May 23rd, 2017



STEPS Sustainable Transportation Energy Pathways

Hydrogen Energy Storage for Renewable-Intensive Electricity Grids

A WECC Case Study

Z. McDonald, C. Yang, J. Ogden, A. Jenn

THE LEIGHTY FOUNDATION

NCST National Center for Sustainable Transportation

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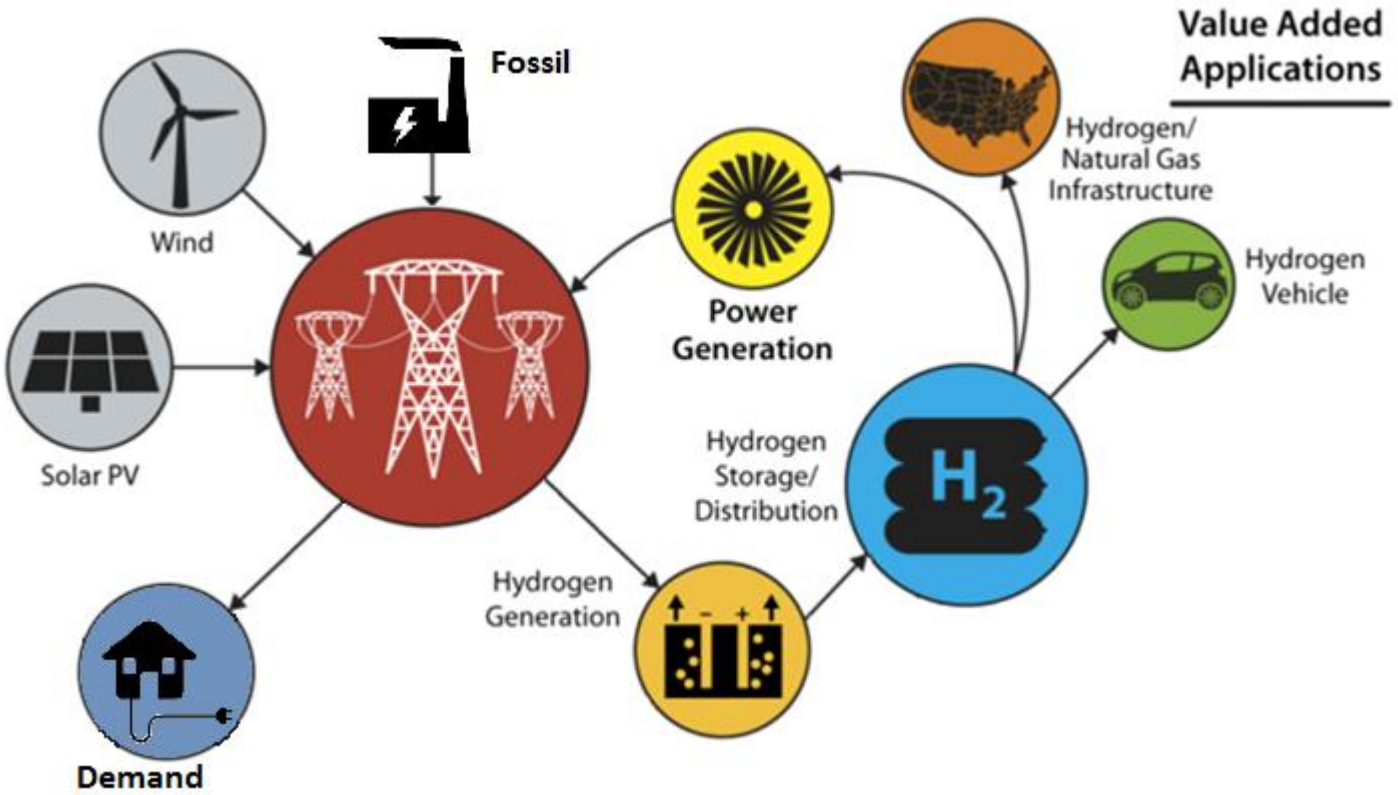
PG&E

ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

Project Structure

Investigate the feasibility and costs/benefits of hydrogen energy storage (HES)

Analyze incorporating polymer electrolyte membrane (PEM) electrolysis into a high-renewable 2050 scenario to produce low-carbon H_2 for diverse energy applications



- **Integration of intermittent renewables**
- **Grid supply and demand shaping**
- **Produce low cost H_2**
- Reduced cost to operate the grid
- Grid services – ramping, frequency reg, black start, spinning reserve

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1. Kothari, R., Buddhi, D., & Sawhney, R. L. (2008). Comparison of environmental and economic aspects of various hydrogen production methods. *Renewable and Sustainable Energy Reviews*, *12*(2), 553–563. http://doi.org/10.1016/j.rser.2006.07.012

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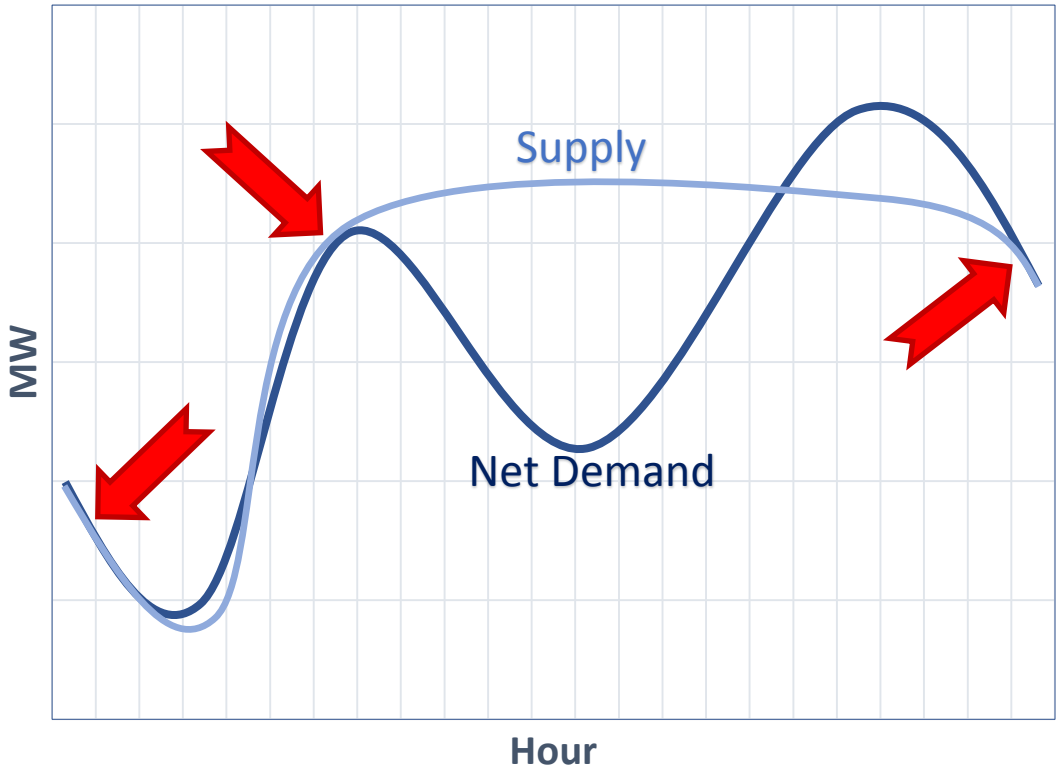

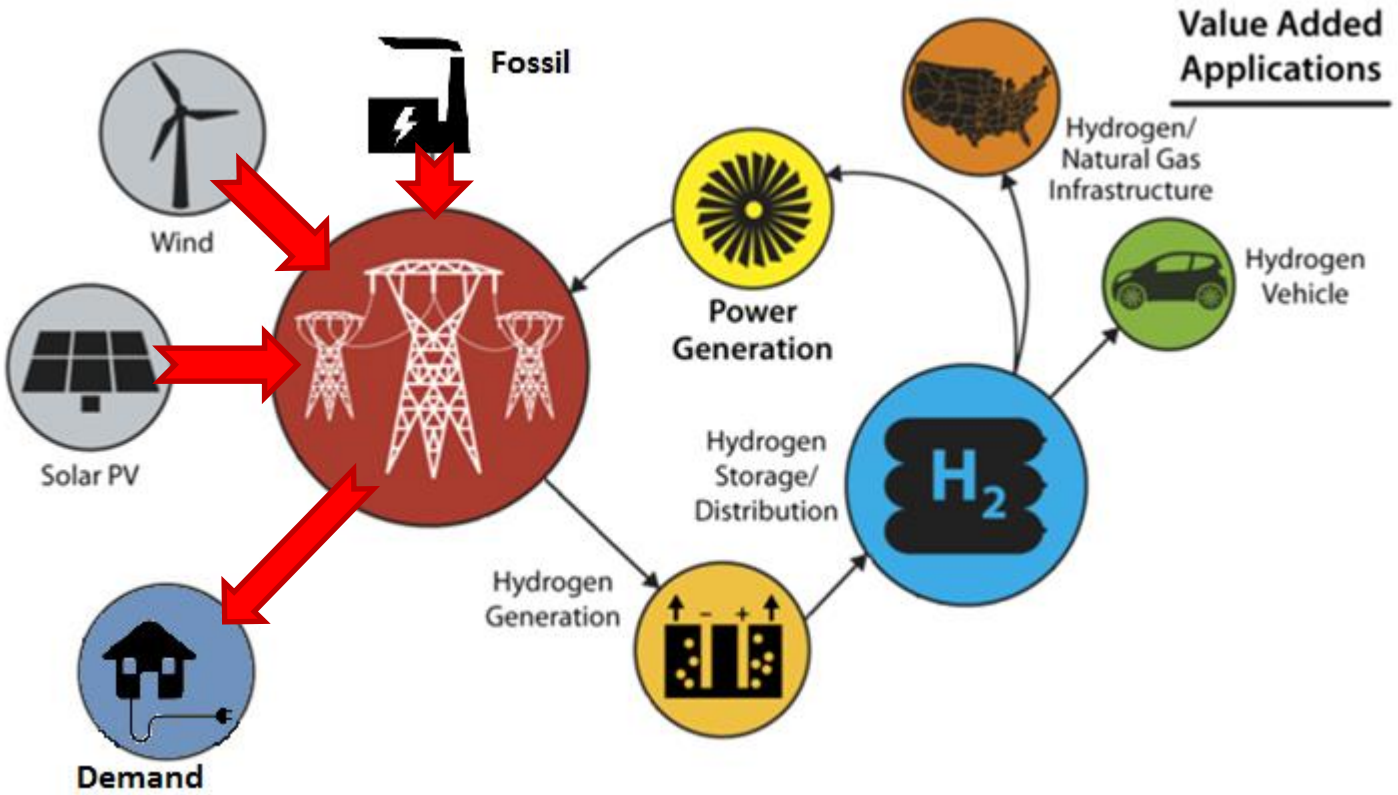

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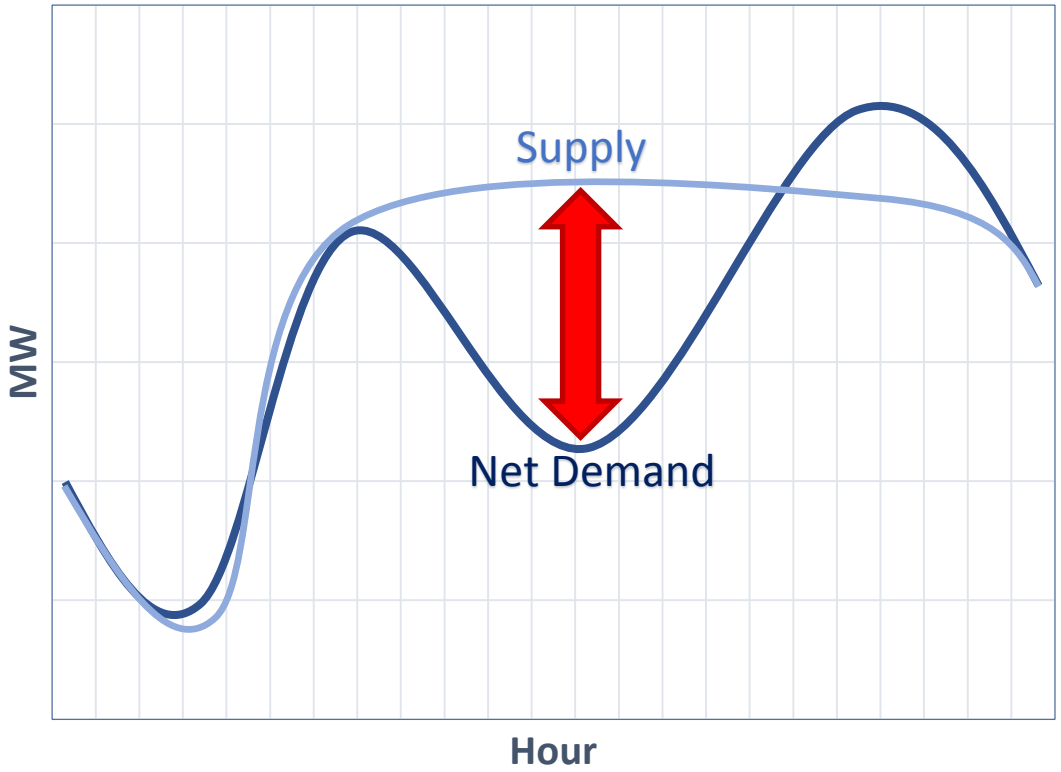

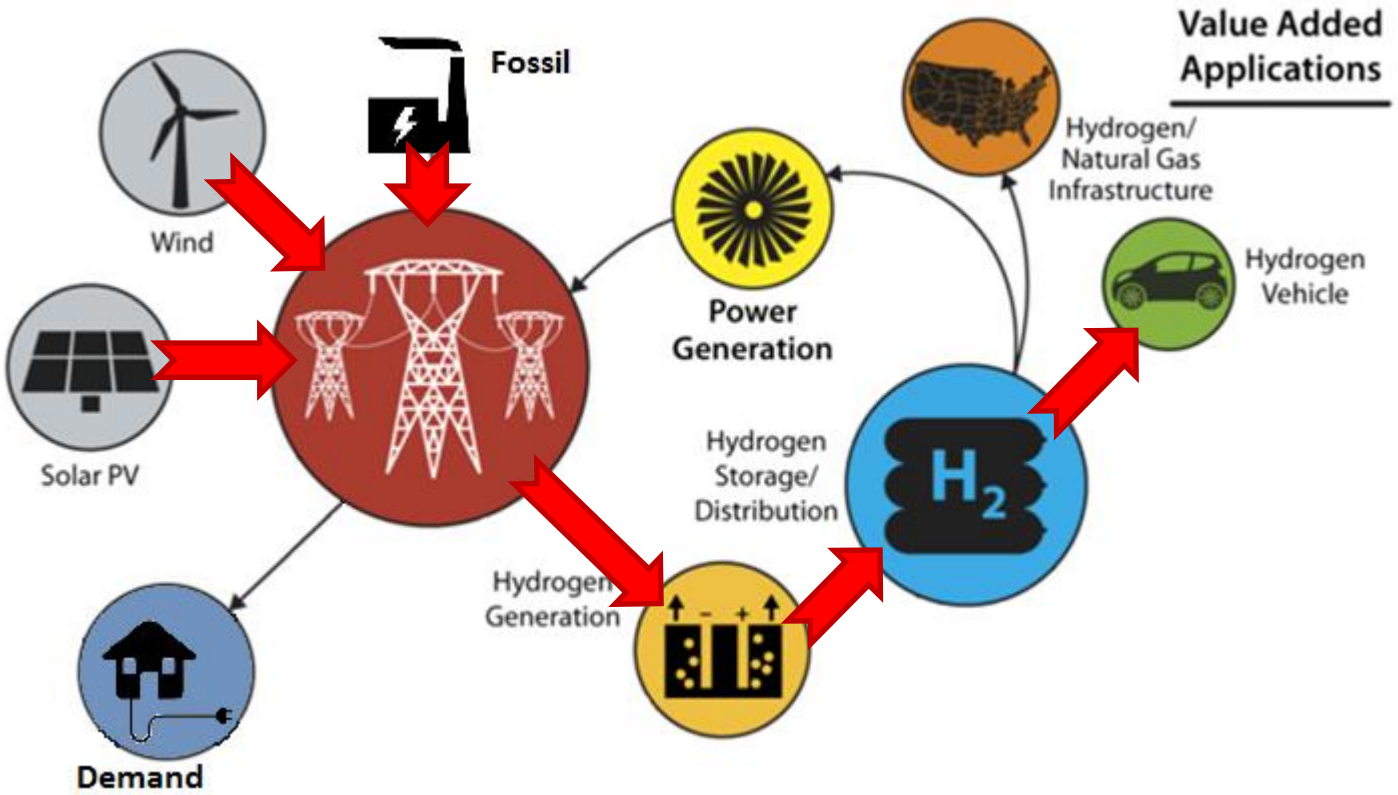

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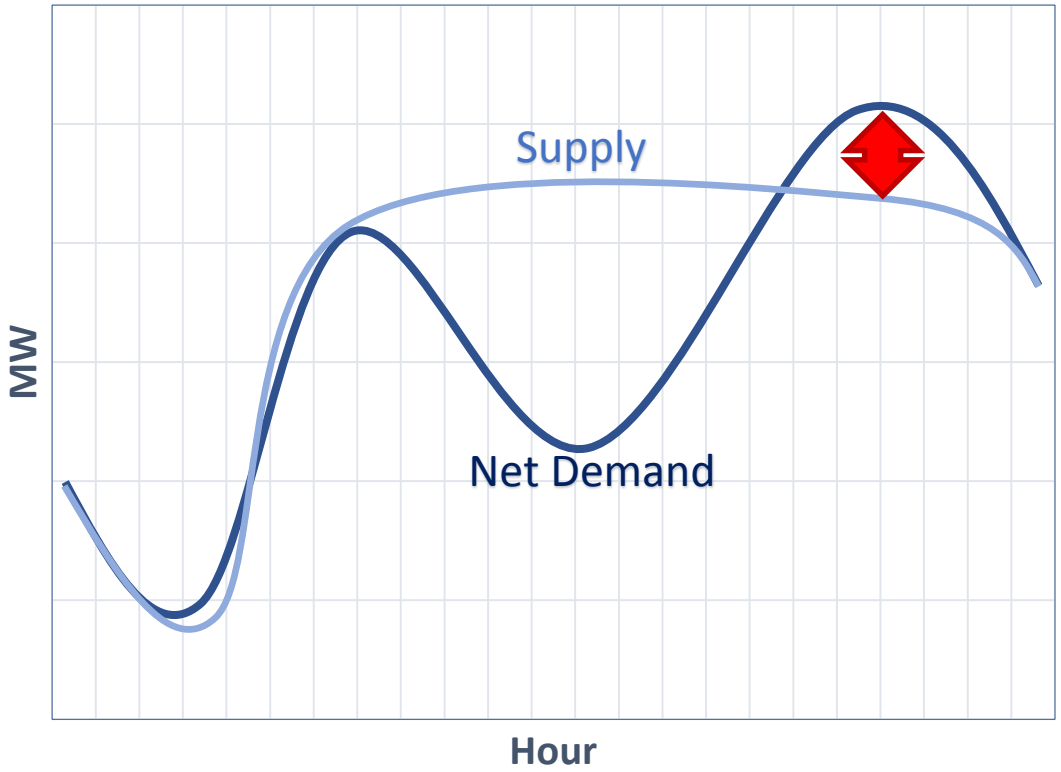

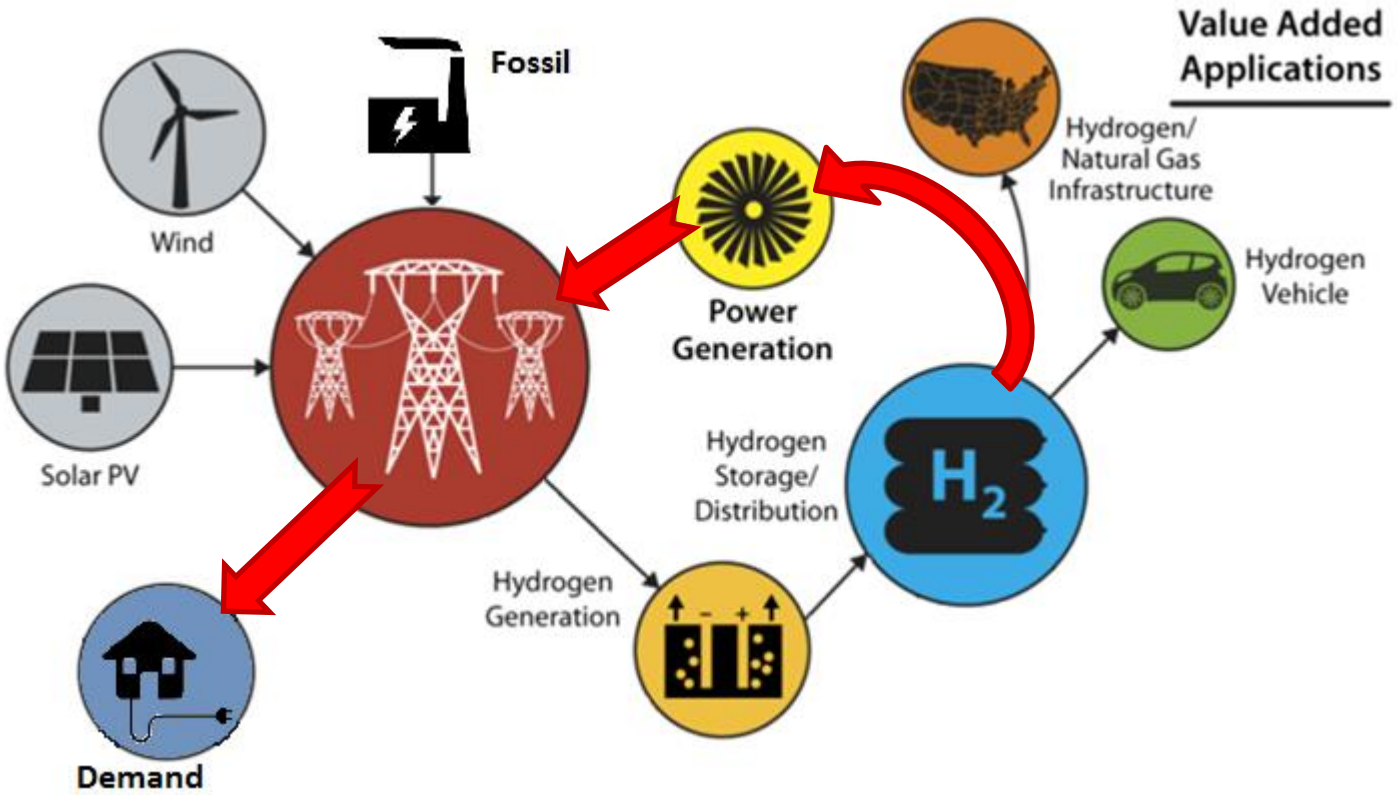

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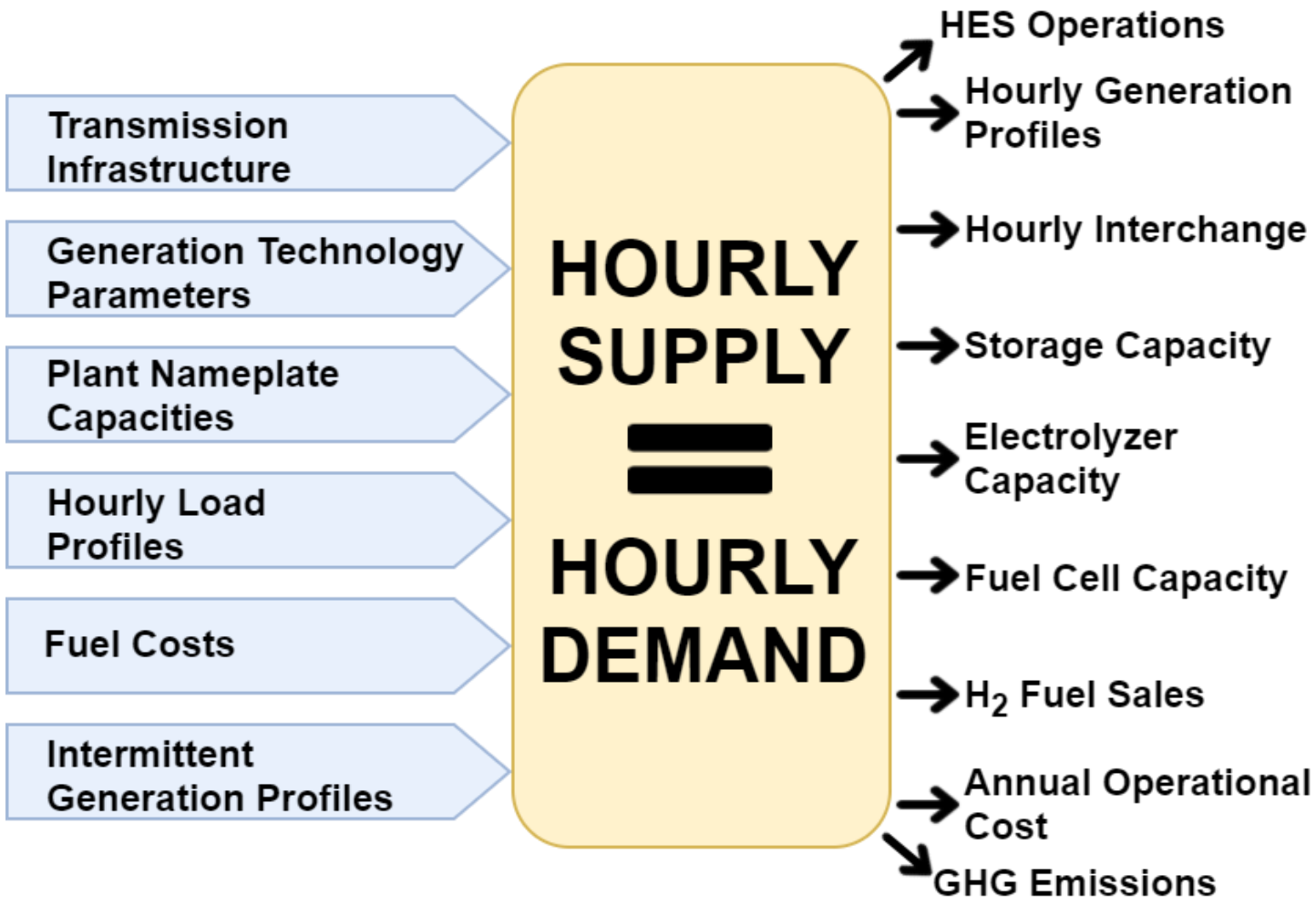
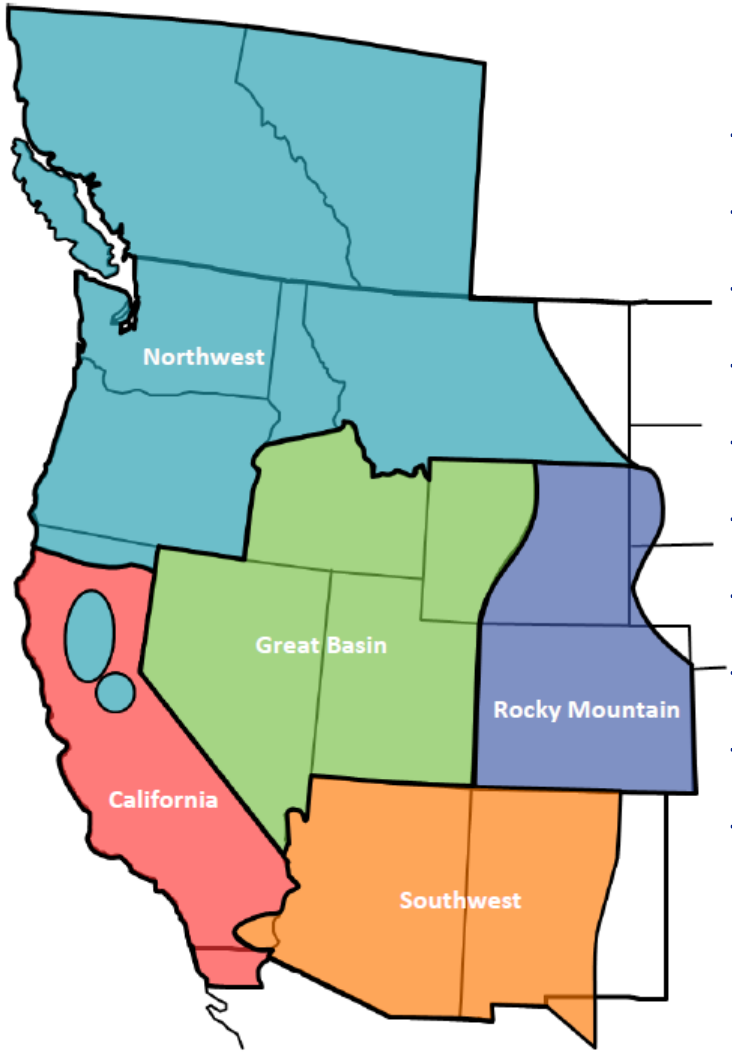
Methodology – Developing an economic dispatch model

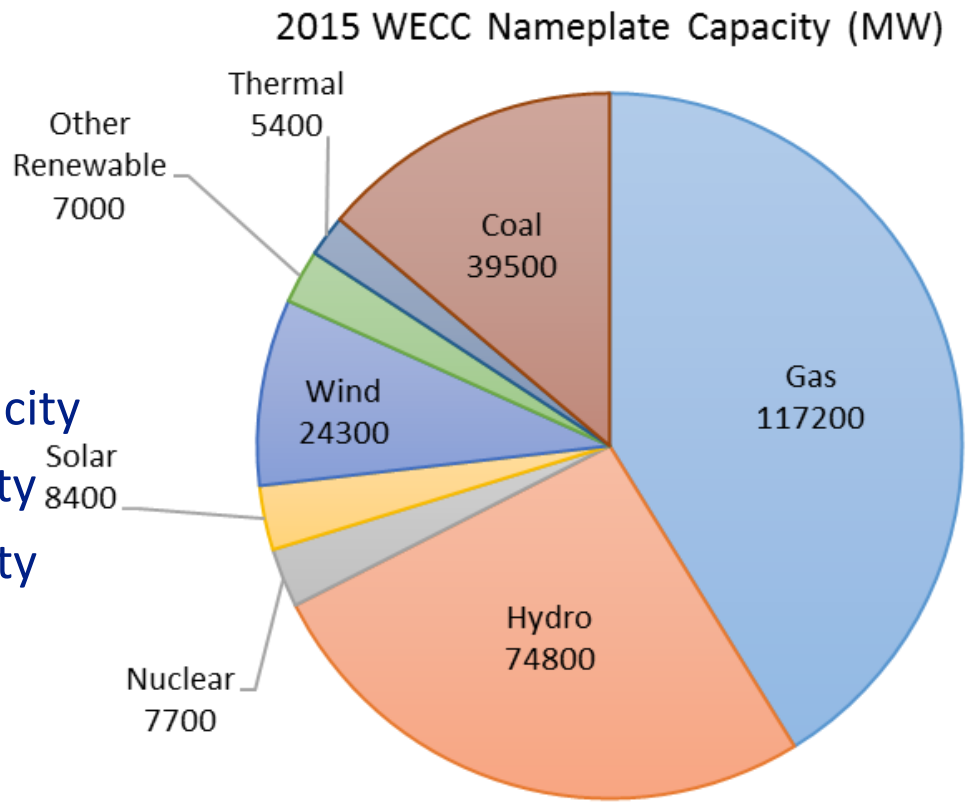
- Economic dispatch is utilized to optimize the operation of a hydrogen energy storage system
- Determine what characteristics are formative in optimally operating a hydrogen energy storage system
- Analyze these characteristics and their potential impact on a transition to alternative generation integration andlong-term viability of alternative transportation fuels



Western Electricity Coordinating Council



- 2 Canadian Provinces
- 14 states (whole or fractional)
- Northern Baja, Mexico
- 82.2 mil in population
- 4.7 mil km^2
- 284,300MW total installed capacity
- 80% of installed US solar capacity
- 30% of installed US wind capacity
- Coal trending down
- Solar and wind trending up



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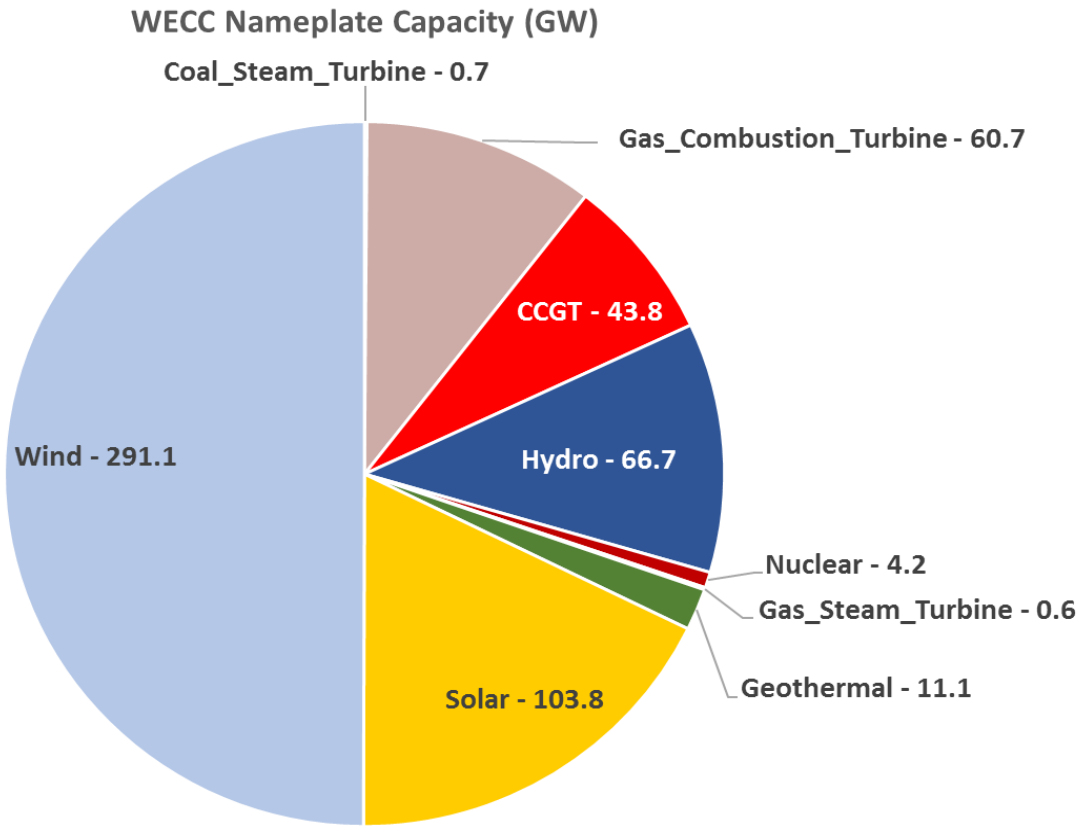
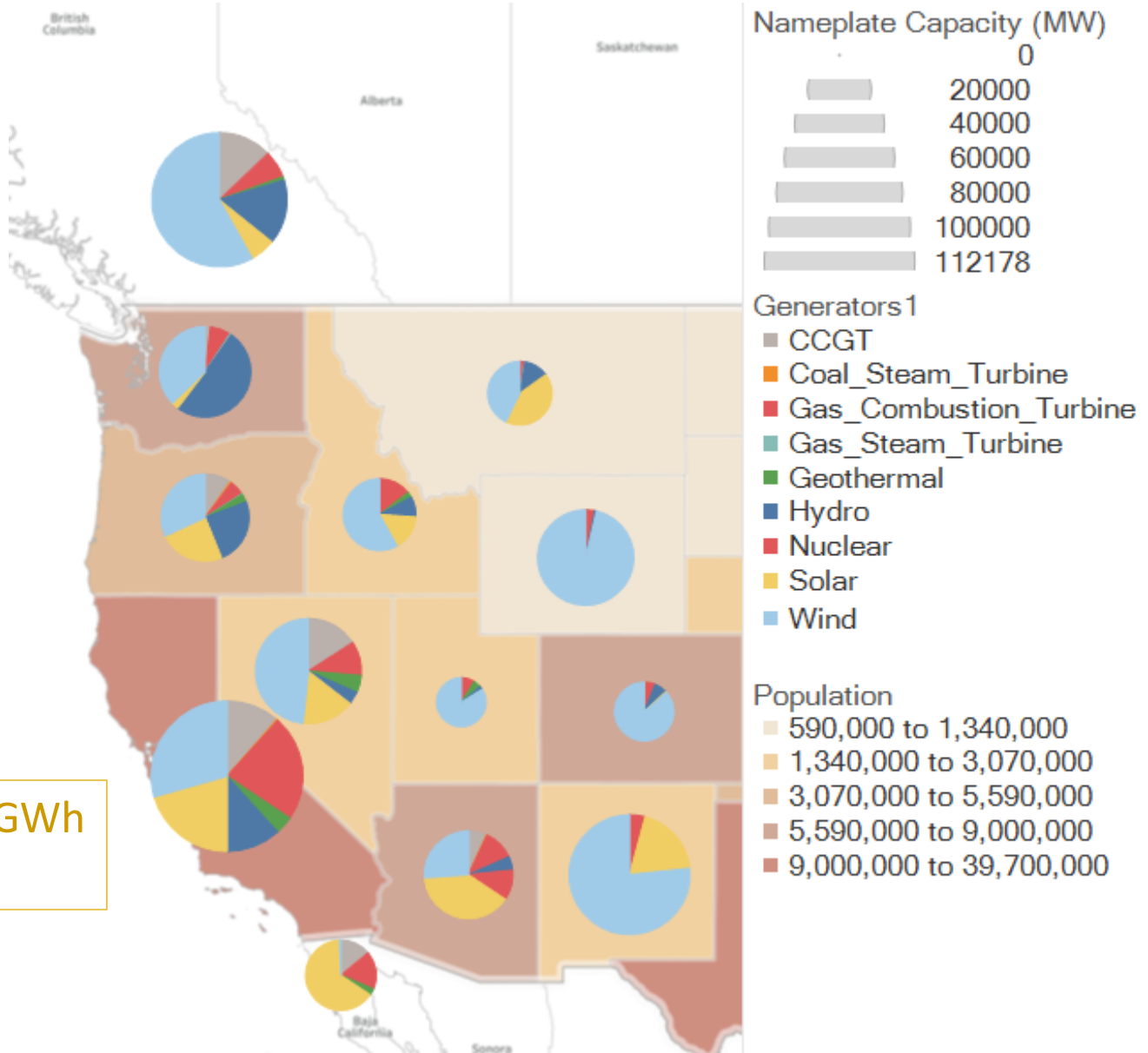
Western Electricity Coordinating Council. (2015). 2015 State of the Interconnect. *CIO*, (January), 1–5. Retrieved from http://www.cio.com/documents/pdfs/2015 State of the CIO Exec Summary.pdf

WECC in 2050 – High Intermittent Renewables





Average Hourly Demand: 163.9 GWh
Peak Hour Demand: 248 GWh

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Modeling Parameters and Assumptions

- FCEV ≈ 8-15% of WECC PLDVs in 2050 (Approximately 6.8 million in the WECC)
- 93% transmission efficiency
- Current policy goals are met
- Hydro dispatch constrained to 10 year monthly avg flowrate and ecological regulation
- Advanced H_2 storage technology (1000USD/MWh, 10yr lifespan)
- Polymer Electrolyte Membrane Electrolyzer (640/kW, 10yr lifespan)
- Polymer Electrolyte Membrane Fuel Cell (660/kW, 10yr lifespan)
- Perfect foresight for grid operation
- No outages or malfunctioning
- No ramping constraints or minimum operating time

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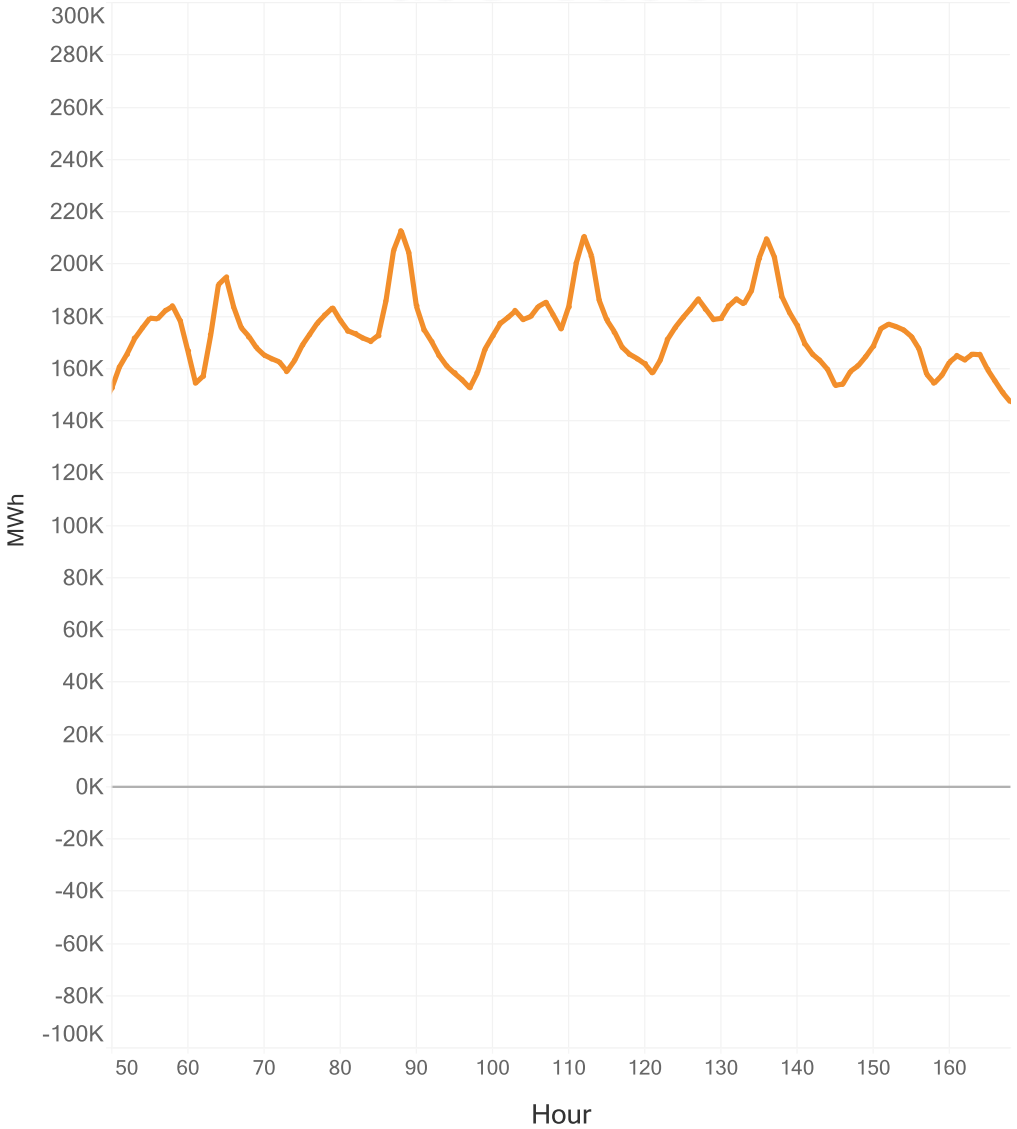
2050 base case modeling

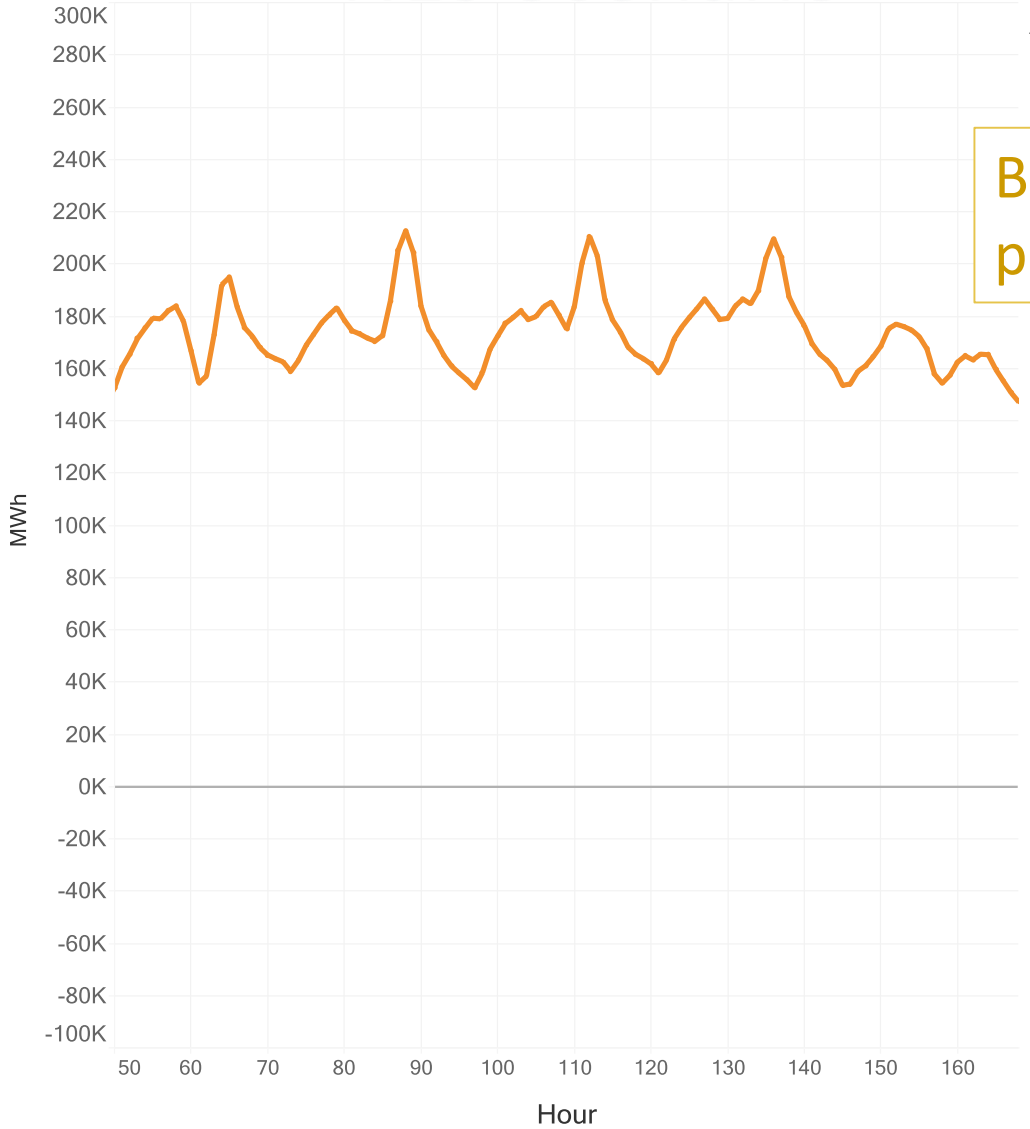
COSTS AND BENEFITS OF H_2 ENERGY STORAGE

Comparison of base case (no storage) to HES Scenario

Base Case



HES Scenario

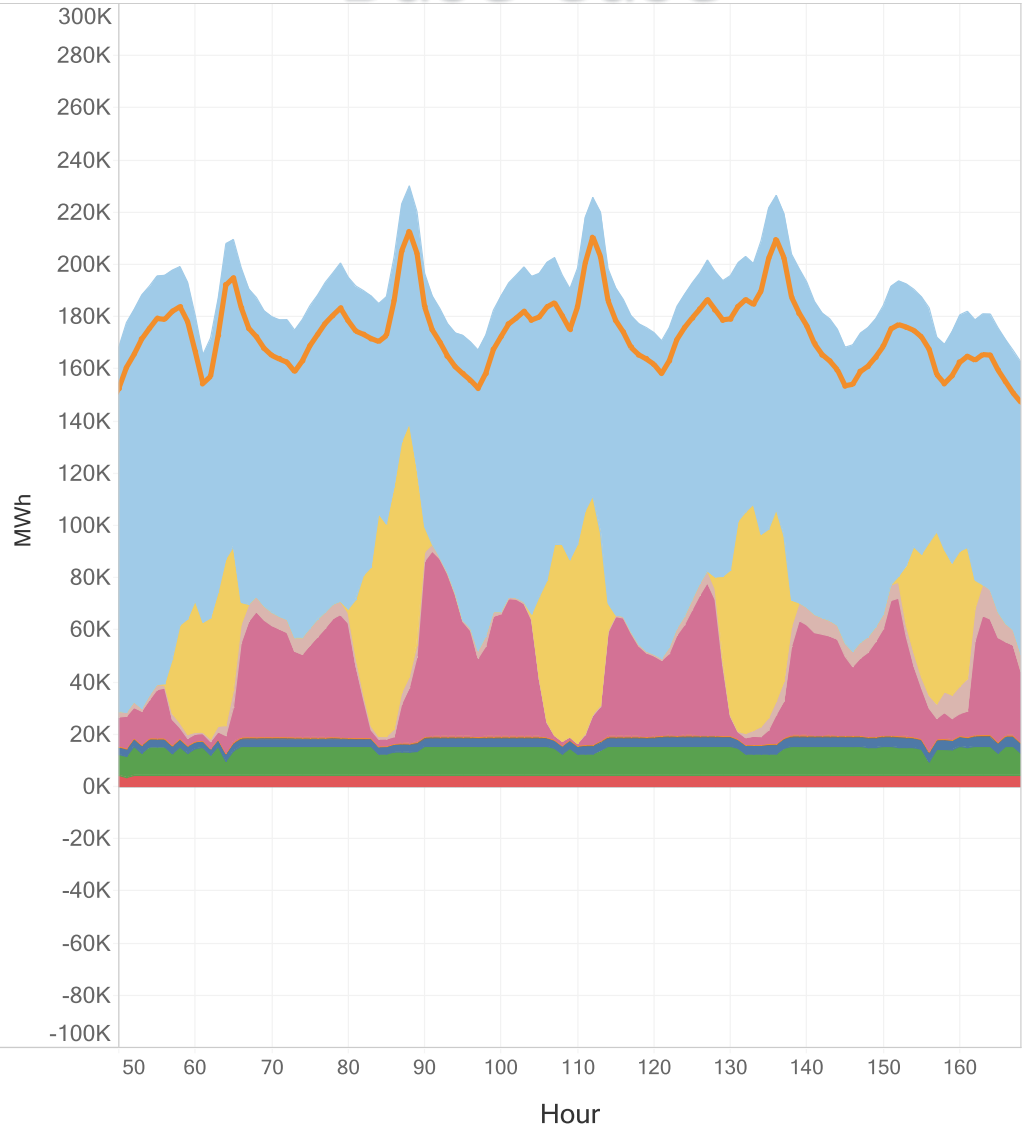


Activity
■ Demand, MWh

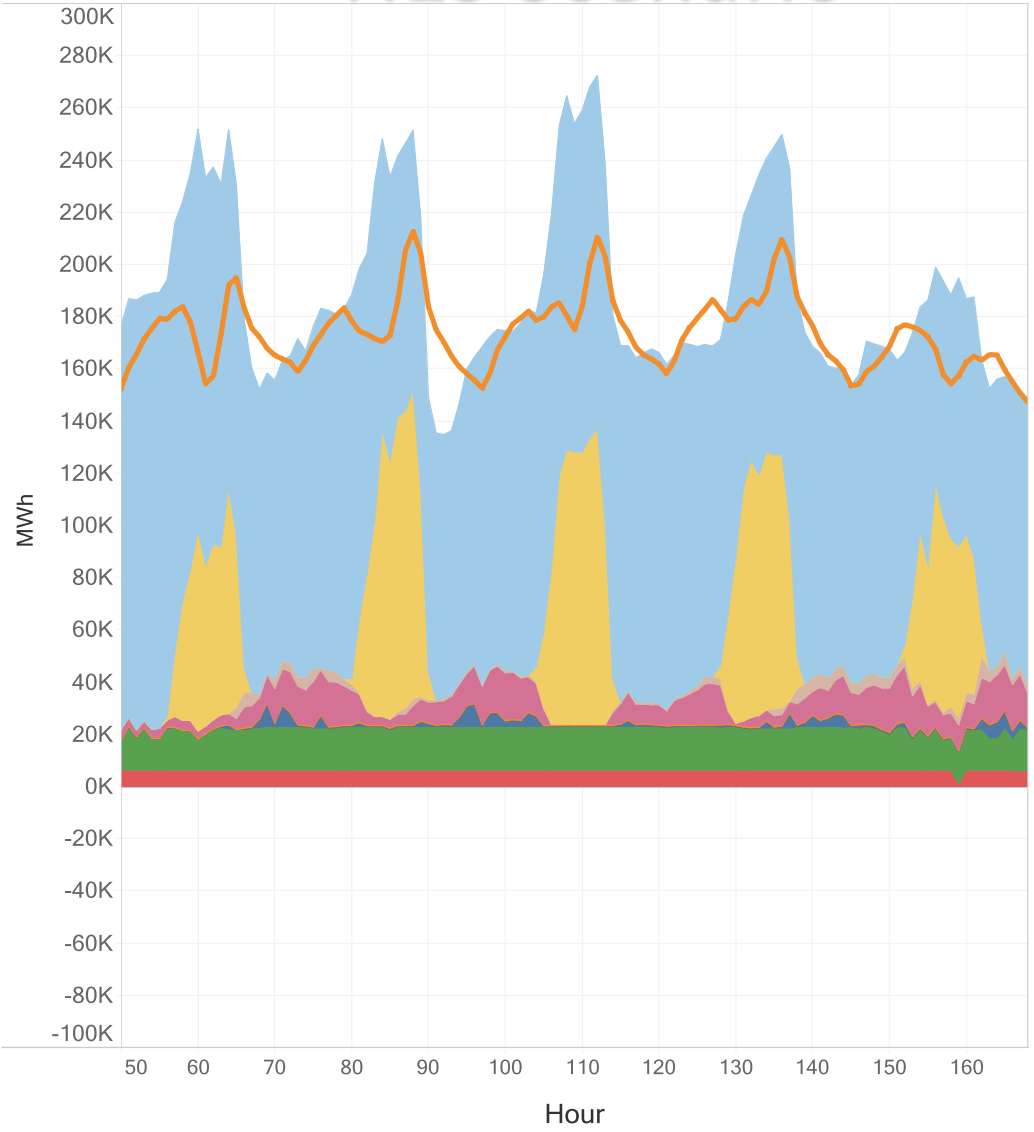
Both demand profiles are equal

Comparison of base case (no storage) to HES Scenario

Base Case



HES Scenario

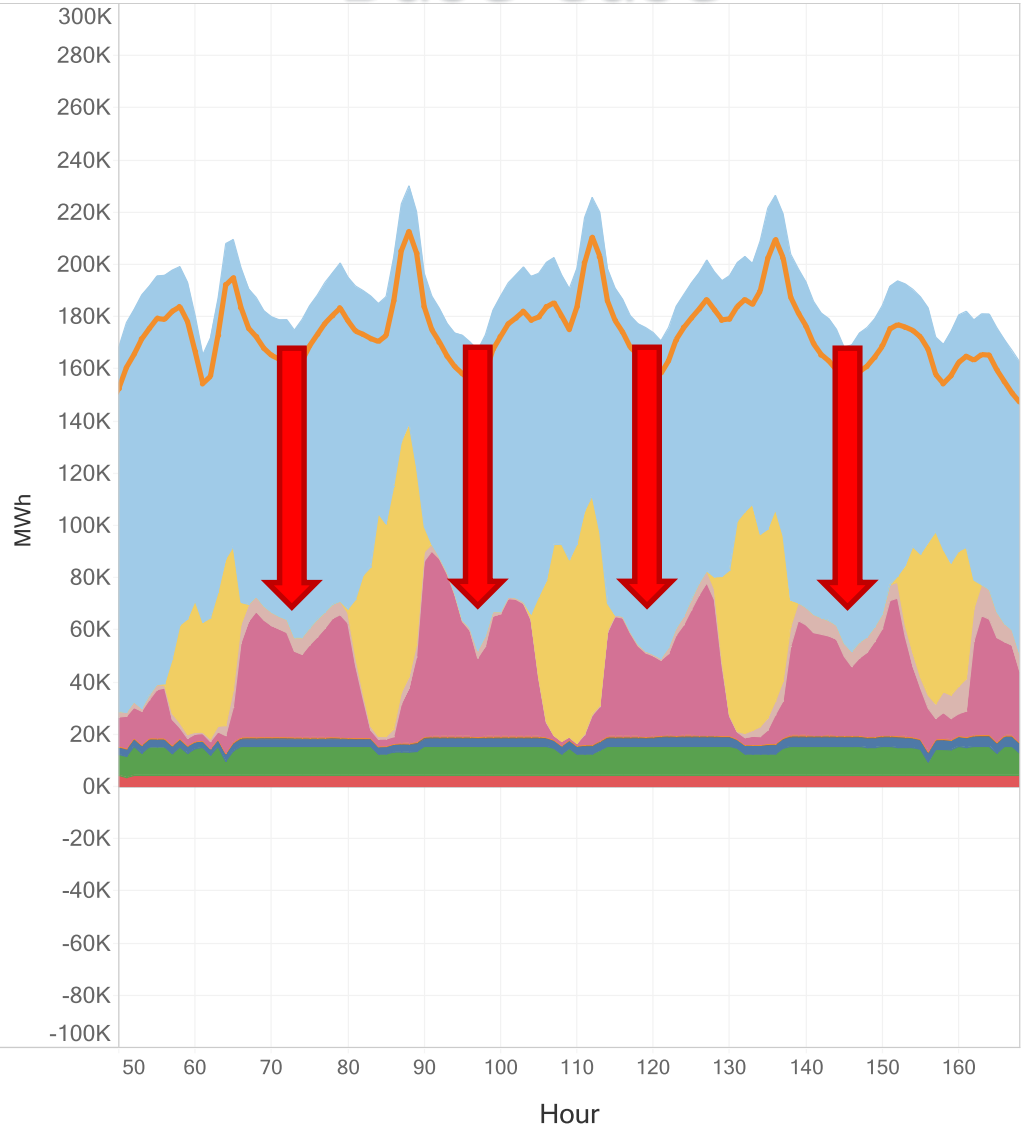


Activity
- Demand, MWh

Generation Technology
- Wind
- Solar
- CCGT
- Gas_Combustion_Turbine
- Gas_Steam_Turbine
- Coal_Steam_Turbine
- Hydro_NonPumped
- Geothermal
- Nuclear

Comparison of base case (no storage) to HES Scenario

Base Case



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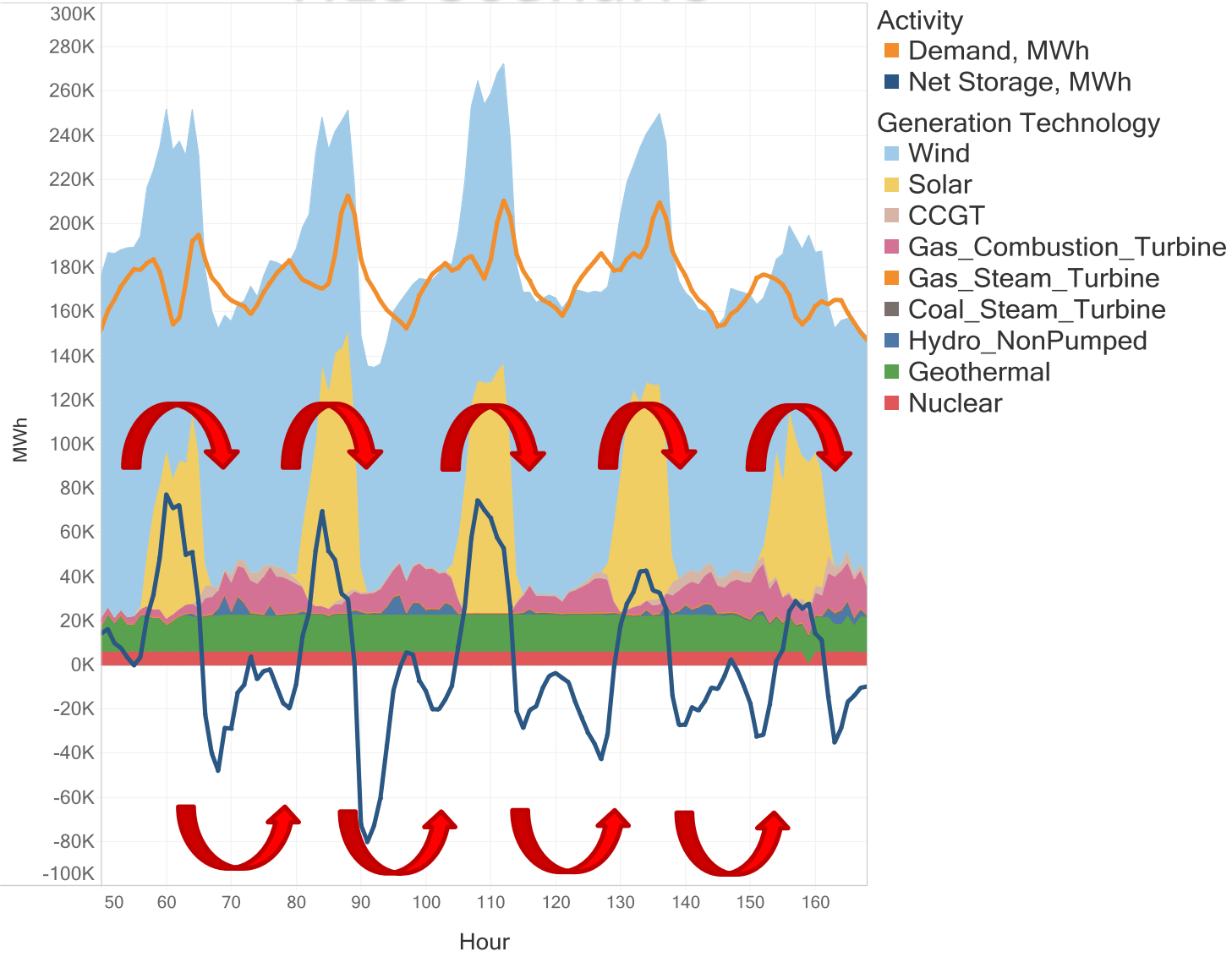

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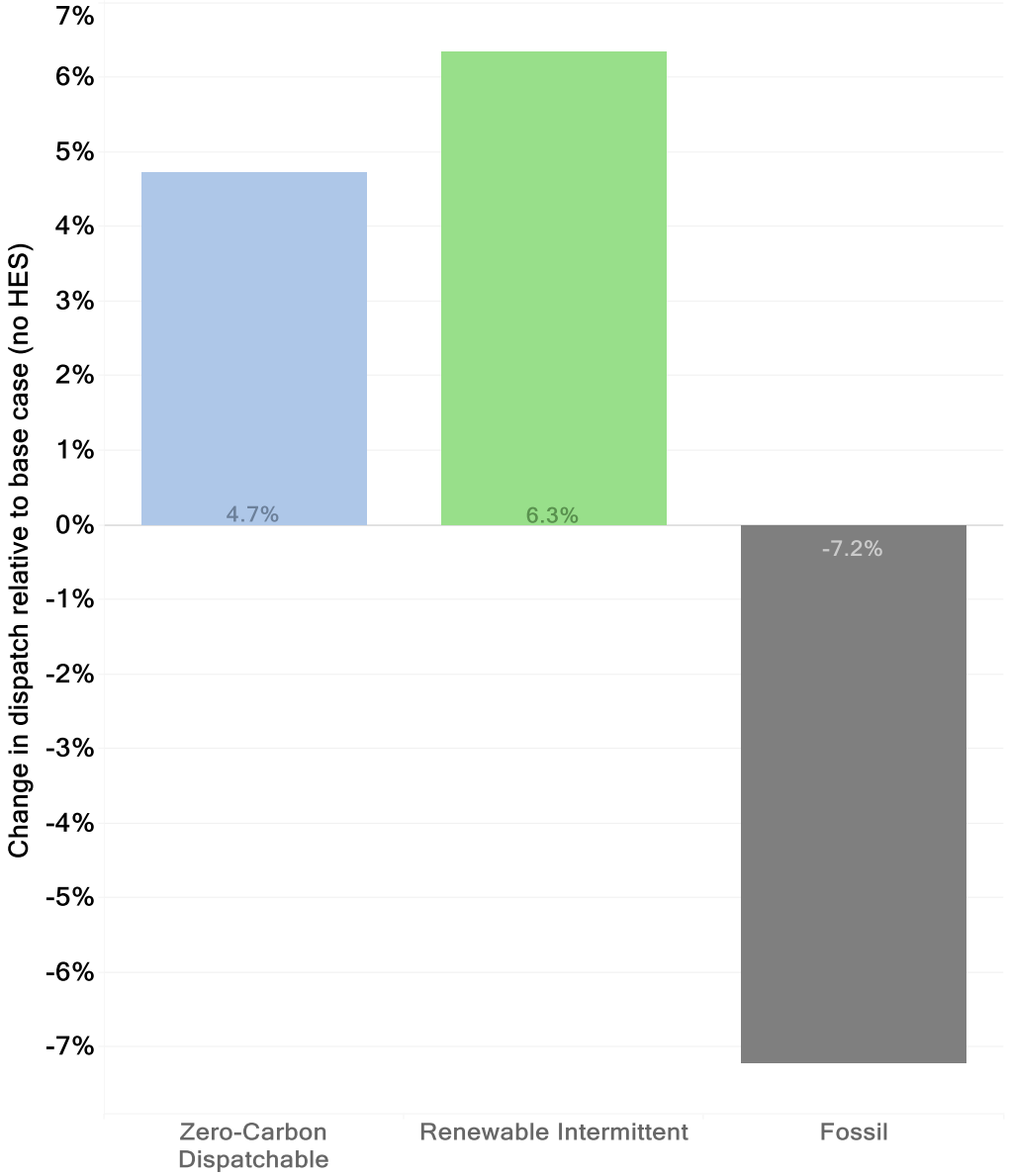

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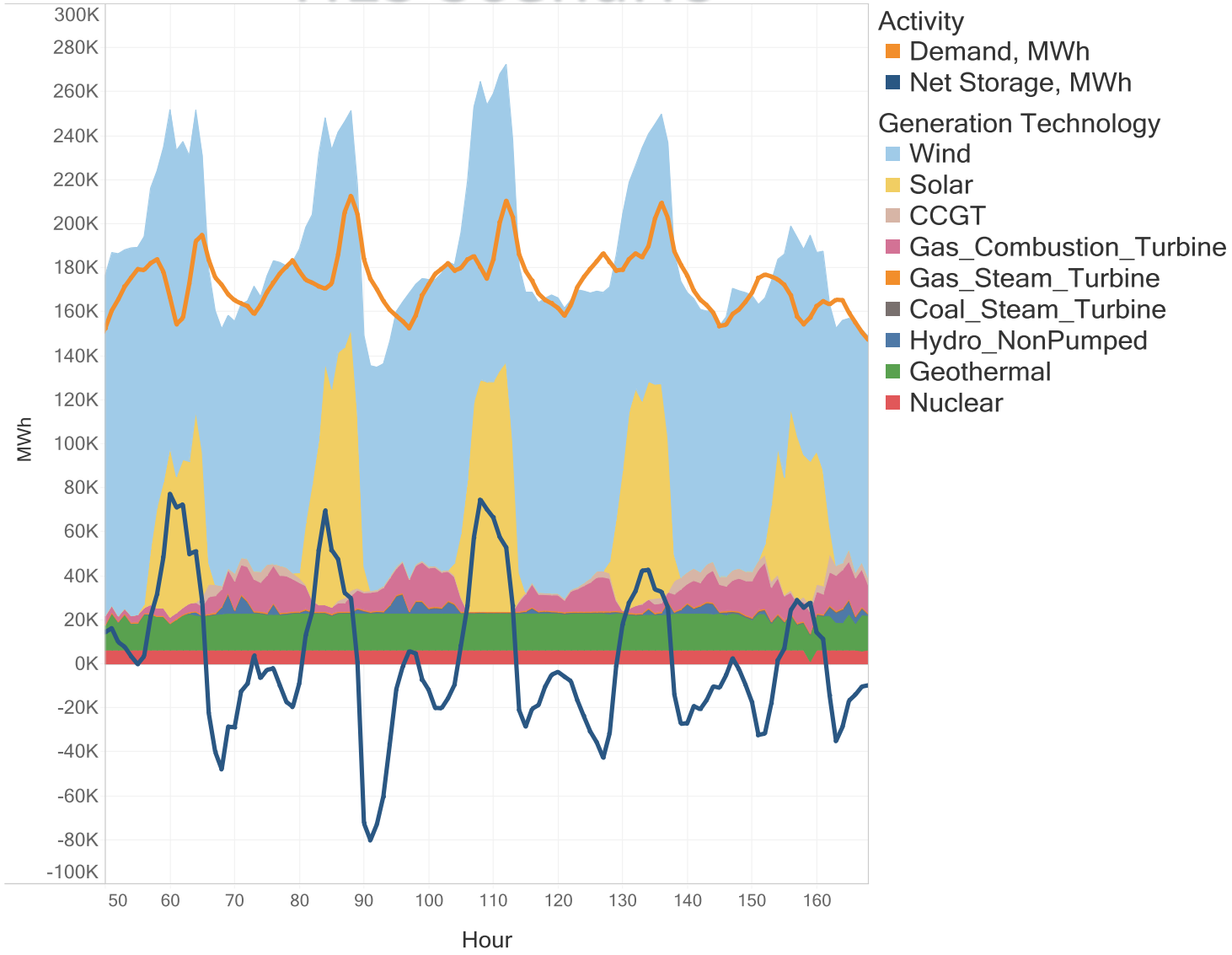
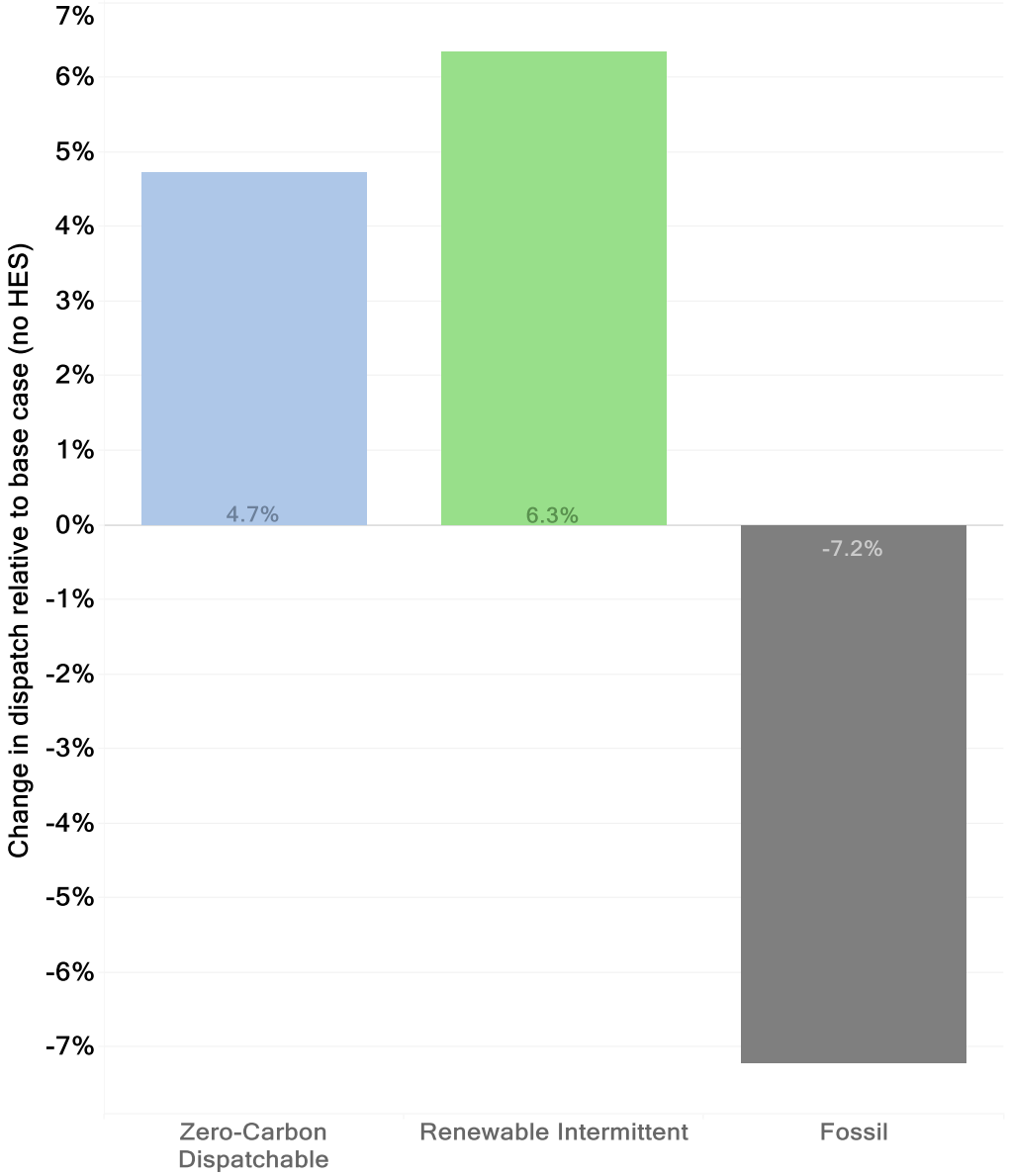


Comparison of base case (no storage) to HES Scenario



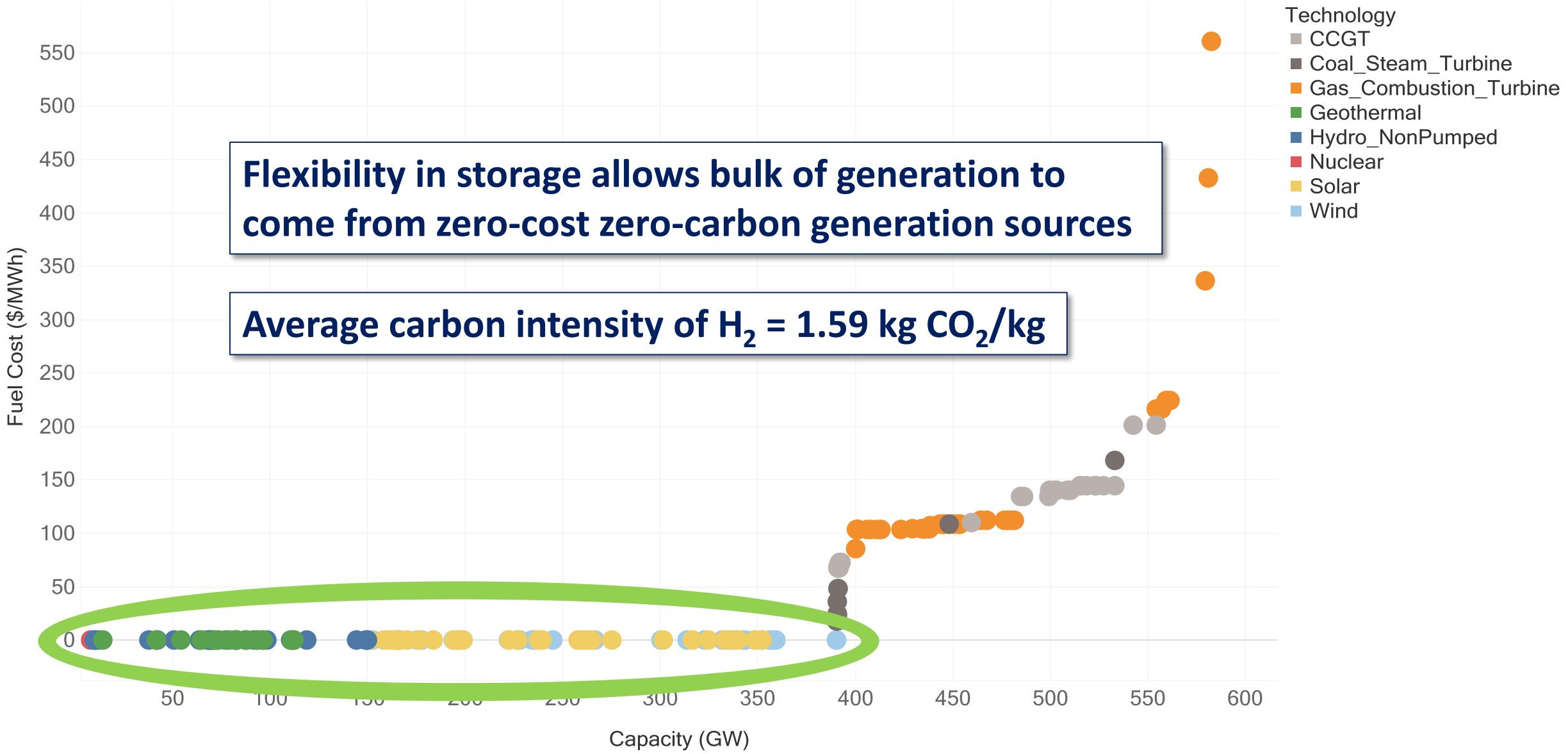
Base Case

Carbon Intensity (g CO_2/kWh)	Fossil Fuel Emissions (Mtonnes CO_2 (annual))	Curtailed Wind + Solar (TWh (annual))	H_2 generated for FCEV fuel (ktonnes (annual))
77.61	30.28	133.1 ≈ 31% curtailment	0

HES Scenario

Carbon Intensity (g CO_2/kWh)	Fossil Fuel Emissions (Mtonnes CO_2 (annual))	Curtailed Wind + Solar (TWh (annual))	H_2 generated for FCEV fuel (ktonnes (annual))
64.89	26.54	≈ 26% curtailment 115.1	477 ≈ 4.3M FCEVs @ $4.24/kg

Dispatch Supply Curve



Flexibility in storage allows bulk of generation to come from zero-cost zero-carbon generation sources

Average carbon intensity of H_2 = 1.59 kg CO_2/kg

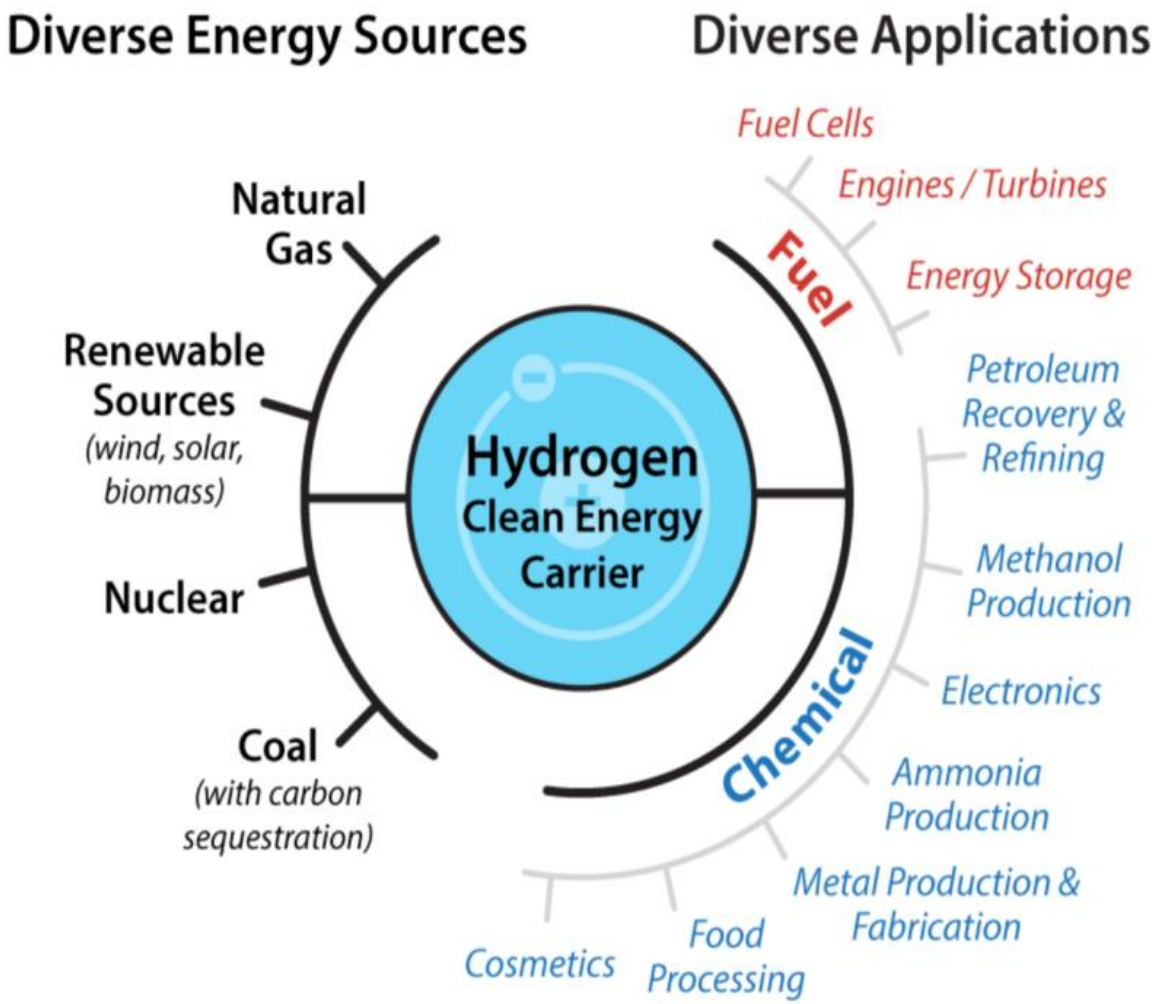
Preliminary Conclusions

- High renewable penetration yielding a continuous surplus of (free) electricity results in a favorable scenario for HES
- Majority of the value of HES comes from providing H_2 for transportation fuel
- Majority of the value of HES for arbitrage is seen in < 24hr turn around
- Increased integration of HES results in
  - reduced cost to generate through increased utilization of low cost generation sources
  - reduced emissions of greenhouse gases through increased utilization of renewable generation sources
- HES systems have the capacity to, in a high renewable grid, produce H_2 for millions of FCEVs at projected competitive prices to gasoline

Future Work

- Exploration of various scenarios
  - High penetration FCEVs
  - Less optimistic H_2 production scenarios
  - High efficiency / high(er) electrification
  - Cheap fossil fuels
- Comparison of various storage techniques
  - Li-ion Battery Storage
  - Compressed Air Energy Storage

Questions?



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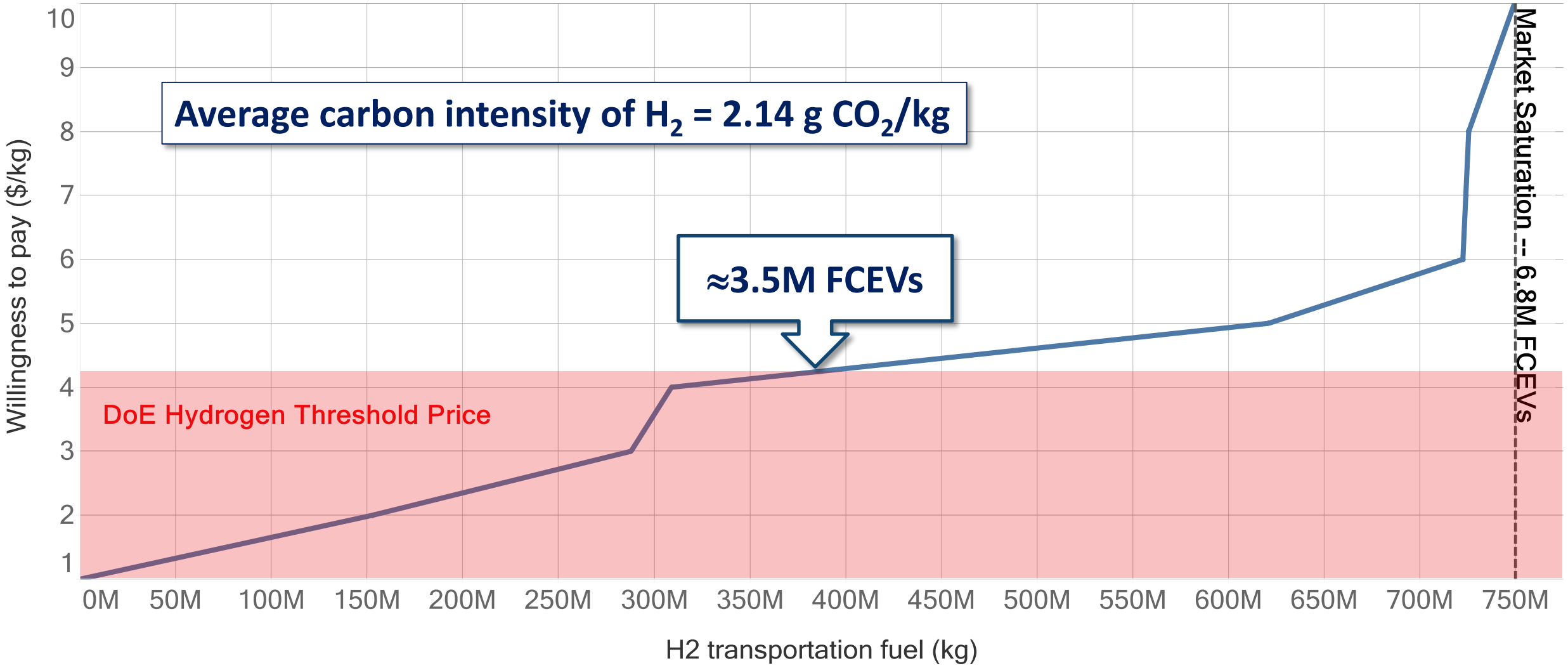
Low carbon transportation fuel



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Notable California / WECC Policies, Initiatives, and Goals

- SB32 – California Senate
  - Reduce GHG emissions to 40% below 1990 levels by 2030
- Zero Emission Vehicle (ZEV) Mandate – California Air Resources Board
  - Electric vehicles representing 15% of all new vehicle sales in 2025
- Clean Vehicle Rebate Program (CVRP)
  - Financial incentive available to purchasers of ZEVs
- Renewable Portfolio Standards – Senate Bill 350
  - Public utilities must procure at least 50% of electricity from renewable sources by 2030
- CA Energy Storage Mandate
  - 1,325 MWh by 2024
- California Solar Initiative
  - 3,000MW of distributed solar by 2016
- Net Energy Metering
  - CA subsidies for distributed generation

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