POWER-TO-GAS: Enabling Rapid Response, Variable-Duration Energy Storage at Grid Scale

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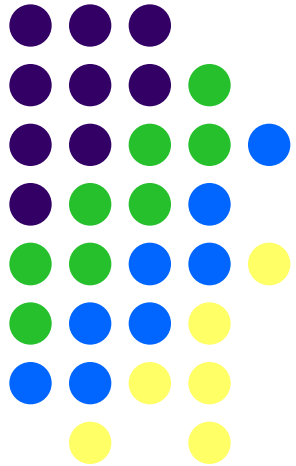

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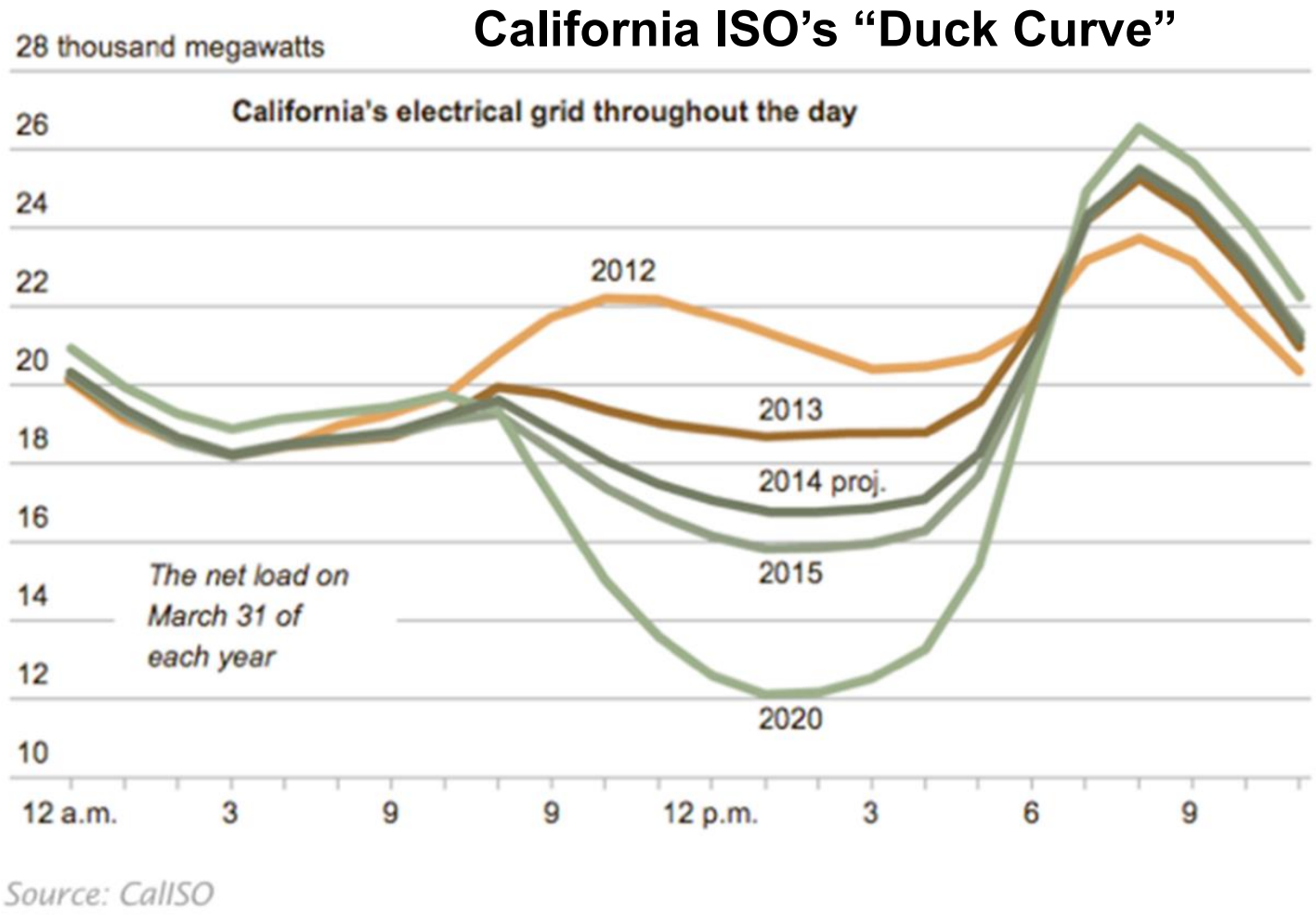
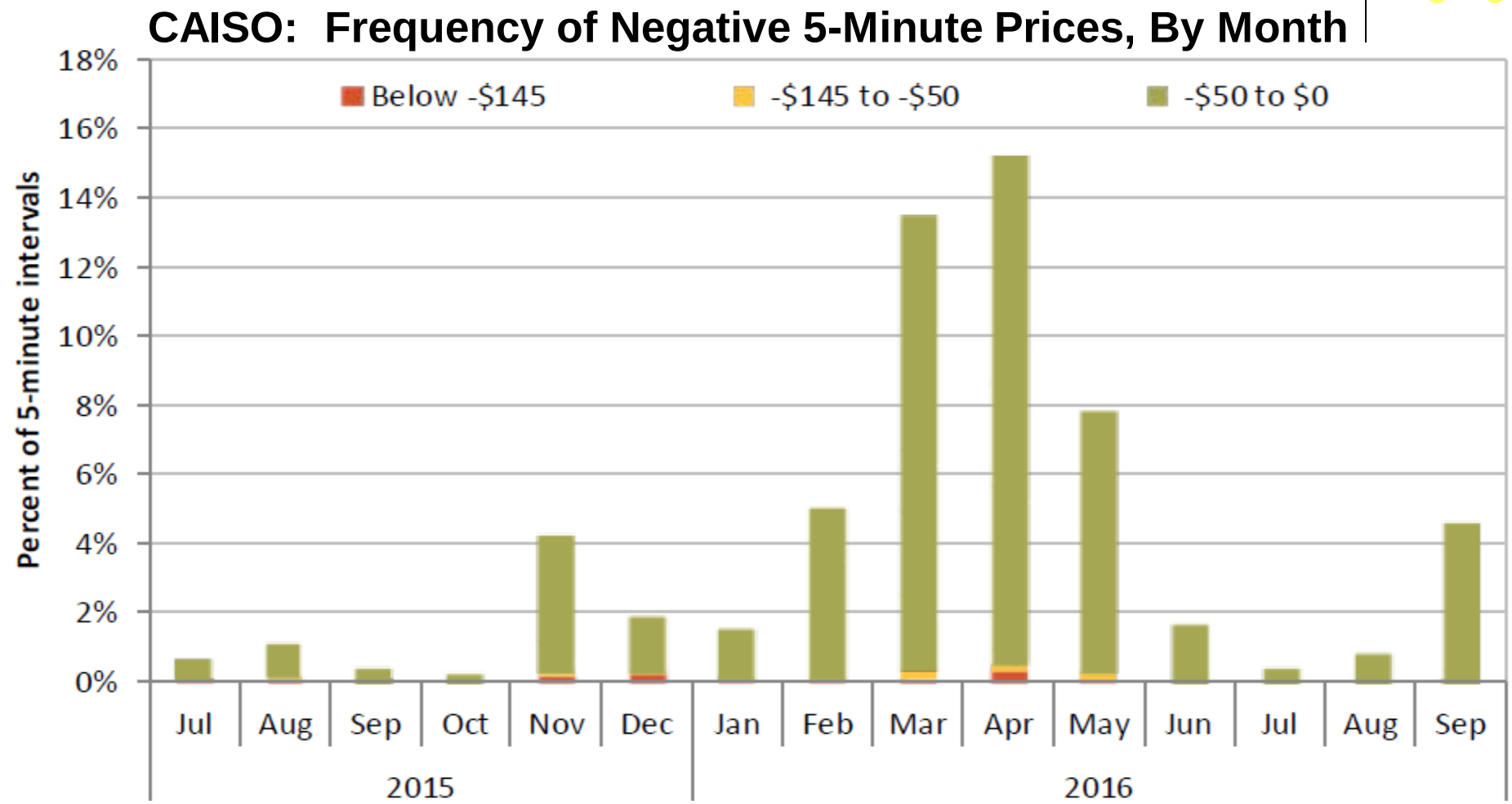
Increased Renewables Are Impacting Electric Grid Flows…



Source: CalISO

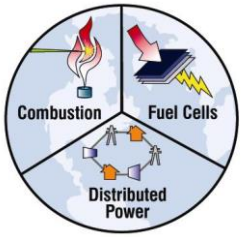
As Well As Wholesale Electricity Pricing…



Source: www.caiso.com/market/Pages/MarketMonitoring/MarketIssuesPerfomanceReports/Default.aspx (Third Quarter 2016)

HiGRID Results: Renewables Integration

- **Task 4.1: Perform spanning analysis for different resources in California**
  - **Installation of renewables affects how other generators operate**



Advanced Power and Energy Program

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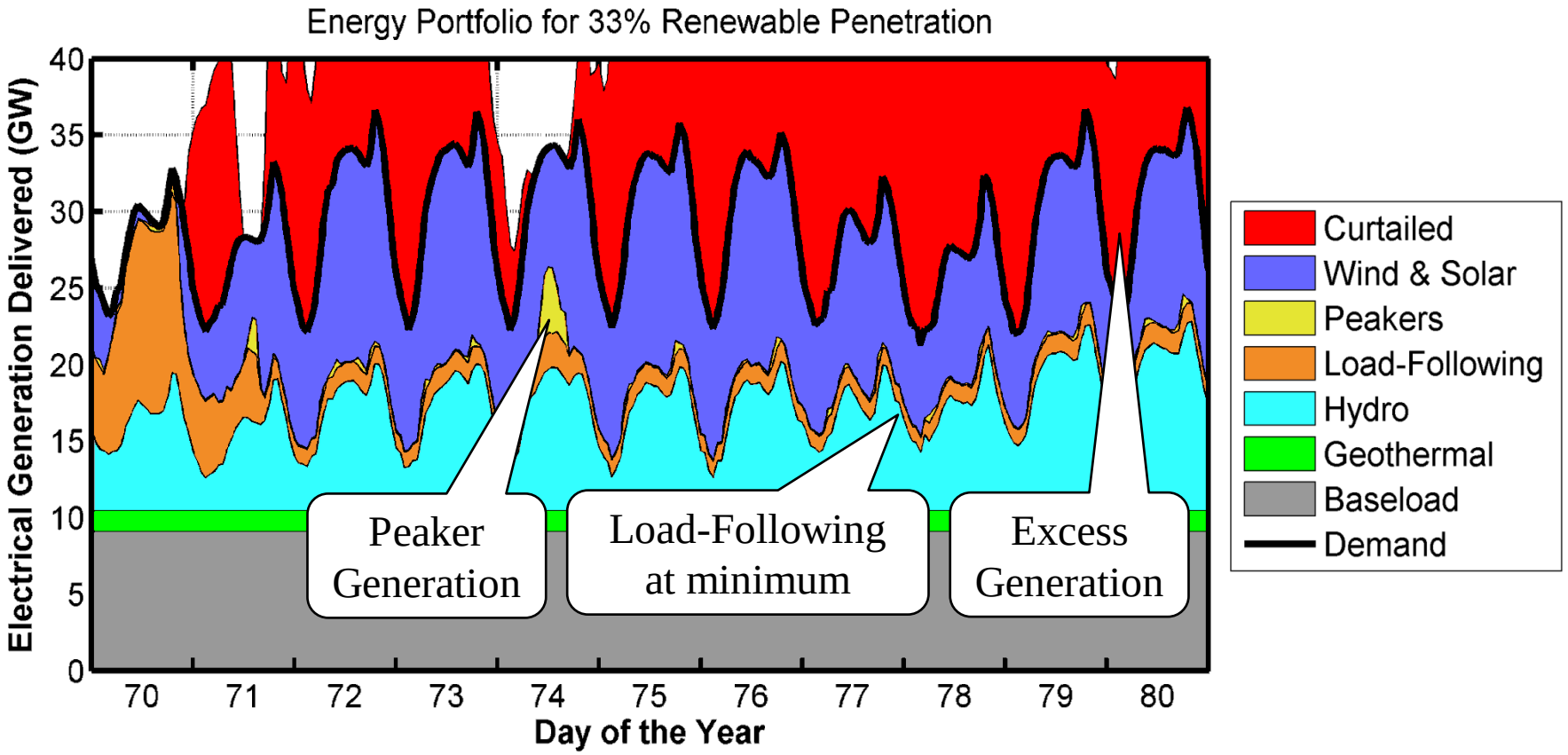
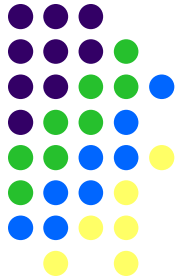
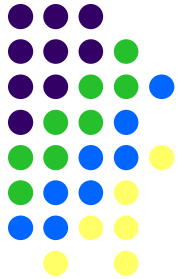


Electrolysis Using Renewables Helps Balance Grid Operations



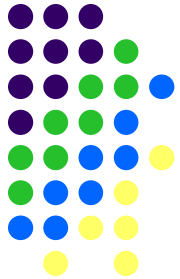
- Produced Hydrogen: Multiple Potential Uses
  - Power-to-Gas
    - Direct Injection into Natural Gas Pipeline System
    - Feedstock for Methanation of H2 to CH4
    - Dispensed Fuel for Fuel Cell Vehicles
  - Power-to-Gas-to-Electricity
    - Fuel Cell Feedstock for Electricity Generation
- “Battery” Aspect of Hydrogen Use Cases
- How Do Economics of Hydrogen Use Cases Compare to Traditional Batteries?

Multiple Technology Mixes Make for Multiple Use Cases



- Electrolyzers: Highly flexible, fast on and off
  - PEMEC, AEC, SOEC
- Fuel Cells
  - PEM, Alkaline, SOFC, MCFC
- Hydrogen Fuel Dispensing
  - Central Production: Gaseous, Liquid
  - Onsite Production: Gaseous
- Batteries
  - Li-Ion, ZnBr (Flow), NaS, Advanced Lead-Acid

Technologies Are Developing Rapidly; Costs Are Declining



- CASE 1: Current Costs
  - 50% Annual Average Capacity Factor (“CF”) for All Use Cases to Level the Playing Field
- CASE 2: Current Costs
  - 90% CF for Electrolysis-Based Use Cases
  - 45% CF for Battery Use Cases
- CASE 3: Future Costs
  - 90% CF for Electrolysis-Based Use Cases
  - 45% CF for Battery Use Cases

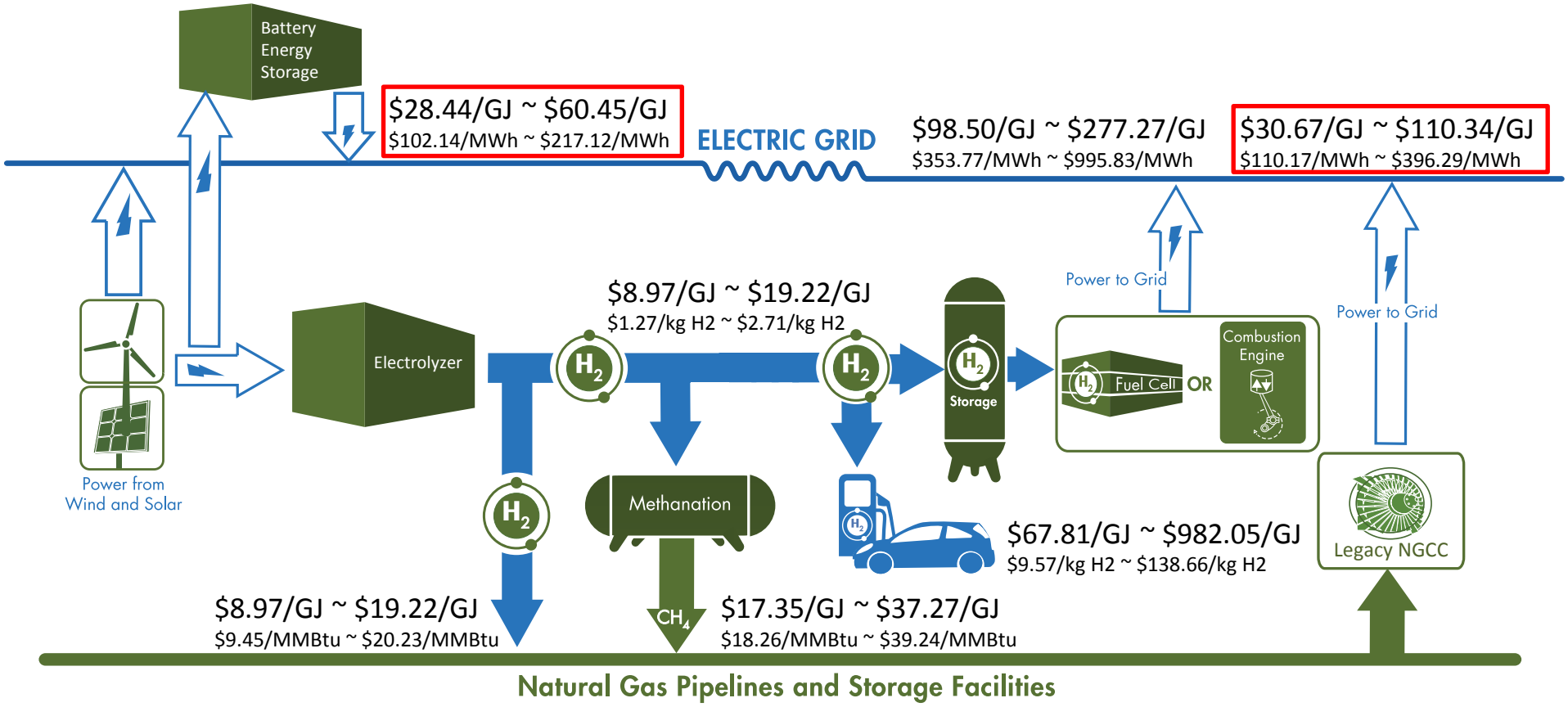
Levelized Cost of Returned Energy ("LCORE") Concept

- Use Case Electricity Input Assumptions:
  - If not input to electrolyzers or batteries, the renewable-based electricity would otherwise be curtailed
  - 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
  - Is the same as the Levelized Cost of Electricity but with all input fuel costs set to zero.

LCORE Results

CURRENT COSTS & EFFICIENCES

50% Capacity Factor for All Equipment

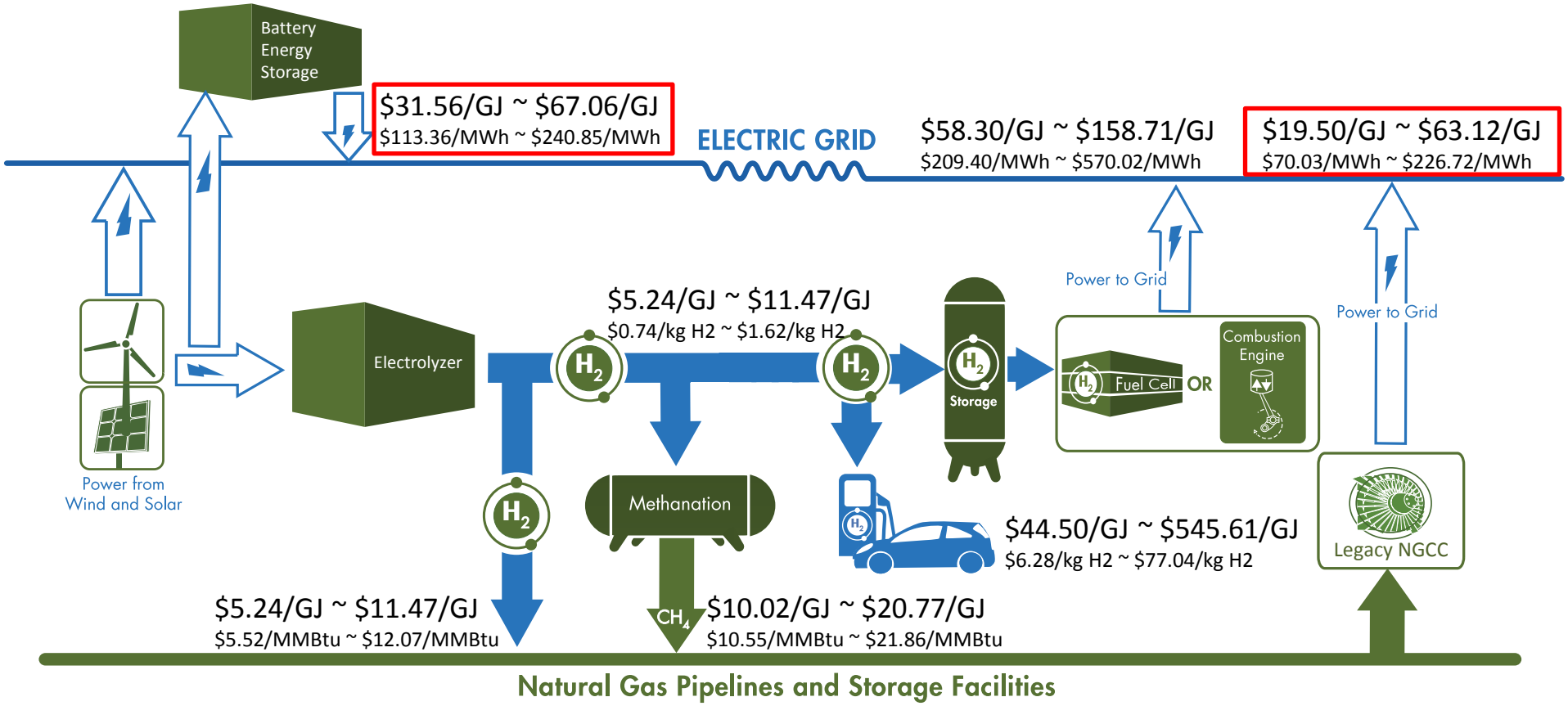


ALL RESULTS PRELIMARY – DO NOT QUOTE

LCORE Results

CURRENT COSTS & EFFICIENCES

45% Capacity Factor for Batteries;
90% Capacity Factor for All Other Equipment



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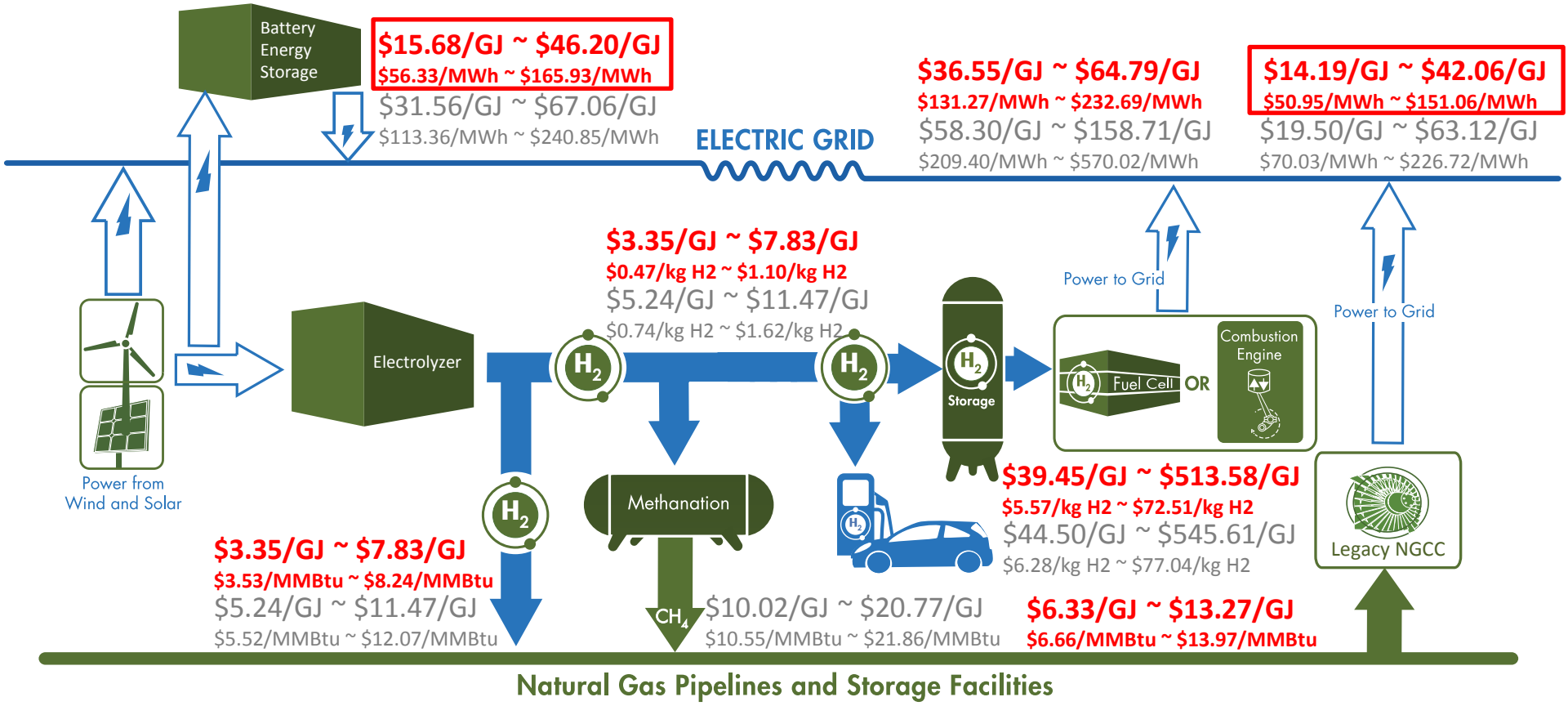

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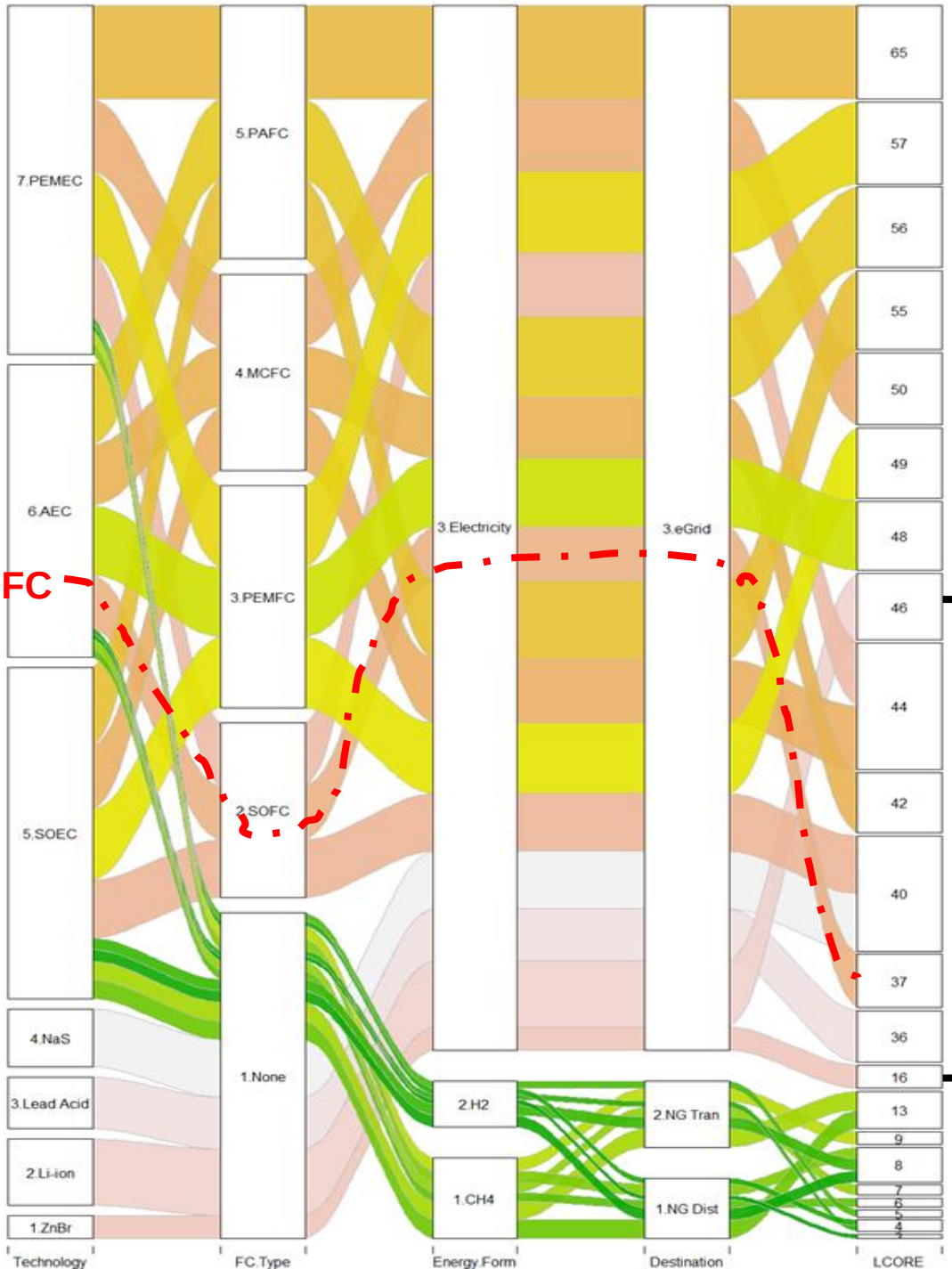
LCORE Results

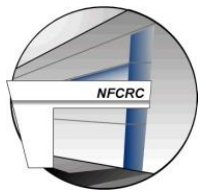
FUTURE COSTS & EFFICIENCES
45% CF for Batteries;
90% CF for All Other Equipment

Alluvial Diagram: Different Presentation, *Same Results*

Pathways compared here:

- Electrolyzer + Fuel Cell = Electricity to Electric Grid
- Electrolyzer + H2 = H2 to Natural Gas Grid
- Electrolyzer + Methanator = Natural Gas to Natural Gas Grid
- Battery Energy Storage = Electricity to Electric Grid





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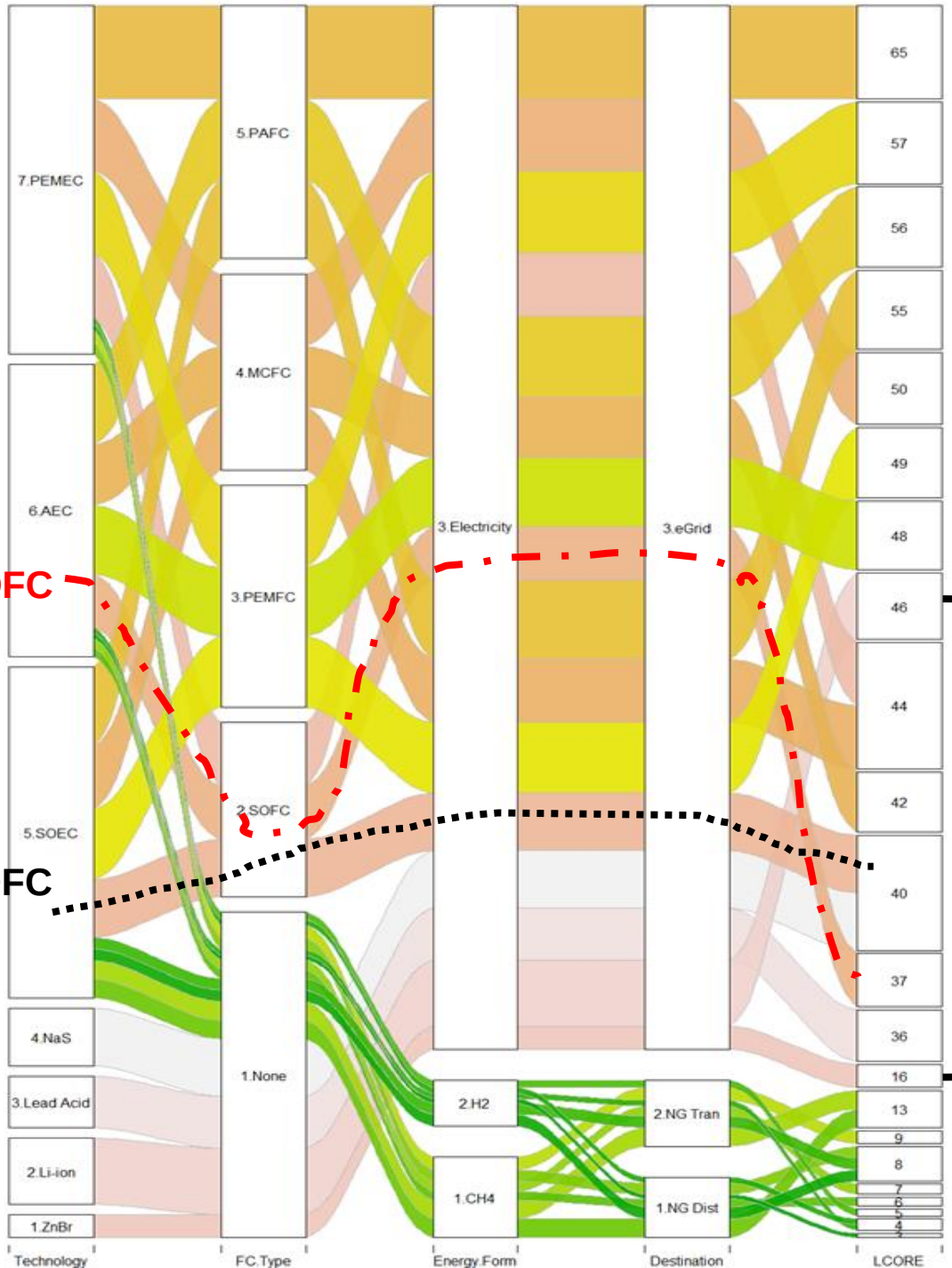

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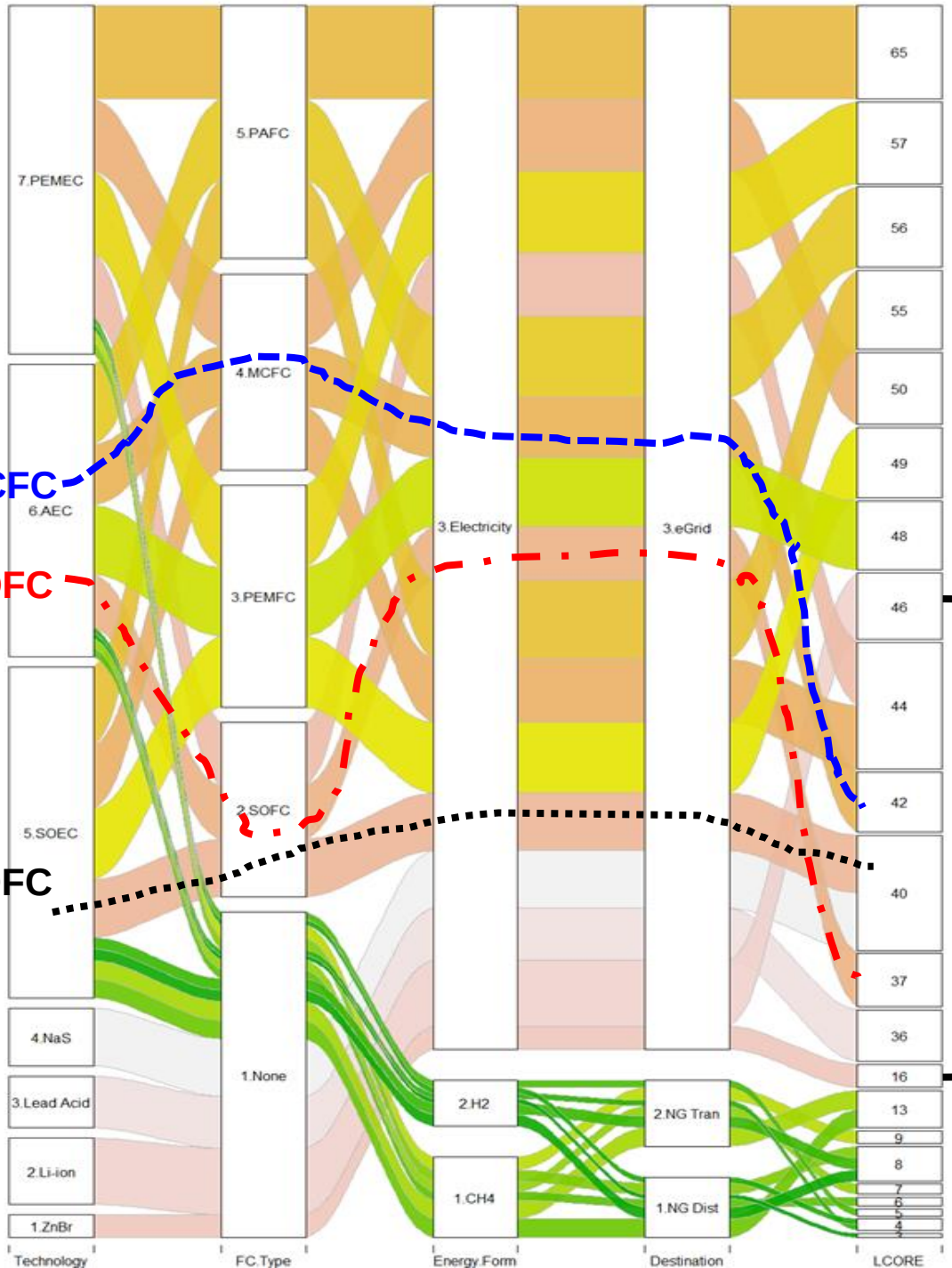

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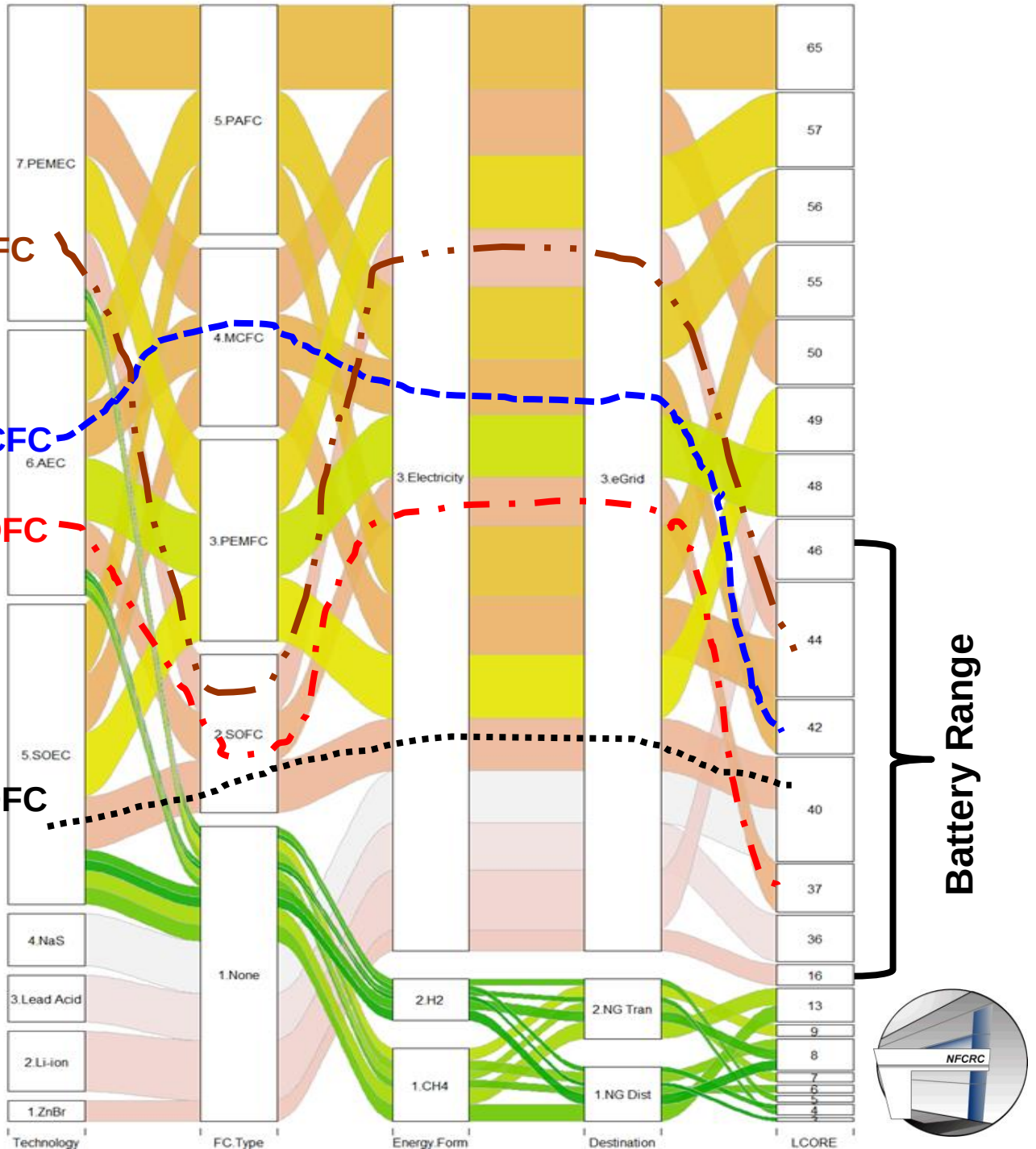
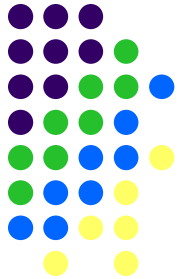
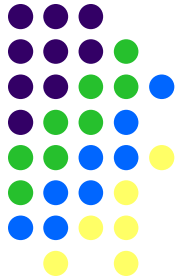


LCORE Results by Use Case: Comparative Economics



- At Current Costs + 50% CF:
  - H2 production for direct fueling quite competitive
  - Batteries more competitive for electricity delivery
- At Current Costs + 90% vs. 45% CF:
  - H2 fuel into legacy central station generation competitive with batteries for electricity delivery
- At Future Costs + 90% vs. 45% CF:
  - H2 & CH4 for pipeline injection competitive
  - H2 for fuel cell electricity generation competitive.

POWER-TO-GAS: LCORE Analysis Conclusions



- Power-to-Gas Can Provide Economic Grid-Scale Storage of Hydrogen Using Otherwise-Curtailed Renewable Generation
- Power-to-Gas Increases Grid and Fuel Flexibility Through Multiple Use Cases
- Current Economics Support Hydrogen Generation for Fueling
- Future Economics Support Hydrogen Use in Fuel Cells for Electricity Generation.

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THANK YOU!

QUESTIONS?

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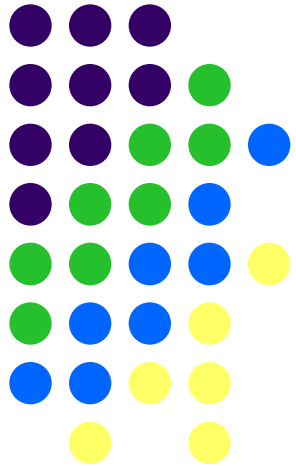

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