Data Driven U.S. Passenger Vehicle Life-Cycle Emissions Comparisons

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Life-Cycle Analysis for Transportation Symposium

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EER

Vehicle Comparisons For Consumers

- Battery Electric Vehicle Equivalent CO_2 per km ansatz
  - $ER_{BEV} = EC(1+TC)(1+AC)\frac{EER}{(1-UE)(1-T\&D)} + \frac{BPCO2}{BL} = CEC \cdot CEER + \frac{BPCO2}{BL}$

Electricity Generation Emission Rate

Unadjusted Electricity Consumption

Driving Temperature Correction

Driving Aggressiveness Correction

Upstream Emissions

Transmission & Distribution Losses

Battery Pack Life

Battery Pack Production CO_2

- Full Hybrid Electric Vehicle Equivalent CO_2 per km ansatz
  - $ER_{FHEV} = FC(1+TC)(1+AC) \cdot \frac{GER}{1-UE} + \frac{BPCO2}{BL} = CFC \cdot CGER + \frac{BPCO2}{BL}$

Unadjusted Fuel Consumption

Gasoline Emission Rate

Green Consumer Wishlist

1) Corrected Electricity Consumption (CEC)
2) Corrected Electricity Emission Rate ($CEER$)
3) Corrected Fuel Consumption (CFC)
4) Corrected Gasoline Emission Rate ($CGER$)
5) $BPCO2/BL$

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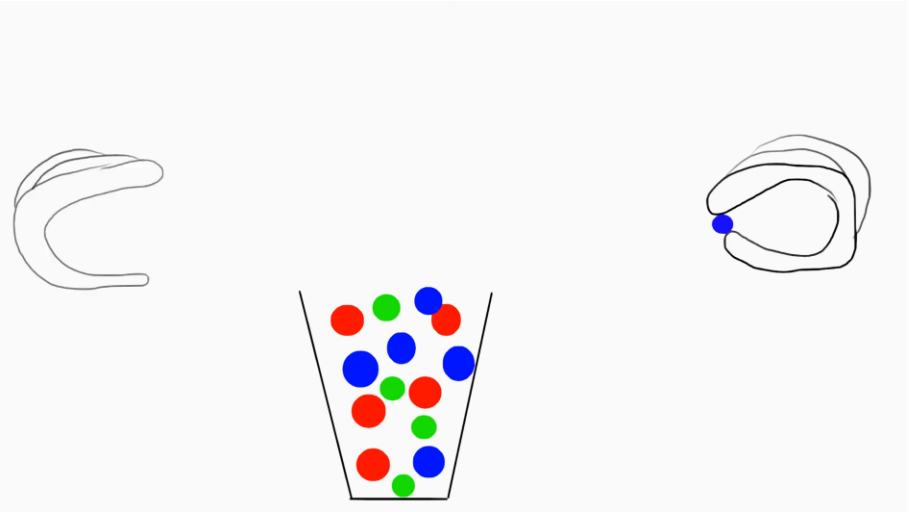
Which Electricity Emission Rate?

- Conventional Battery Electric Vehicle Manufacturer Marketing Wisdom
  - "Use the average electricity mix."
    - Sum up all the greenhouse gas emissions (kg CO_2eq) and divide by the total generation (MWh)
  - The only thing that is correct about this is the units!
  - It ignores:
    - Demand dependency of emissions
    - Demand response of electricity sources
    - Geographic and temporal variation
    - Electricity exchange between regions
  - "But …., don't those things 'average' out?"
    - Absolutely not!



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Conserving Mass Is Usually Important

- A Contrived Example
  - 1 TWh integrated load capacity grid
    - One non-emitting source of electricity e.g. wind, solar, hydro, nuclear
    - One emitting source of electricity e.g. coal, gas, oil (assume 500 kg CO_2/MWh)
  - How much CO_2 is emitted by a 0.1 MWh integrated load on the grid?
    - Average mix proponent: "Multiply the average mix electricity emission rate by the load."
    - Data driven analysis proponent: "Let's remove it and see."

	Actual Emissions (kg CO_2)	Average Mix Emissions (kg CO_2)	Final Average Mix Emissions (kg CO_2)
10% non-emitting			
Nominal Load	4.5e8	4.5e8	4.49999995e8
Load Reduction	50	45	44.9999995
50% non-emitting			
Nominal Load	2.5e8	2.5e8	2.49999975e8
Load Reduction	50	25	24.9999975

Cleaner (dirtier) grid when loads are removed (added)

449.999995 kg CO_2/MWh

249.999975 kg CO_2/MWh

To get the emissions correct, you need before and after values for both the average mix emission rates and the load.

Change in emissions per change in load is the quantity of interest

Average Mix Flaws

Changes to the emission rates are small, but when they're applied across the entire grid, it's a meaningful amount of CO_2.

Error gets worse at higher non-emitting fractions.

Future predictions assuming renewable fractions are inherently limited.

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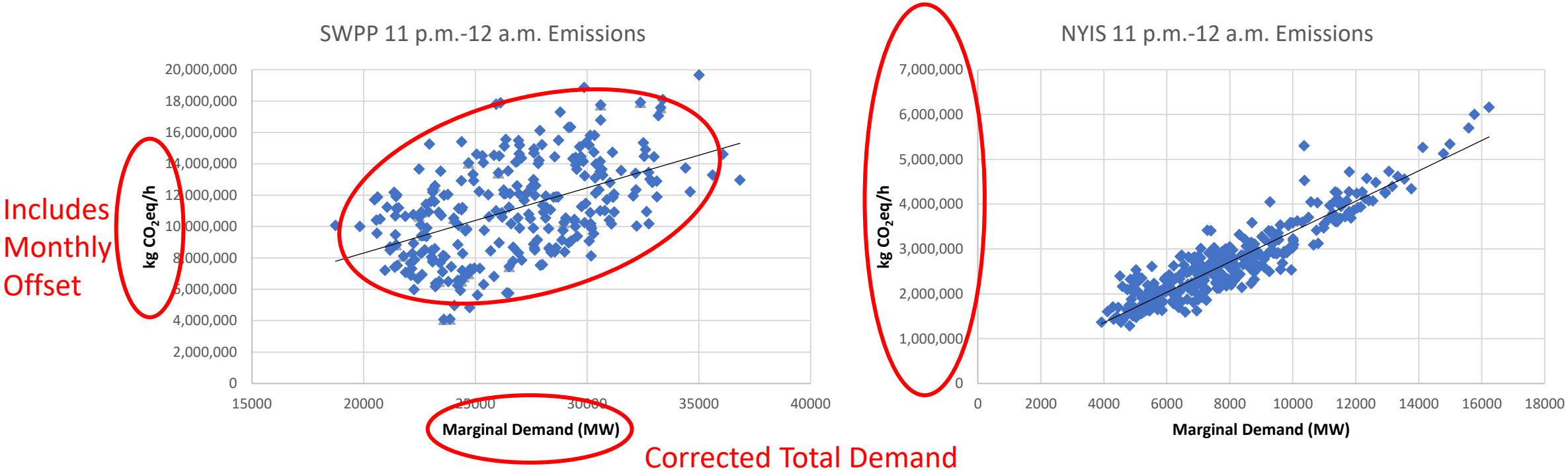
Real Data

- 2019 U.S. Emissions & Generation Data
  - EPA Air Markets Program Data: hourly CO_2 emissions and gross generation for power plants
  - EIA: hourly demand, generation by electricity source, electricity imports and exports



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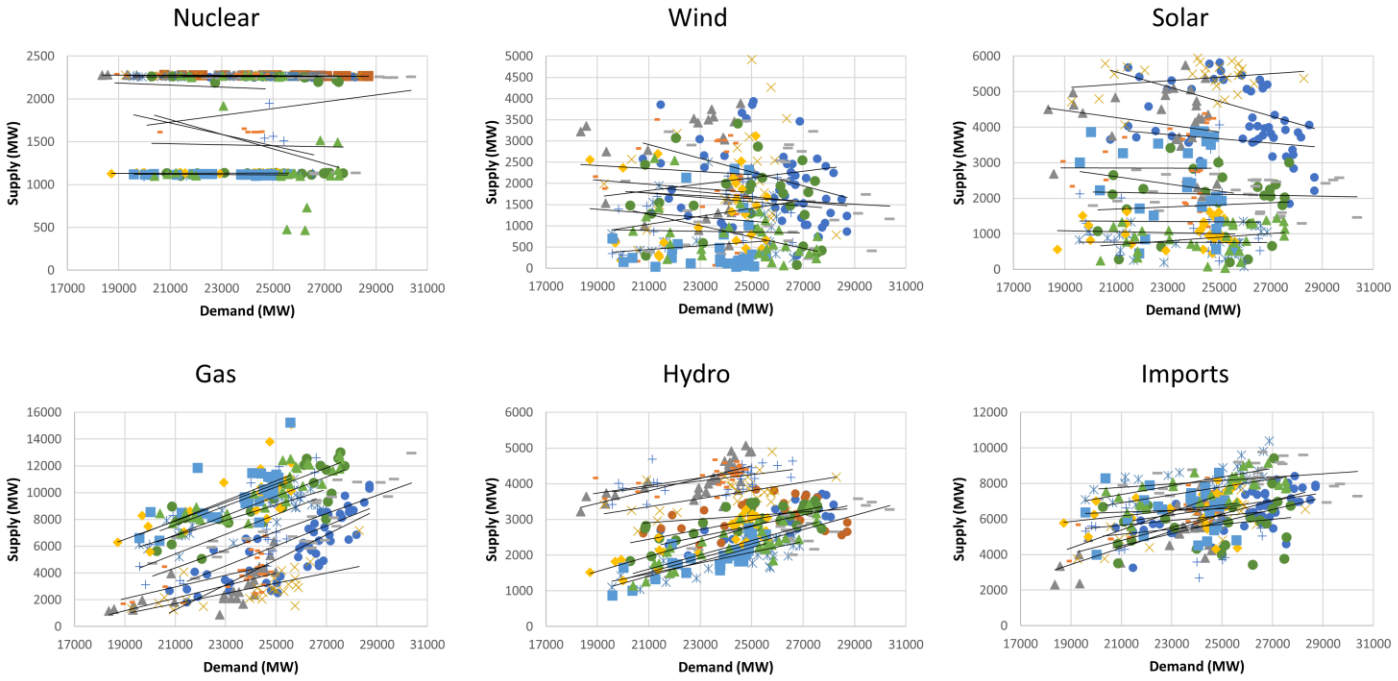
Marginal Demand and Imports

- Many sources do not respond to demand
  - You get what you get and you don't get upset
- Marginal demand is the part of the demand met by sources that do respond to demand
  - For CISO at 8 a.m.
    - Gas
    - Hydro
    - Imports
    - All have statistically significant slopes
- Approximately 25% of California's electricity is imported
  - Need to account for this along with local generation emissions

2019 CISO 8 a.m. generation data



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Correct Electricity Emission Rate Definition

- GHG emission mass flow rate (kg CO_2eq/h) increase/decrease due to the addition/removal of a load (MW) from a grid, divided by the load

Emission mass flow rate on grid r for hour of day h

Expected change in emission mass flow rate on grid due to additional load Δx

Current grid (r)

$$\frac{E[Y_{rh}|X_{rh} = x + \Delta x] - E[Y_{rh}|X_{rh} = x]}{\Delta x}$$

$$= \hat{\beta}^{Y}_{rh} + \sum_{q \in R^{M}_{rh}} \hat{\beta}^{T}_{rqh} \frac{E[Y_{qh}|X_{qh} = x + \Delta x] - E[Y_{qh}|X_{qh} = x]}{\Delta x}$$

Demand met by sources that respond to demand

Generation regression parameter

Imports regression parameter

Neighboring grids (q)

- Coupled system of geographically and temporally resolved emission rates

Burton, Powers, Burns, Conway, Leach & Senecal (2021) "A Data-Driven Greenhouse Gas Emission Rate Analysis for Vehicle Comparisons", Under Review

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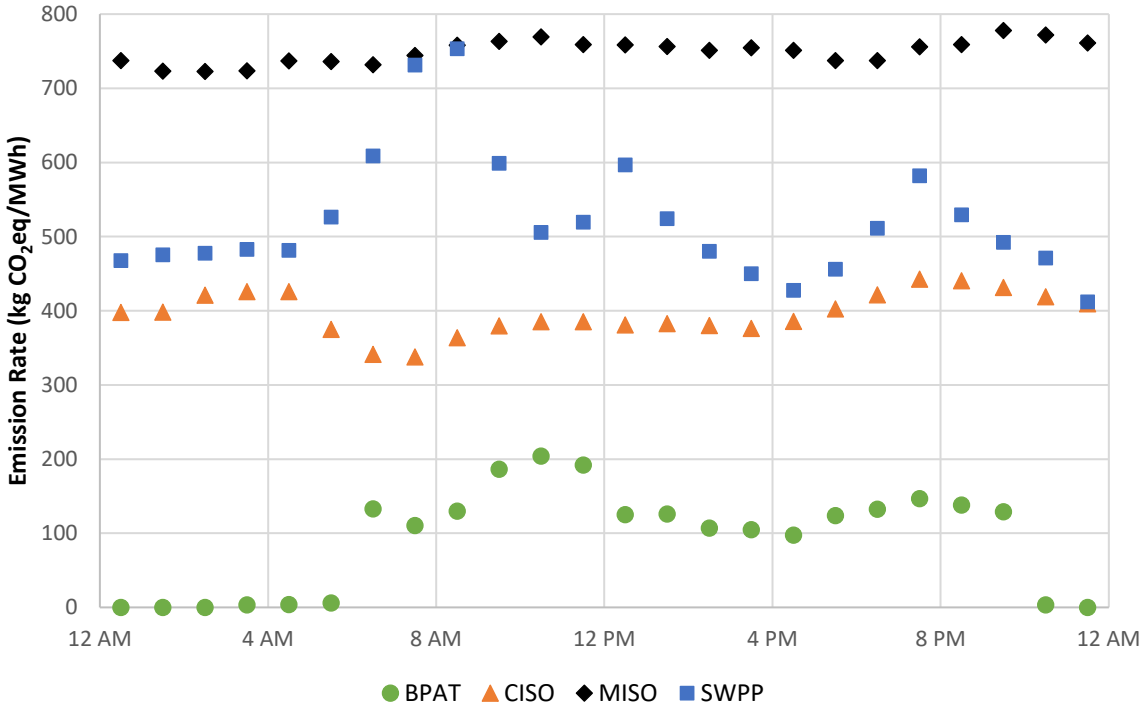
How Much Difference Can It Possibly Make?



Average Mix Electricity Emission Rates (2018 eGrid)

- CA 191.4 kg CO_2eq/MWh
- OR, WA 109.1 kg CO_2eq/MWh
- ND, SD, NE, KS, OK 497.4 kg CO_2eq/MWh
- IA, IL, IN, MI, MO, MS, MN, WI 552.0 kg CO_2eq/MWh

Coupled Regression Analysis (Min/Max/Average)

- CISO 337.7 / 431.7/ 396.3 kg CO_2eq/MWh
- BPAT 0 / 204.3 / 93.4 kg CO_2eq/MWh
- SWPP 411.9 / 753.5 / 523.5 kg CO_2eq/MWh
- MISO 722.9 / 778.0 / 749.1 kg CO_2eq/MWh

2019 U.S. Total (for entertainment purposes only)

- Average Mix 410 kg CO_2eq/MWh
- Regression Analysis 587.2 kg CO_2eq/MWh

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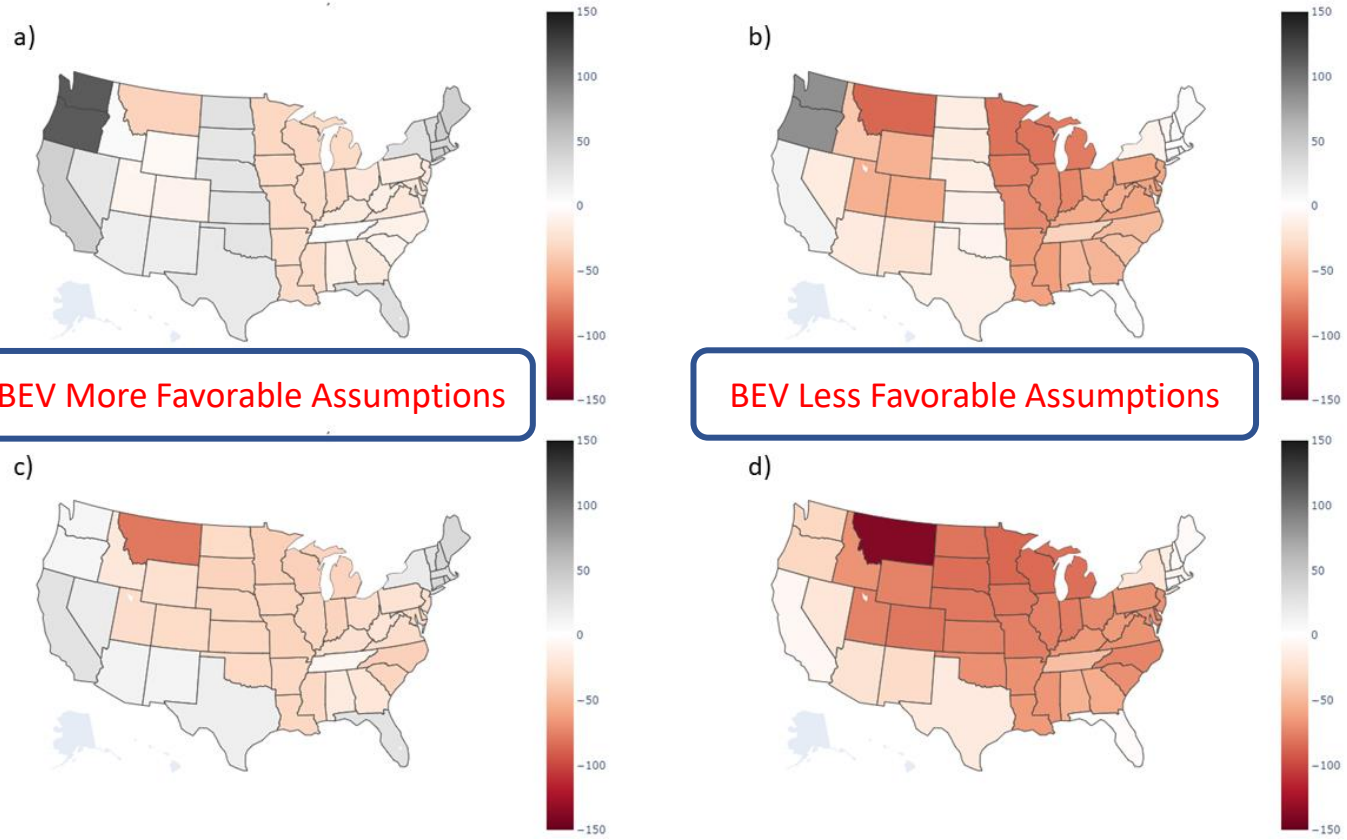
	BEV Lower CO_2eq	FHEV Lower CO_2eq
All Marginal Source ER	20% of demand	52% of demand
Fossil Only Marginal Source ER	0% of demand	66% of demand

2020 Kia Niro Emission Rate Differences

$ER_{FHEV} - ER_{BEV}$

- Similar production CO_2 except for battery
- BL: 105-160% of warranty (100,000 miles)
- $BPCO2$: 61-106 kg CO_2eq/kWh
- $BPCO2/BL$
  - BEV (67.5 kWh)
    - 16.0-42.1 g CO_2eq/km
    - Uncertainty equivalent to 5/7.5 mpg at 40/50 mpg
    - Bigger pack, bigger problem
  - FHEV
    - 0.37-0.97 g CO_2eq/km
- TC and AC from AAA Study (2019) or 5-cycle test data

Top Row: Statistically Significant Regression Parameters



BEV More Favorable Assumptions

BEV Less Favorable Assumptions

Bottom Row: Statistically Significant Emitting-Only Regression Parameters

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Parting Thoughts

- All loads are marginal (don't forget battery production and well-to-tank gasoline refining)
  - If you remove a load from the grid, wind/solar/nuclear usually don't shut down (CA excluded), we just need less of the emitting sources
  - "Too much CO_2" conundrum is solved by realizing that demand-response based emission rates would drop with demand
- U.S. vehicle LCAs which use average mix emission rates are not accurate
  - The most egregious use is for future emission rate predictions on grids with prescribed non-emitting generation percentages
  - 9% increase in renewable generation in 2020 (69 TWh), another 7% projected increase in 2021 (58 TWh) , 127 TWh total, but removing 117 TWh from the 2019 dataset did nothing to the emission rates (CAUTION: Processing of 2020 data in progress)
- U.S. emissions and generation data are available to calculate more accurate emission rates for the present
  - Demand-response based modeling must be used for the future
- BEV is most likely favorable to fossil-fueled ICEV, but not FHEV (yet, depending on location)
  - Front-loading CO_2 into the atmosphere for infrastructure and battery production is premature for the U.S.

THANK YOU!

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