Levelized Cost of Returned Energy for Comparing Hydrogen End-Uses & Battery Storage Economics

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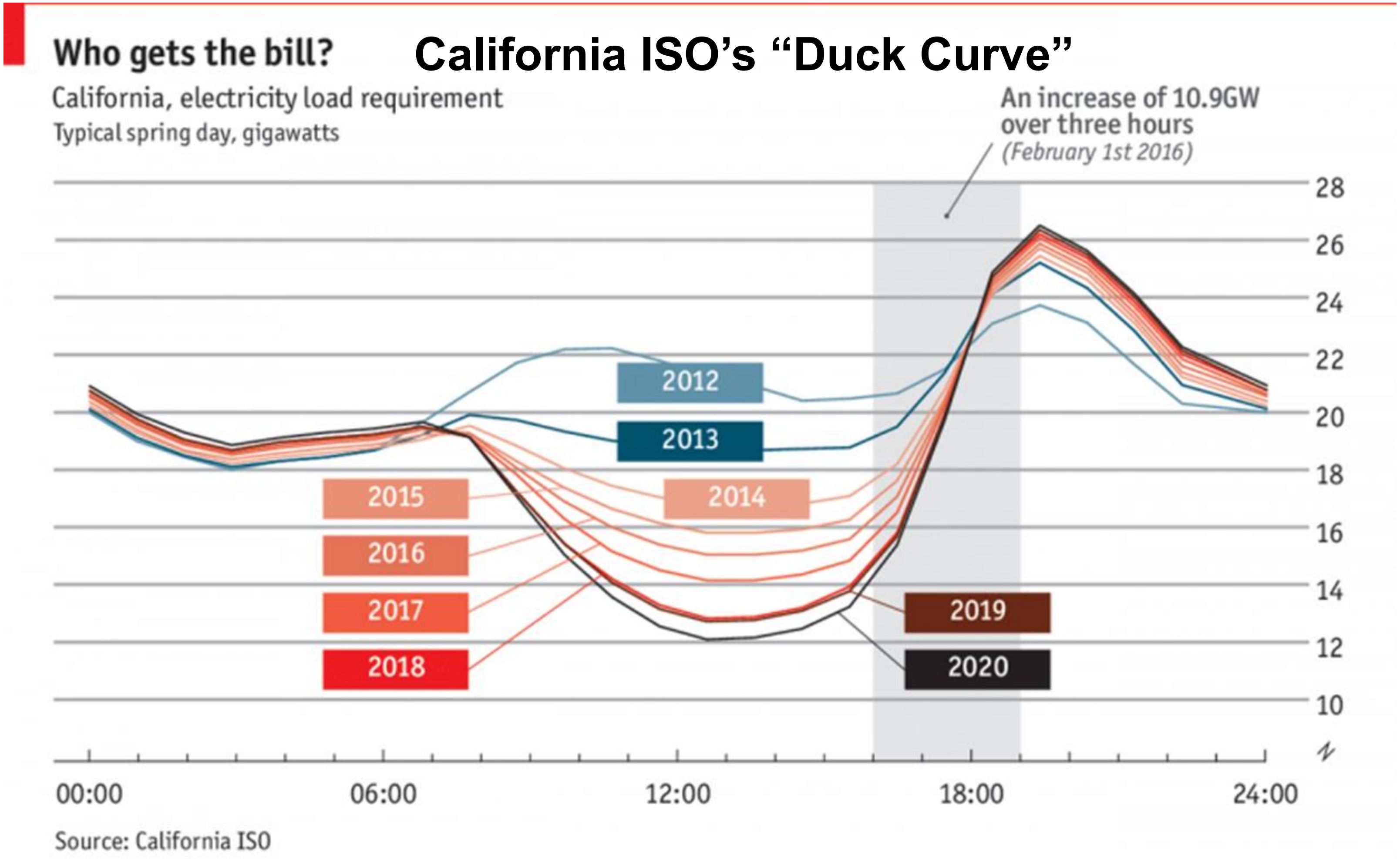
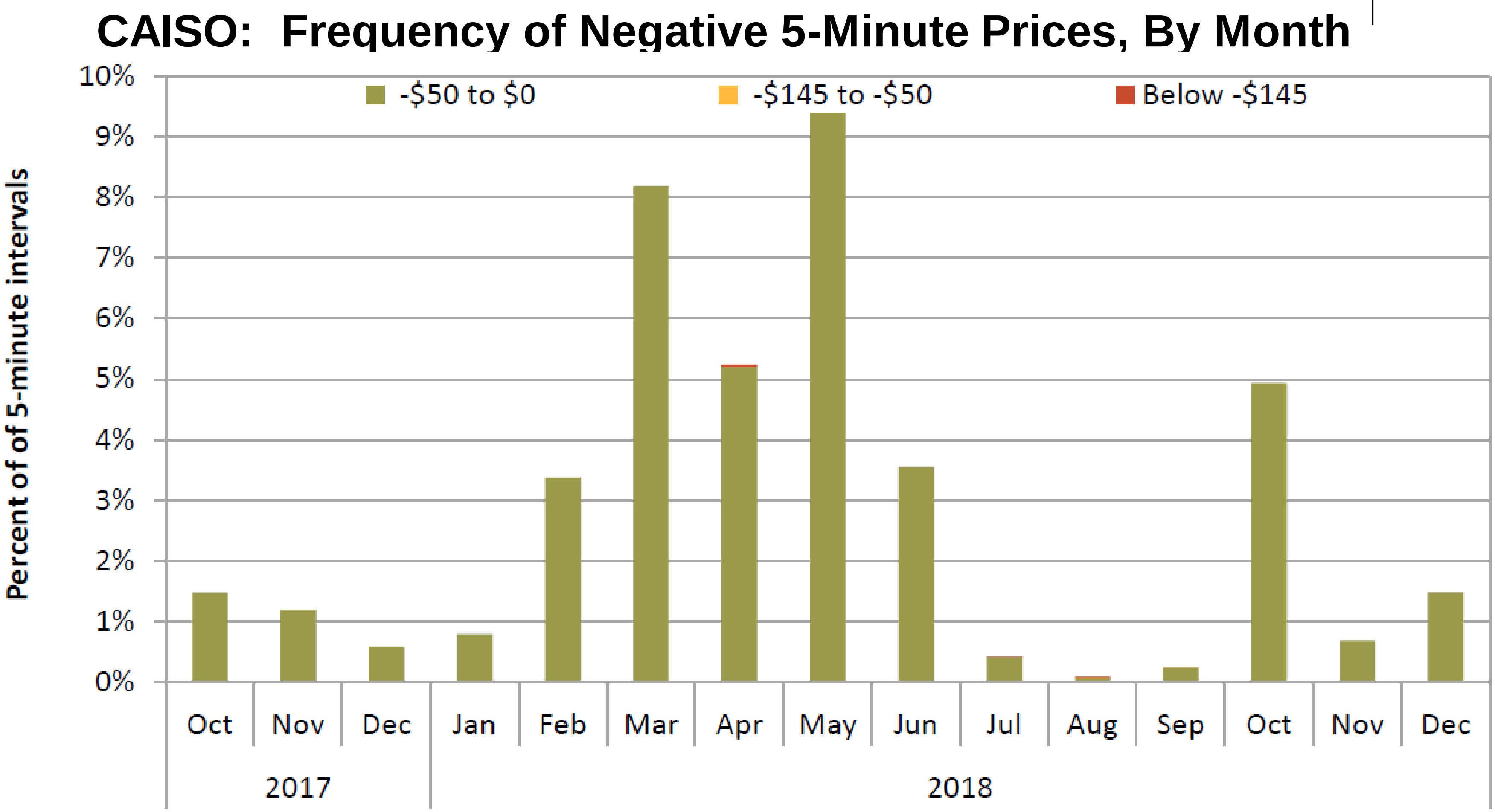
Increased Renewables: Load Impact & More Curtailment…



Source: The Economist, 3/28/2018, *What a ten-year-old duck can teach us about electricity demand*.
https://www.economist.com/graphic-detail/2018/03/28/what-a-ten-year-old-duck-can-teach-us-about-electricity-demand

Impact Wholesale Electricity Pricing (Not Just in California)



Source: California Independent System Operator, February 13, 2019, *Q4 2018 Report on Market Issues and Performance*. http://www.caiso.com/Documents/2018FourthQuarterReportonMarketIssuesandPerformance.pdf#search=negative%205%2Dminute%20prices

Electrolysis Using Renewables Helps Balance Grid Operations

- Multiple End-Uses for Produced Hydrogen (H2)
  - Power-to-Gas (P2G)
    - Direct Injection into Natural Gas Pipeline System
    - Feedstock for Methanation of H2 to CH4
    - Dispensed H2 Fuel for Fuel Cell Vehicles (FCVs)
  - Power-to-Gas-to-Electricity (P2G2E)
    - H2 Fuel Cell Feedstock for Electricity Generation
- "Battery" Aspect of H2 Use Cases
- Comparative Economics: H2 vs. Batteries
  - Capacity Factor (CF): 90% H2 vs. 45% Batteries.

Multiple Technologies and Use Cases, Current & Future Costs

- Electrolyzers (EC): Flexible, fast on and off
  - Polymer Electrolyte Membrane (PEMEC), Alkaline (AEC), Solid Oxide (SOEC)
- Fuel Cells (FC)
  - PEMFC, AFC, SOFC, Molten Carbonate (MCFC)
- Dispensed H2 Fuel for FCVs
  - Central H2 Production: Gaseous, Liquid
  - Onsite H2 Production: Gaseous
- Batteries
  - Li-Ion, ZnBr (Flow), NaS, Advanced Lead-Acid.

Levelized Cost of Returned Energy (“LCORE”) Concept

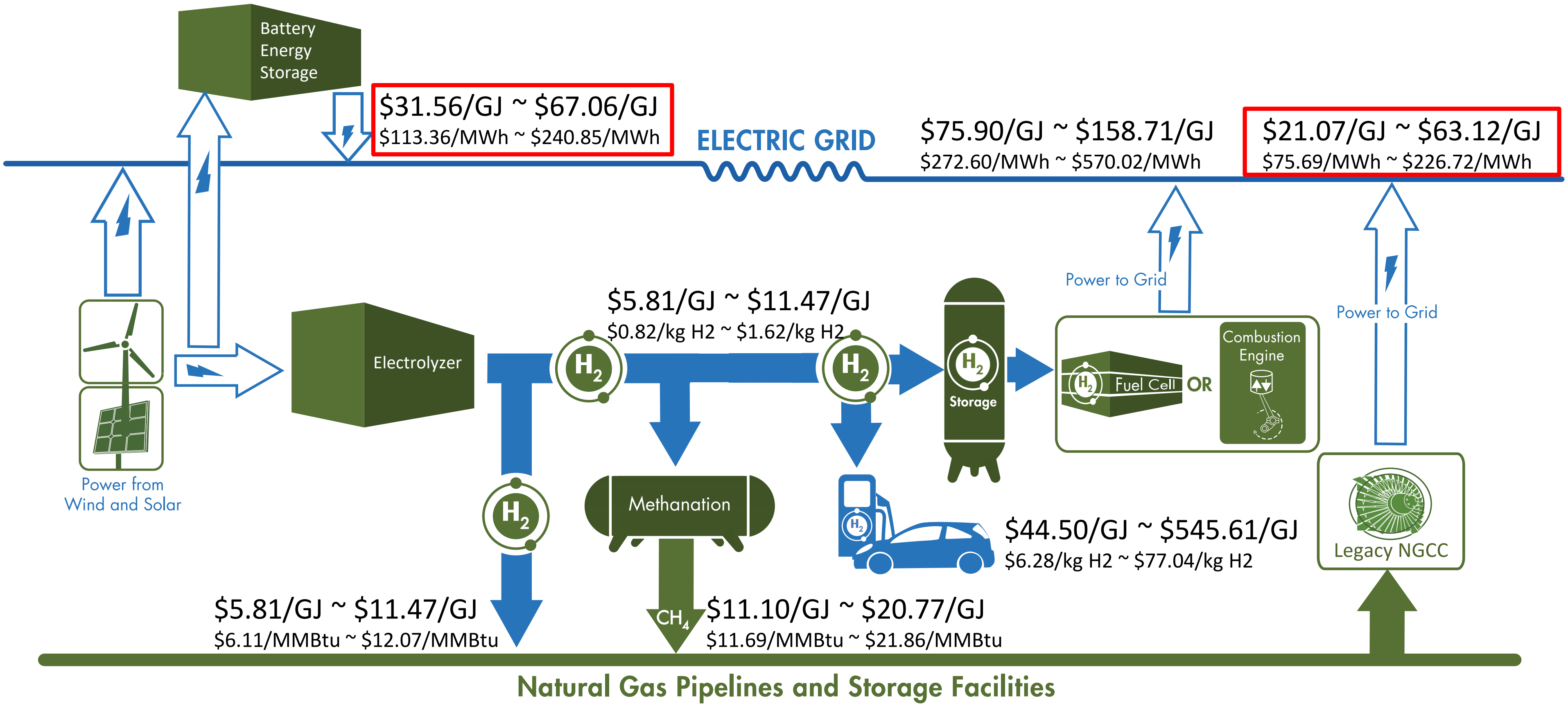
- Use Case Electricity Input Assumptions:
  - The renewable-generation electricity would have to be curtailed if it were not used onsite as input to electrolyzers or batteries
  - Electricity input cost is thus assumed to be ZERO
- LCORE represents the levelized cost of all equipment required to generate the final product for each Use Case
  - Calculated same as Levelized Cost of Electricity (LCOE) but with all input fuel costs set to zero.

LCORE Results

CURRENT COSTS & EFFICIENCES

45% Capacity Factor for Batteries;

90% Capacity Factor for All Other Equipment



LCORE Results

LCORE Results

CURRENT COSTS & EFFICIENCES

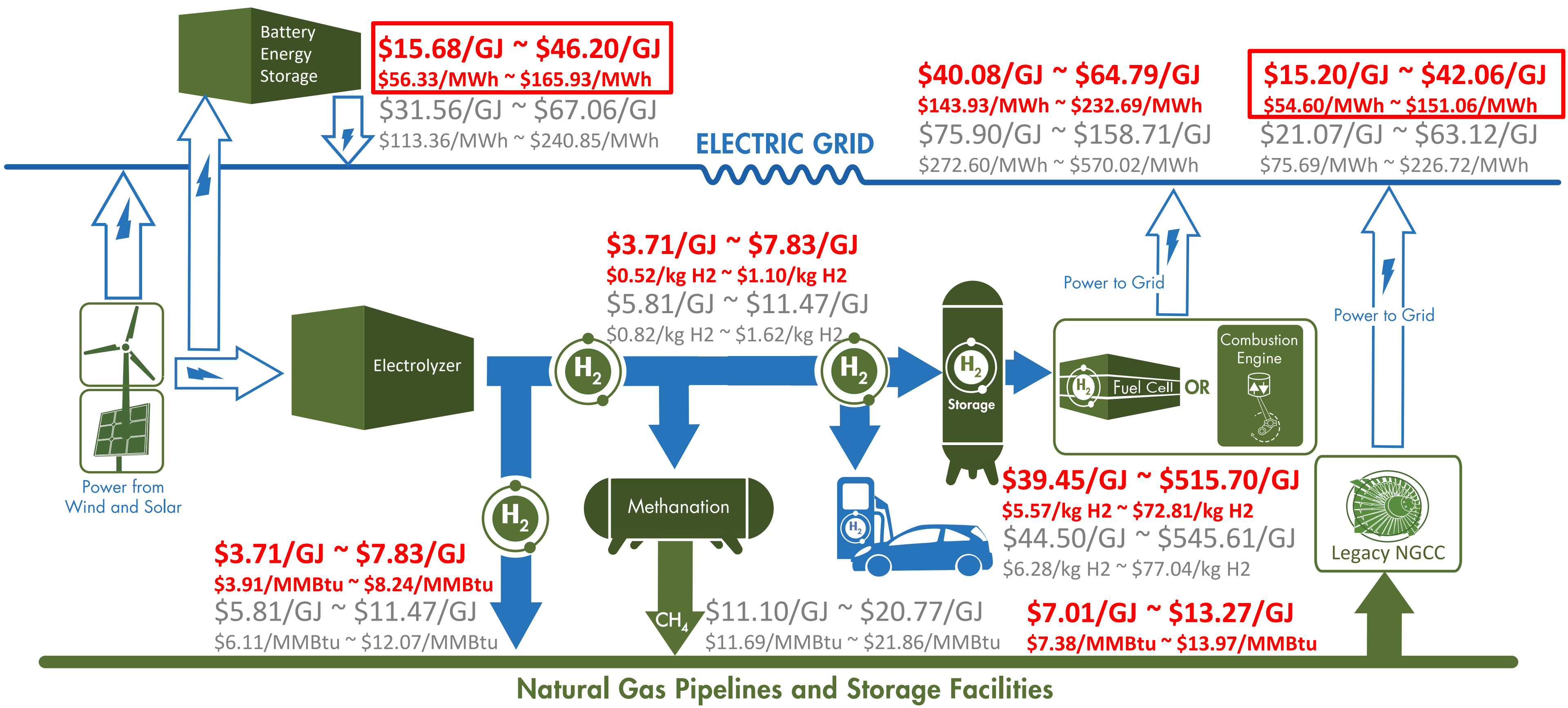
45% Capacity Factor for Batteries;

90% Capacity Factor for All Other Equipment

FUTURE COSTS & EFFICIENCES

45% Capacity Factor for Batteries;

90% Capacity Factor for All Other Equipment



LCORE Results ($/GJ)

FUTURE COSTS & EFFICIENCES
45% CF for Batteries;
90% CF for All Other Equipment

PEMEC+ SOFC

Alluvial Diagram: Different Presentation, *Same Results*

AEC + MCFC

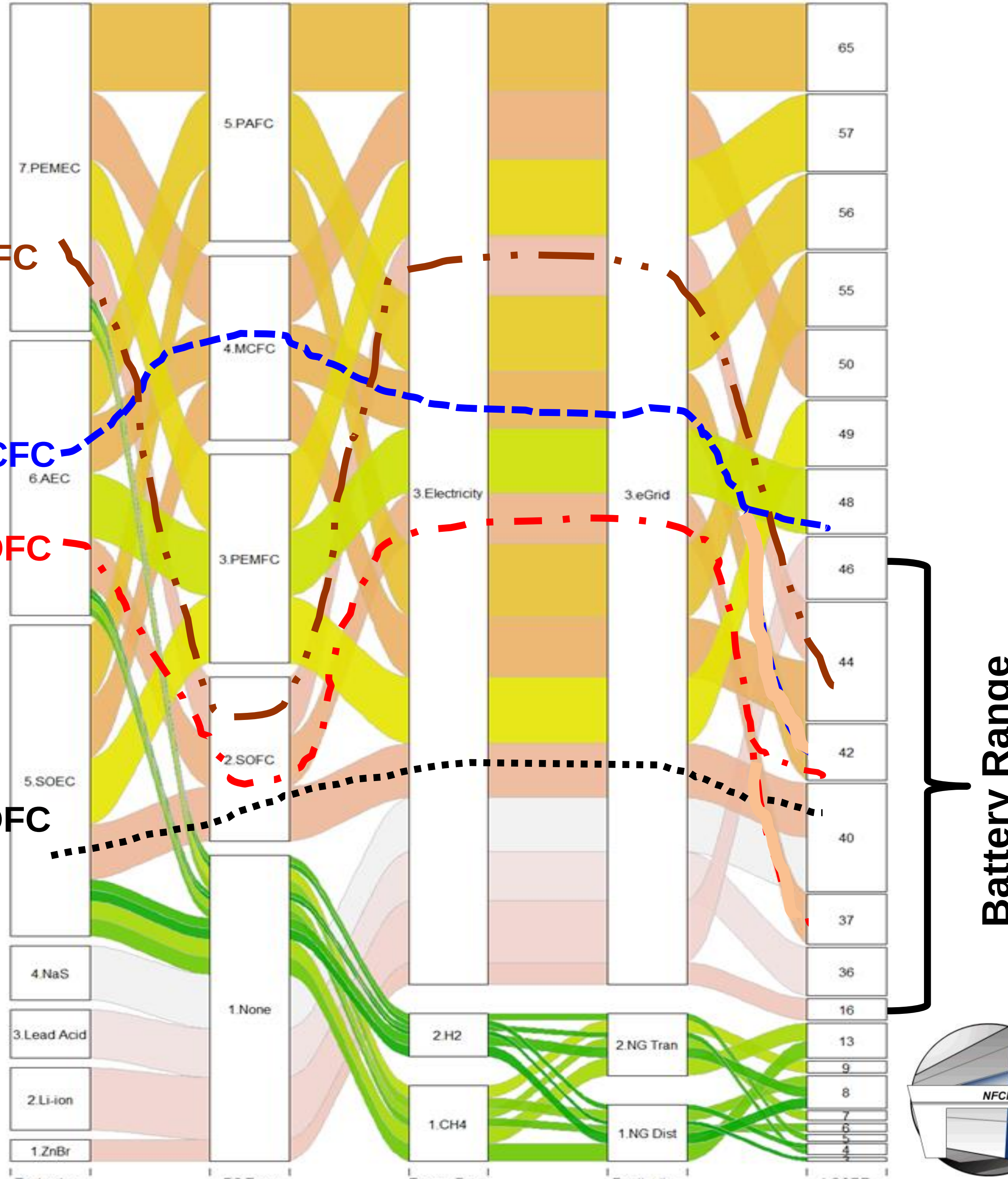
Pathways compared here:

AEC + SOFC

- Electrolyzer + Fuel Cell = Electricity to Electric Grid
- Electrolyzer + H2 = H2 to Natural Gas Grid

SOEC + SOFC

- Electrolyzer + Methanator = Natural Gas to Natural Gas Grid
- Battery Energy Storage = Electricity to Electric Grid



LCORE Results by Use Case: Comparative Economics

- At Current Costs (using 90% vs. 45% CF):
  - H_2 fuel competitive in high-gasoline tax states
  - H_2 fuel into legacy central station generation competitive with batteries for electricity delivery
- At Future Costs (using 90% vs. 45% CF):
  - H_2 for pipeline injection competitive
  - CH_4 for pipeline injection seasonally competitive
  - Some competition between FC-generated electricity and battery-generated electricity
- All results depend on future cost evolution.

POWER-TO-GAS (P2G): LCORE Analysis Conclusions

- P2G Can Provide Economic Grid-Scale Storage of H2 Using Otherwise-Curtailed Renewable Generation
- P2G Increases Grid and Fuel Flexibility through Multiple H2 Use Cases
- Current Economics Support H2 as Fuel for FCVs and Legacy Central Plant Electricity Generation via Natural Gas Pipeline System
- Future Economics Support H2 into FCs for Shifting Timing of Electricity Generation.

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THANK YOU!

QUESTIONS?

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