature.
- Report available, peer-reviewed publication is currently under preparation
  - Kyle.McGaughy@erg.com
- Appropriate comparisons require: Similar scope, assumptions, and methodology
- For GHG emissions from vehicles: What is the general consensus of scientific literature, and what are best practices for future automotive LCAs?

Review Methodology

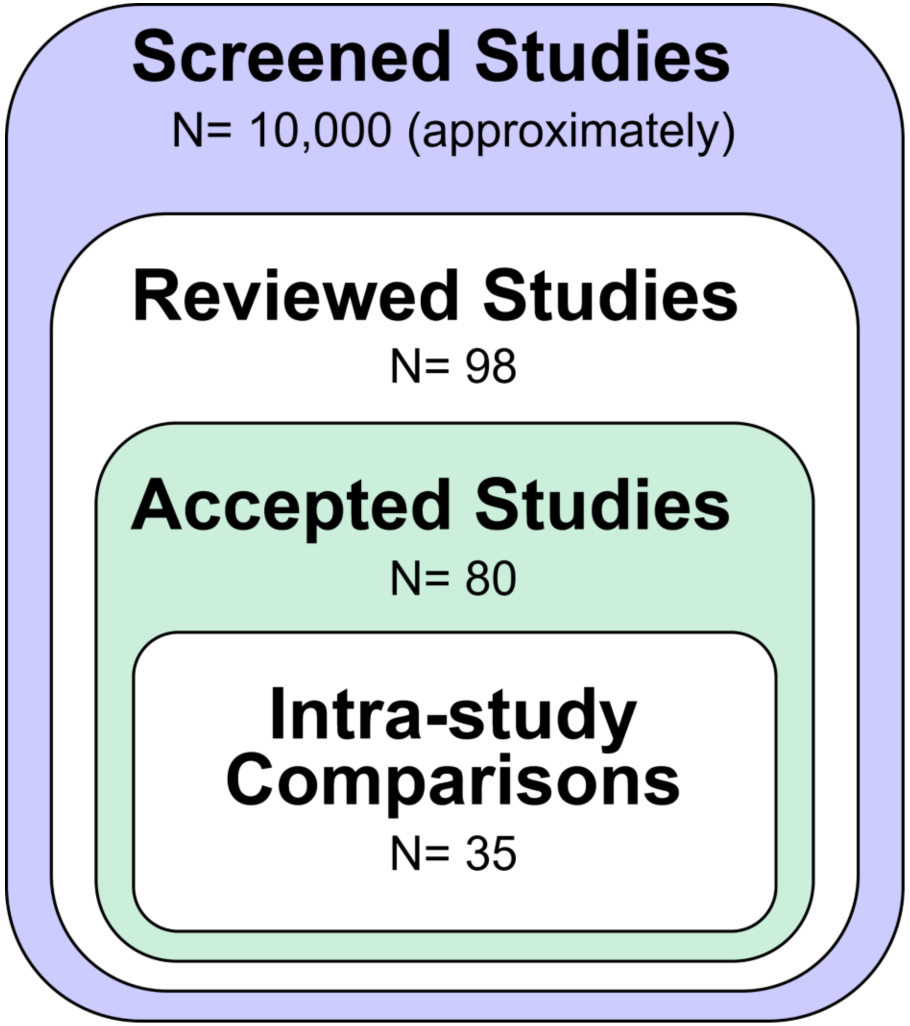
Literature Search Methodology

- Searched for passenger vehicle LCAs published 2019-Mid 2024
- This search was focused on scientific articles, but did include government reports and vehicle manufacturer white papers

<u>Search term examples</u>

Vehicle Technology	LCA Element	Emissions Type
Battery Electric Vehicle	Cradle-to-grave	Environment
Electric Vehicle	Manufacture	Greenhouse Gas
Plug-in Hybrid Electric Vehicle	Maintenance	Particulate Matter
Fuel Cell Electric Vehicle	Disposal	Ozone

Literature Acceptance Criteria

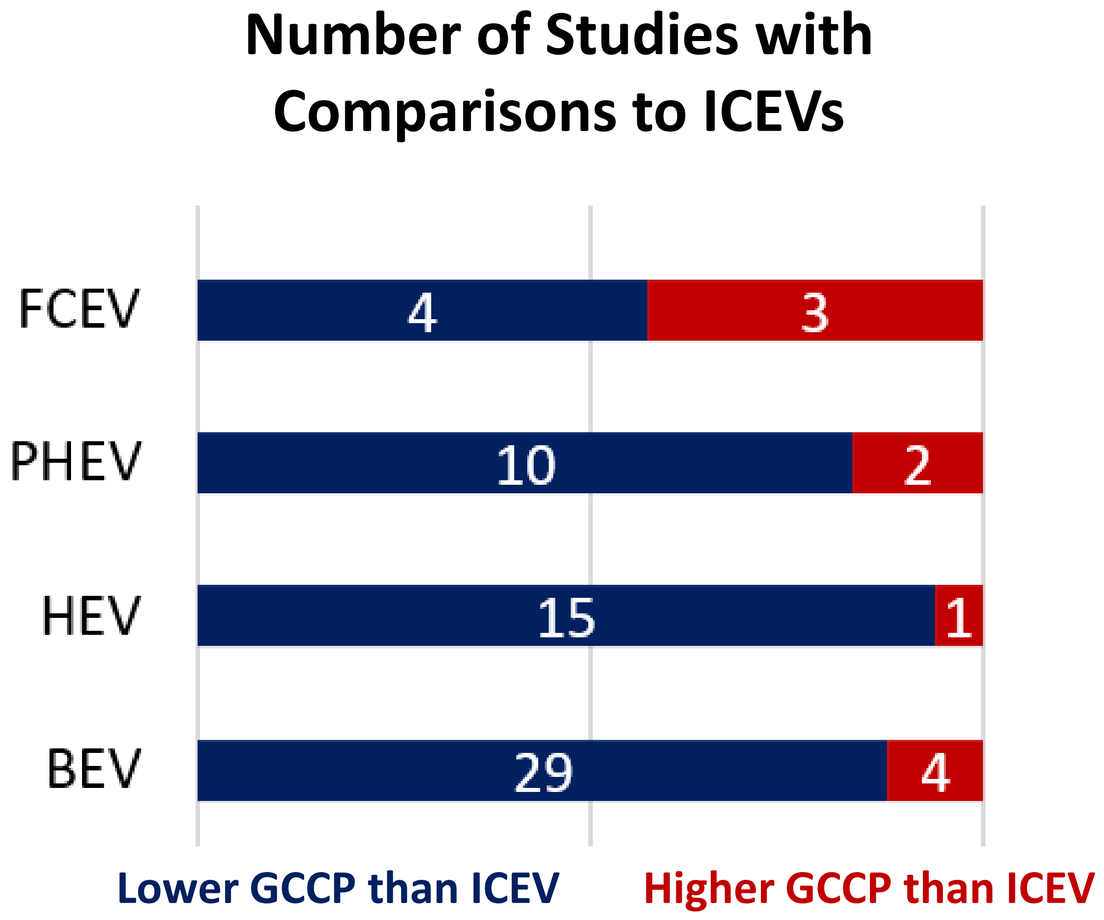


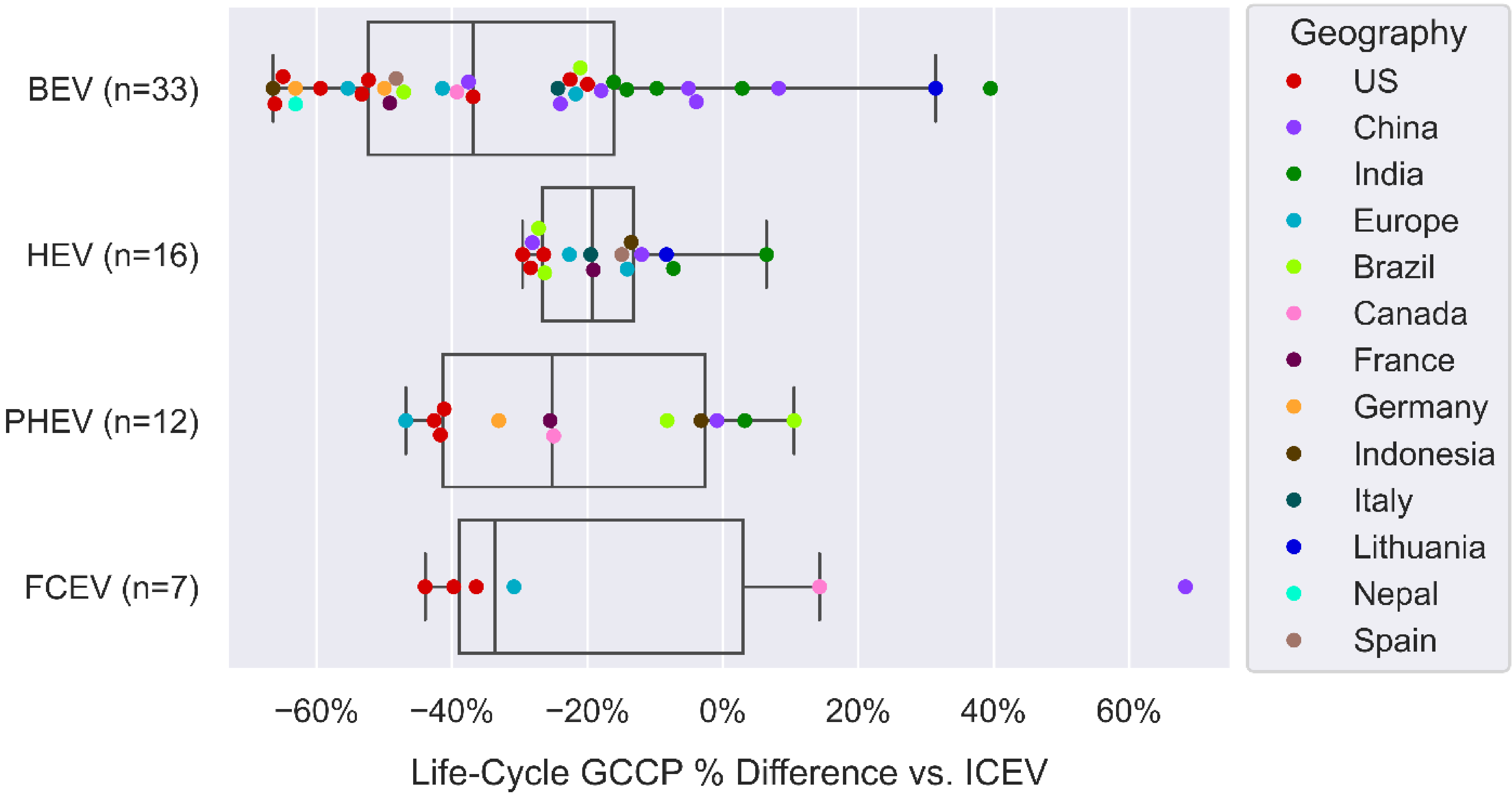
- 98 studies were fully reviewed and documented
  - Study scope (geography, year, vehicle type)
  - Key assumptions about life cycle stages
  - Availability of LCI
  - Peer-review
- 80 studies were accepted and used for developing best practice recommendations
  - Attributional LCA
  - Peer reviewed
  - Generally followed ISO-14040/14044 guidelines
- 35 Studies used for intra-study comparisons
  - Full life cycle scope
  - Multiple vehicle types

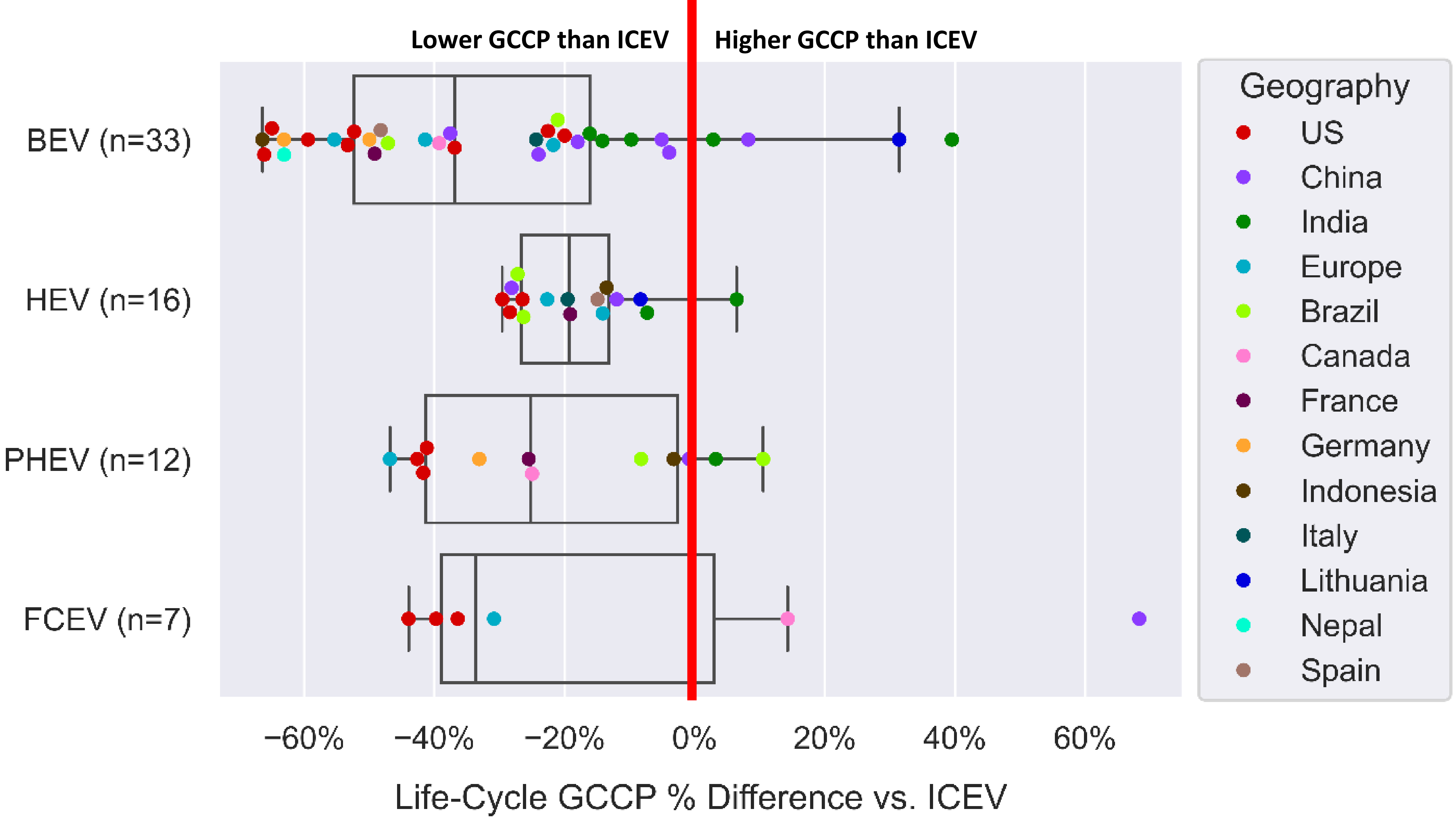
Intra-study Comparisons

Intra-study Comparisons (GHG Impacts)

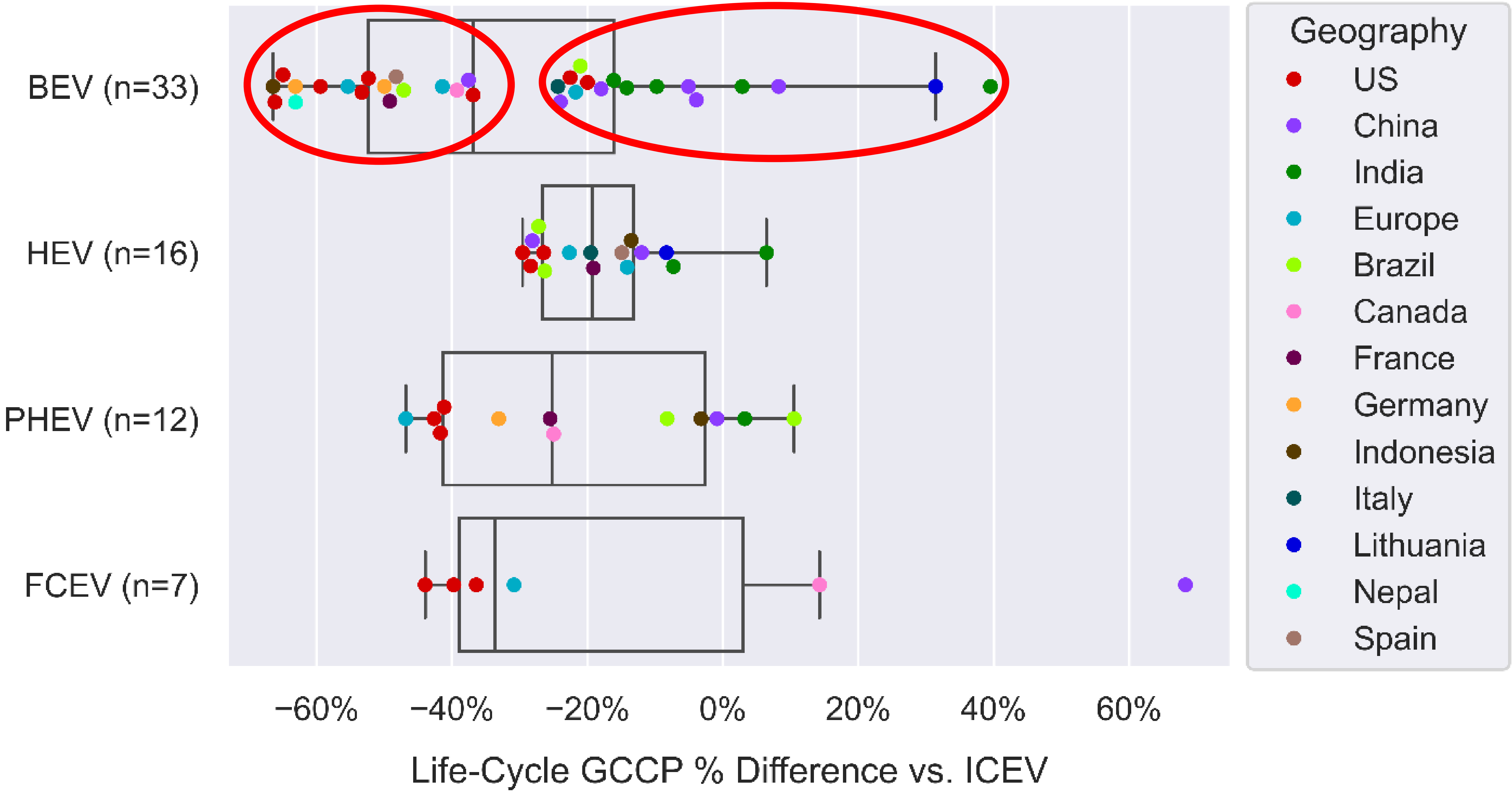
- Results were compiled based on global climate change potential (GCCP) impacts
  - gCO_2eq/km
- Intra-study comparisons only
- Alternative power trains generally had lower GCCP than ICEV
- Most studies included BEVs and ICEVs
- Fuel Cell, Hybrid, and Plug-in Hybrid vehicles were included less than often

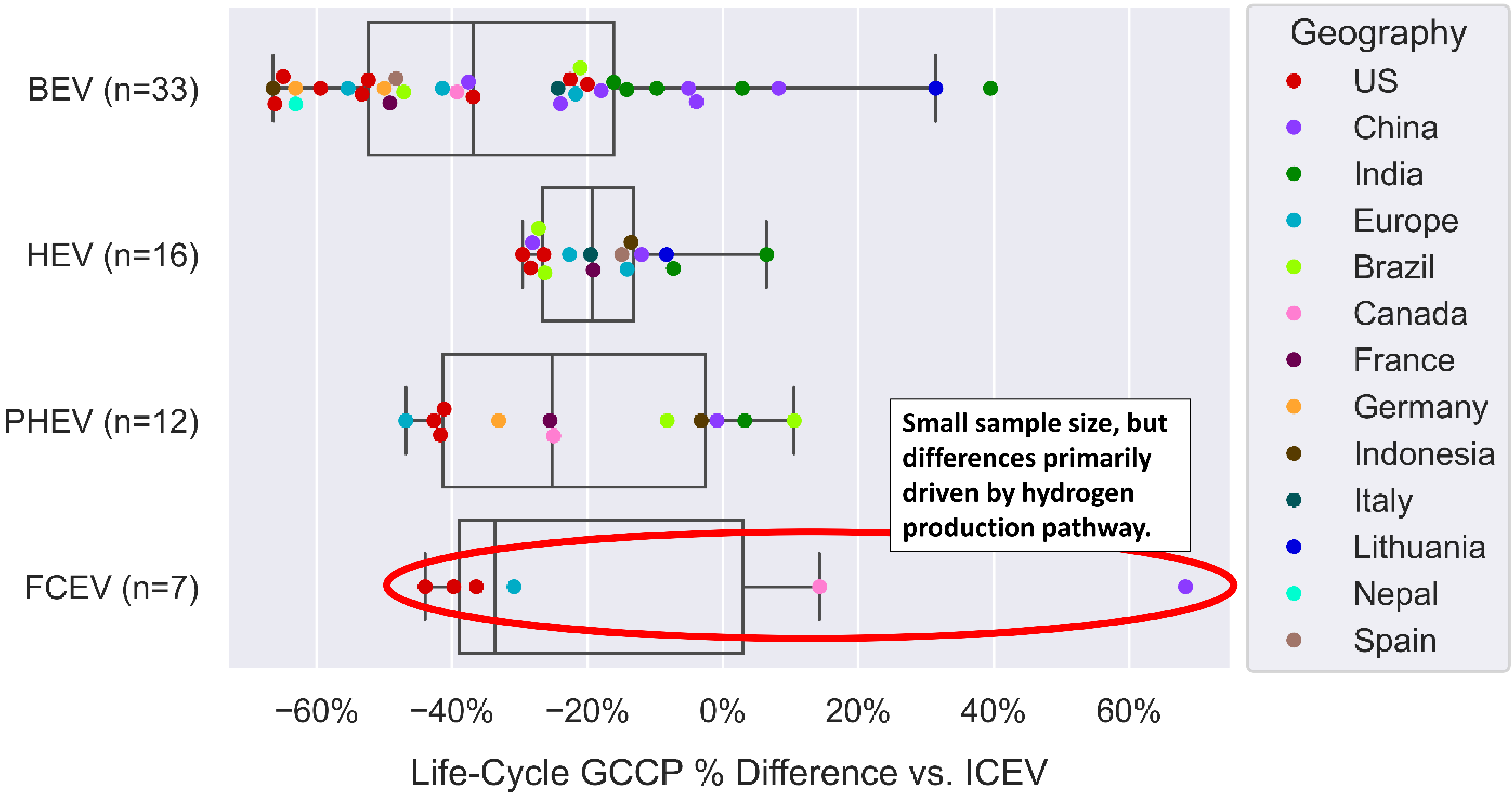



BEV (n=33)
HEV (n=16)
PHEV (n=12)
FCEV (n=7)
−60%
−40%
−20%
0%
20%
40%
60%
Life-Cycle GCCP % Difference vs. ICEV
Geography
US
China
India
Europe
Brazil
Canada
France
Germany
Indonesia
Italy
Lithuania
Nepal
Spain


Lower GCCP than ICEV
Higher GCCP than ICEV
BEV (n=33)
HEV (n=16)
PHEV (n=12)
FCEV (n=7)
−60%
−40%
−20%
0%
20%
40%
60%
Life-Cycle GCCP % Difference vs. ICEV
Geography
US
China
India
Europe
Brazil
Canada
France
Germany
Indonesia
Italy
Lithuania
Nepal
Spain

Differences primarily driven by electricity grid examined. Some difference due to battery materials.




BEV (n=33)
HEV (n=16)
PHEV (n=12)
FCEV (n=7)
Small sample size, but differences primarily driven by hydrogen production pathway.
Geography
US
China
India
Europe
Brazil
Canada
France
Germany
Indonesia
Italy
Lithuania
Nepal
Spain
−60%
−40%
−20%
0%
20%
40%
60%
Life-Cycle GCCP % Difference vs. ICEV

Life Cycle Stage Highlights

Life Cycle Stages

Number of Reviewed Studies that Included Each Life Cycle Stage

	Extraction & Refining	Part, Component, Module Mfct.	Vehicle Mfct.	On-road use	End-of-life
Extraction & Refining	61				
Part, Component, Module Mfct.	57	62			
Vehicle Mfct.	53	56	57		
On-road use	56	55	54	66	
End-of-life	46	49	47	48	50

Least Common — Color Scale — Most Common

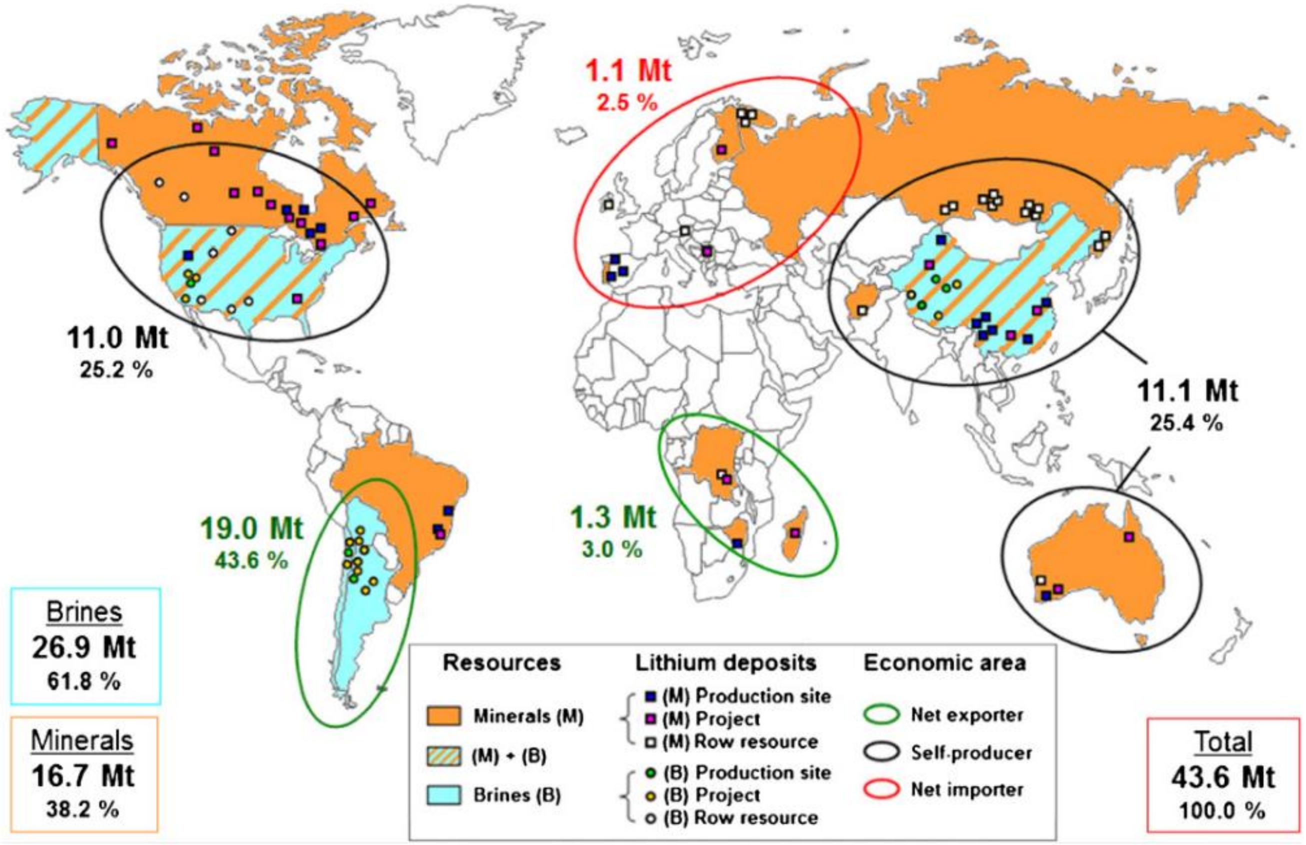
- Most studies were full life cycle
- Most common single-stage focus was on-road use
- Vehicle manufacturing and end-of-life were both excluded or not detailed in some studies (minority of studies overall)

Life Cycle Stage Highlights

- The most accurate life cycle assessments require very specific information about a vehicle’s supply chain
- This data is not always available or may not even be known and instead secondary data must be used
- These highlights are intended to show how secondary data sources must still be selected with care to best match the scope of the life cycle assessment
  - Scope: year, location, vehicle type

Highlights: Resource Extraction and Refining

- Lithium production impacts vary depending on country and process
  - Impurities can increase energy consumption
  - Range of 2.7-31.6 $kgCO_2eq/kg\ Li_2CO_3$
  - Water scarcity impacts were also examined
  - Schenker et al. 2022, Kelly et al. 2021
- Similar trends for other key resources for vehicles



Map of lithium resource availability (Grosjean et al. 2012)

Highlights: Manufacturing and Assembly

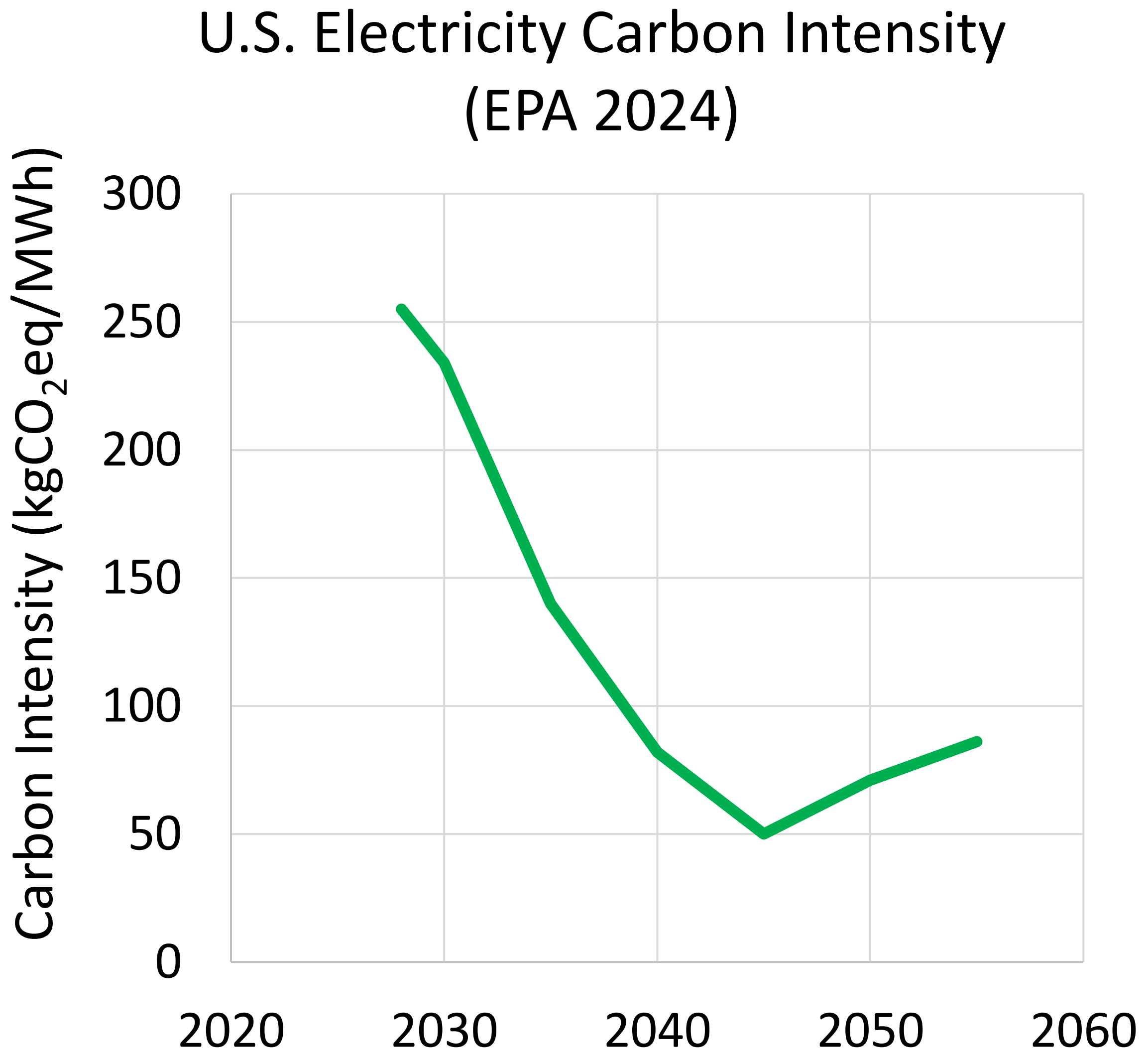
- Manufacturing and assembly methods should use the most recent data to best reflect current supply chains
  - Chordia et al. 2021 found GCCP impacts of battery production to be 30% higher in ecoinvent v3.7.1 than v2.2 to better factory data and more resolved resource supply chains
  - Chordia also modeled larger, more efficient factories finding that battery manufacturing impacts could be lowered by ~ 40%
- Infrastructure is a driver of impacts differences in this stage

Highlights: Use Stage

- Vehicle use stage, most important factor for GHG emissions is fuel consumption
  - Due to tailpipe emissions from combustion and electricity generation for EVs
- Fuel consumption affected by driver, road conditions, weather
  - Zhou et al. 2016
  - EPA MOVES model
- Example: Experiments have found auxiliary loads (air conditioning) can increase fuel consumption by 18%
  - (Carlson, Wishart, and Stutenberg 2016)
- For Plug-In Hybrid vehicles, utilization factor is a major driver of differences between studies, this assumption should be explicitly documented and discussed

Highlights: Fuel Production

- For EVs, electricity production is usually the main driver of impacts and impact differences
- Critical to use both the most recent data, and the most recent projections
- For FCEVs, fugitive hydrogen emissions were generally excluded, but should be included
  - Hydrogen has a GWP of about 12, loss rates can be as high as 20%



Automotive LCA Methodology Recommendations

Best Practices for Automotive LCAs

- Qualitative recommendations are made based on the trends found in the reviewed papers
  - e.g. electricity grid mix was found to be a main driver of impacts, so using the recent data is critical
- No specific quantitative data quality metric is recommended
- The following slides are a condensed version of the full best practices
- Recommendations are framed similarly to EPA guidance on data quality
  - Guidance on Data Quality Assessment for Life Cycle Inventory Data (Edelen and Ingwersen 2016)
  - Data Quality Assessment Method to Support the Label Program for Low Embodied Carbon Construction Materials (EPA 2024b)

Best Practices for Automotive LCAs

- LCI files available (e.g. openLCA database, csv file)
  - Transparently sharing LCI helps study reproducibility
  - Sharing files allows for others to use developed unit processes
- Primary and secondary data <3 years old
  - Fuels LCI explicitly cited and detailed
  - All data appropriate for study scope
- Examine future values of major drivers of impacts
  - Projections should be as recent as possible
- All relevant impacts assessed, not just GHG
  - Impacts should be geospatially resolved if possible

Best Practices for Automotive LCAs

Resource Extraction and Refining

- Major processes and supply chains detailed
  - Where and how?
- Resource depletion and scarcity impacts reported and cited

Manufacturing and Assembly

- Vehicle bill of materials or LCI available in SI
- Transport of materials considered between stages
- Geospatial factors considered

Best Practices for Automotive LCAs

Use Stage

- Fuel consumption reported
- Non-vehicle factors considered in fuel consumption
- Non-tailpipe emissions included in LCI

End-of-Life

- Geospatial/geographic factors considered in end-of-life processes
- ISO 14044 recommended allocations procedures

Best Practices for Automotive LCAs

Fuel Production

- Fuel production data in <3 years old, explicitly reported in methods
- Fuel cycle properties reported (e.g. T&D loss, charging losses, fugitive H_2)
  - Fugitive hydrogen has a GWP of ~12, its impact can be significant
- Future projections of fuel cycle data used in baseline or sensitivity scenarios

Summary

- Electric vehicles generally have a lower GCCP than ICEVs
  - Impact differences between studies driven by assumptions concerning fuel production and battery manufacturing
- Quality life cycle assessments consider that most recent life cycle inventory availability
  - Sensitivity cases that project future fuel production
- For informed decision making, studies should include all relevant impacts and all life cycle elements
  - Does not necessarily mean that all impacts have to be equally weighted in decision making

Contact Information

Kyle McGaughy
Senior Life Cycle Analyst
Kyle.McGaughy@erg.com

Sarah Cashman
Director of Life Cycle Services
Sarah.Cashman@erg.com

Joseph McDonald
McDonald.Joseph@epa.gov

References

- Carlson, R. B., Wishart, J., & Stutenberg, K. (2016). On-road and dynamometer evaluation of vehicle auxiliary loads. *SAE International Journal of Fuels and Lubricants*, *9*(1), 260-268.
- Chordia, M., Nordelöf, A., & Ellingsen, L. A. W. (2021). Environmental life cycle implications of upscaling lithium-ion battery production. *The International Journal of Life Cycle Assessment*, *26*, 2024-2039.
- Edelen, A., Ingwersen, W., (2016). Guidance on Data Quality Assessment for Life Cycle Inventory Data (No. EPA/600/R-16/096). U.S. Environmental Protection Agency.
- Engels, Philipp, et al. "Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data." *Journal of Cleaner Production* 336 (2022): 130474.
- EPA, (2024). Results using 2023 Reference Case [WWW Document]. URL https://www.epa.gov/power-sector-modeling/results-using-2023-reference-case (accessed 10.30.24).
- EPA, (2024b). Data Quality Assessment Method to Support the Label Program for Low Embodied Carbon Construction Materials (Version 1). https://www.epa.gov/system/files/documents/2024-08/dqa-method_v2_final.pdf

References

- Grosjean, Camille, et al. (2012) "*Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry.*" Renewable and Sustainable Energy Reviews 16.3: 1735-1744.

- Iyer, Rakesh Krishnamoorthy, and Jarod C. Kelly. (2022) *Updated Production Inventory for Lithium-Ion Battery Anodes for the GREET® Model, and Review of Advanced Battery Chemistries*. No. ANL-22/74. Argonne National Laboratory (ANL), Argonne, IL (United States).

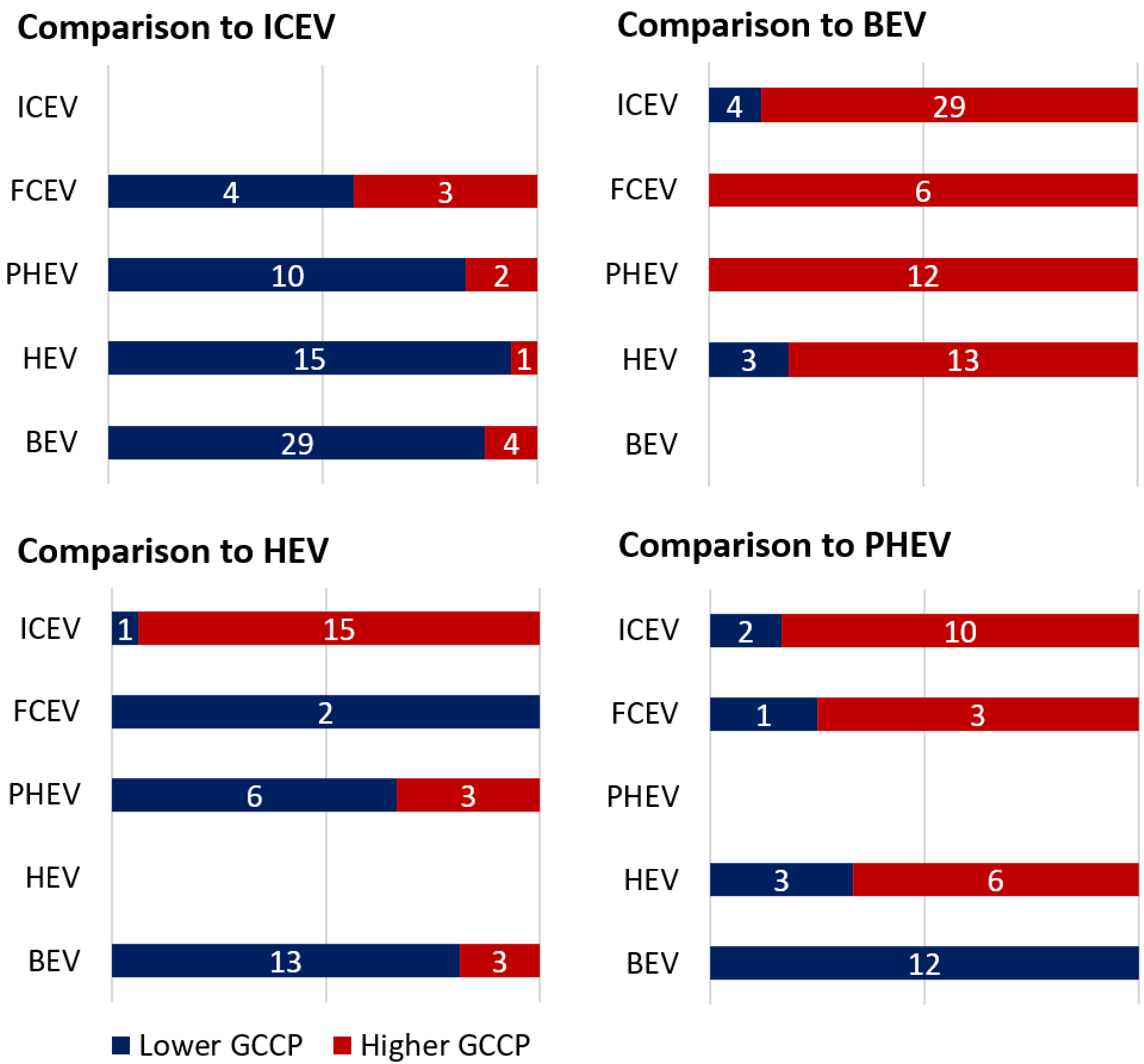
- Kelly, Jarod C., et al. (2021) "Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries." *Resources, Conservation and Recycling* 174: 105762.

- Schenker, Vanessa, Christopher Oberschelp, and Stephan Pfister. (2022) "Regionalized life cycle assessment of present and future lithium production for Li-ion batteries." *Resources, Conservation and Recycling* 187: 106611.

- Shafique, Muhammad, and Xiaowei Luo. (2022). "Environmental Life Cycle Assessment of Battery Electric Vehicles from the Current and Future Energy Mix Perspective." *Journal of Environmental Management* 303 (February):114050. https://doi.org/10.1016/j.jenvman.2021.114050.

- Zhou, Min, Hui Jin, and Wenshuo Wang. (2016). "A Review of Vehicle Fuel Consumption Models to Evaluate Eco-Driving and Eco-Routing." *Transportation Research Part D: Transport and Environment* 49 (December):203–18. https://doi.org/10.1016/j.trd.2016.09.008.

Supplemental Slides


Comparison to ICEV
ICEV
FCEV
PHEV
HEV
BEV
4
3
10
2
15
1
29
4
Comparison to BEV
ICEV
FCEV
PHEV
HEV
BEV
4
29
6
12
3
13
Comparison to HEV
ICEV
FCEV
PHEV
HEV
BEV
1
15
2
6
3
13
3
Comparison to PHEV
ICEV
FCEV
PHEV
HEV
BEV
2
10
1
3
3
6
12
Lower GCCP
Higher GCCP