NREL NATIONAL RENEWABLE ENERGY LABORATORY

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Decision-Making Support Tools for the Hydrogen Economy

(Herramientas para el Apoyo a la Toma de Decisiones en el Desarrollo de Proyectos de Hidrógeno y PtX)

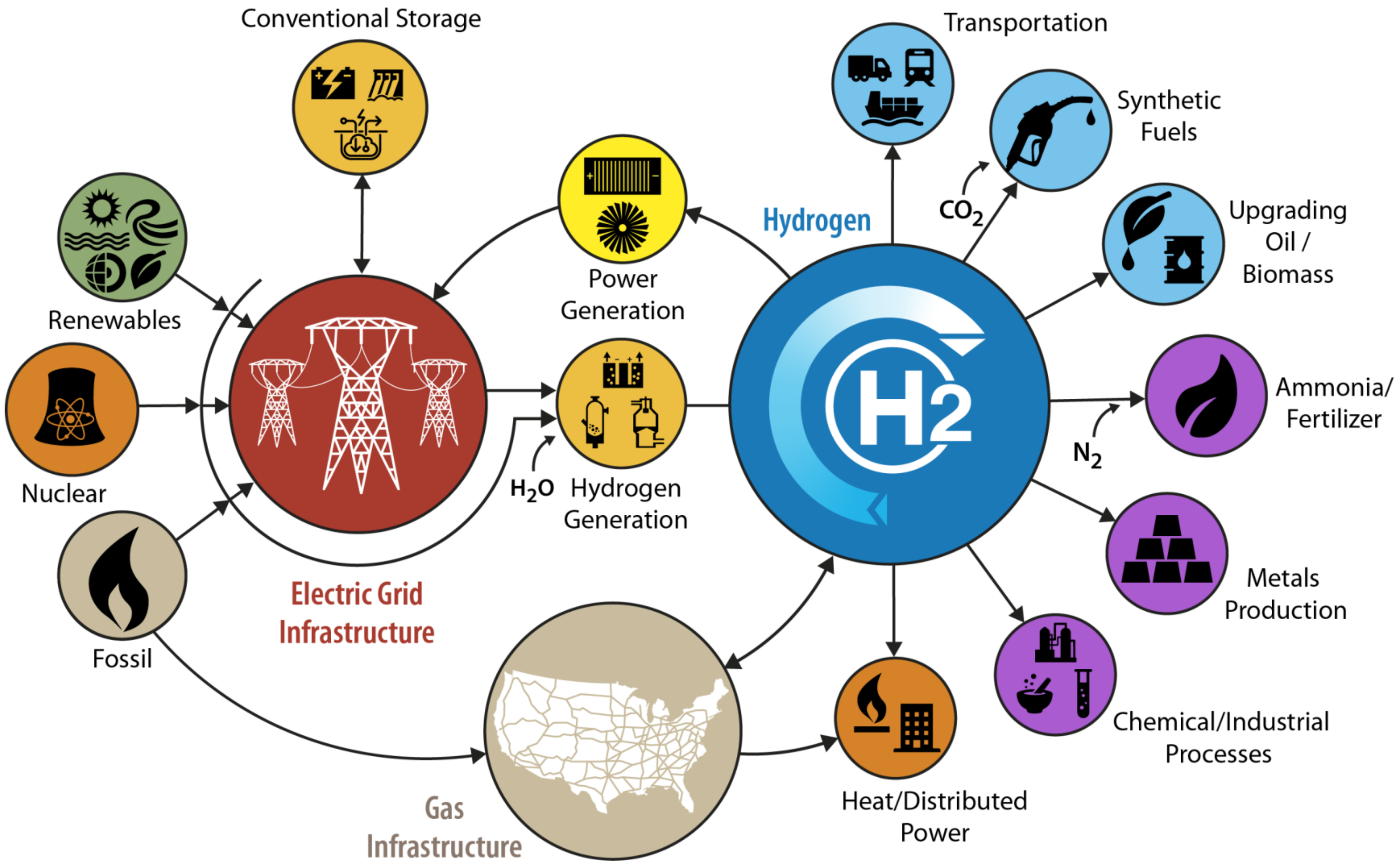
Omar José Guerra Fernández
e-mail: omarjose.guerrafernandez@nrel.gov

Research Engineer
Grid Planning and Analysis Center (GPAC)
National Renewable Energy Laboratory (NREL)

Contents

Contents

Why hydrogen?



Hydrogen is a flexible and potentially a zero-carbon emission energy carrier that could enable the integration of different energy systems.

Considerations for Hydrogen Projects (Based on United States Market)

Largest long-term H2 feedstock TAM

Sector	End-use	Role of H2 in decarb.	Description of switching costs	H2 feedstock TAM[1], $ billion 2030	2040	2050	H2 market size with full adoption[2], $ billion 2030	2040	2050
Industry	Ammonia		**Low:** Process currently uses fossil-based H2, hydrogen supply feed in place	4-10	4-11	5-12	4-10	4-11	5-12
	Refining		**Low:** Hydrogen supply feed in place	6-8			6-8		
	Steel		**Variable:** Highly dependent on current plant configuration and feedstock, may also include hydrogen distribution infrastructure		4-7	4-8	15-30	18-35	20-40
	Chemicals-methanol		**Variable:** Can limit switching costs by adding CCS to SMR, other approaches more costly with higher unit cost savings		2-6	3-7	5-12	5-12	6-14
Transport[1]	Road[3]		**High:** New vehicle power trains with fuel cells, refueling stations & distribution infrastructure	0	25-30	40-55	90-125	110-140	120-160
	Aviation fuels		**Moderate:** Fuel conversion / production facilities		5-15	10-30	8-20	10-25	10-30
	Maritime fuels[4]		**High:** New ship engines, port infrastructure & local storage, and fuel supply, storage, and bunkering infrastructure in ports	< 1	4-10	8-20	5-15	5-15	8-20
Heating	NG blending for building heat[5]		**Variable:** Will depend on pipeline material, age, and operations (e.g., pressure); requires testing for degradation and leakage	0	0	0	2-3	2-3	2-3
	Industrial heat		**Variable:** Dependent on extent of furnace retrofits required	0	1-3	2-5	7-10	7-10	7-10
Power	High-capacity Firm – 20% H2 (Combustion)[6]		**Moderate:** Retrofits to gas turbines, additional storage infrastructure	< 0.2	< 0.1	< 0.1	4-6	5-8	8-12
	Power – LDES[7]		**Moderate:** Retrofits to gas turbines, additional storage infrastructure	0	4-6	8-11	Varies based on cost-downs in other LDES technologies and composition of grid		

TAM: total addressable market

Source: DOE - Pathways to Commercial Liftoff: Clean Hydrogen. https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf

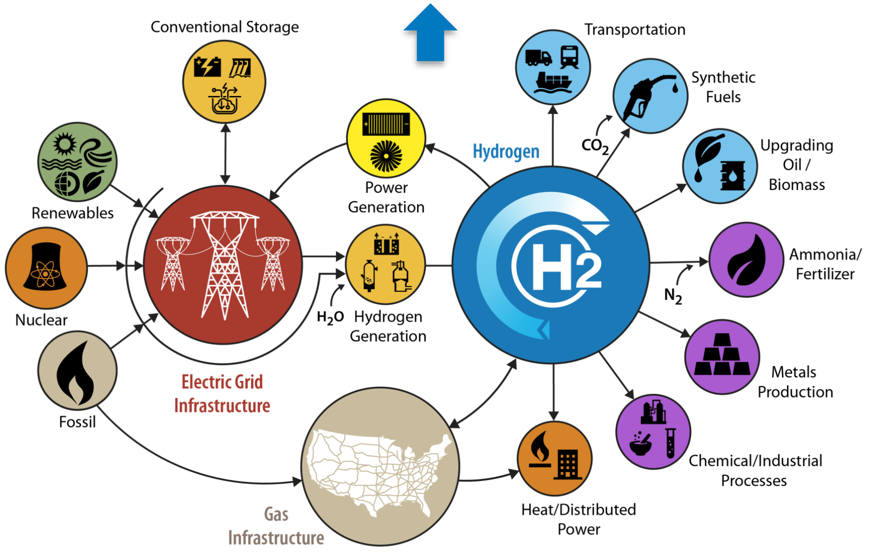
Four Key Elements of a Hydrogen Business Case: Type of Demand, Production Pathways, Storage, and Transportation

II

Hydrogen storage alternatives, e.g., salt cavern (underground), Tank (Gas), Tank (Liquid)?

I

Hydrogen production pathways, e.g., grid-driven electrolysis, renewable-driven electrolysis, steam-methane reforming (SMR), etc.?



III

Type of hydrogen demand and utilization, e.g., fuel cell electric vehicles, refinery operations, etc.?

IV

Mass and energy transportation modes, e.g., pipeline (gas), trucking (gas), trucking (liquid)?

Incentives?

- **Low-Carbon Fuel Standard Credits**
- **Production Tax Credit (PTC)**
- **Etc.**

Regulation?

- **Lifecycle Greenhouse Gas Emissions**
- **Renewable Energy Sources**
- **Etc.**

Contents

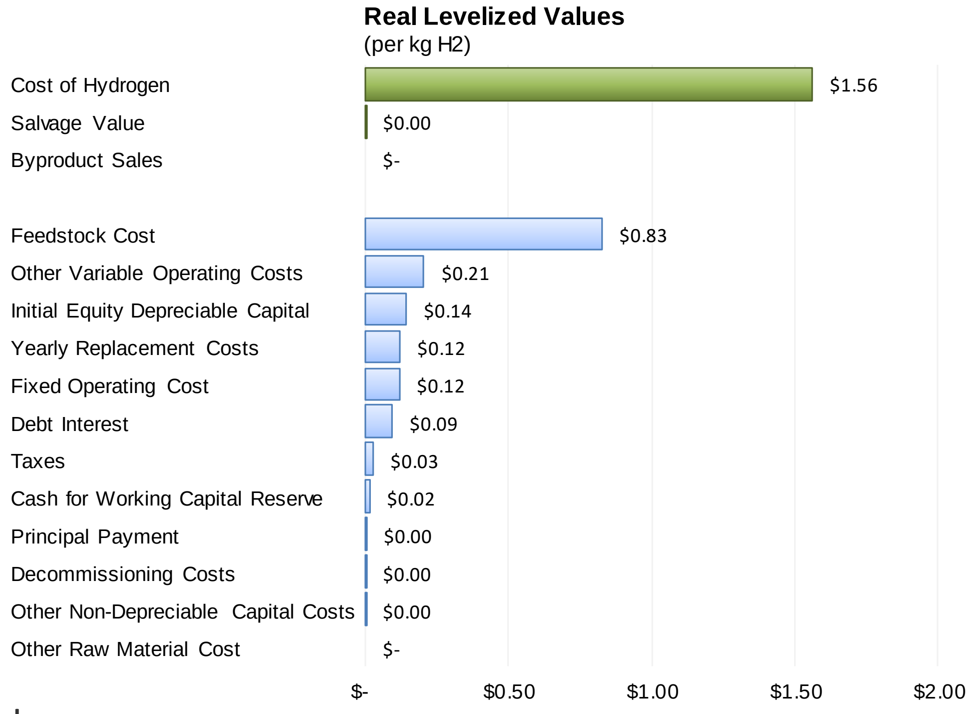
Hydrogen Production Economic Tools: H2A

The Hydrogen Analysis (H2A) hydrogen production models and case studies provide transparent reporting of process design assumptions and a consistent cost analysis methodology for hydrogen production at central and distributed facilities

H2A

Hydrogen Production Technologies

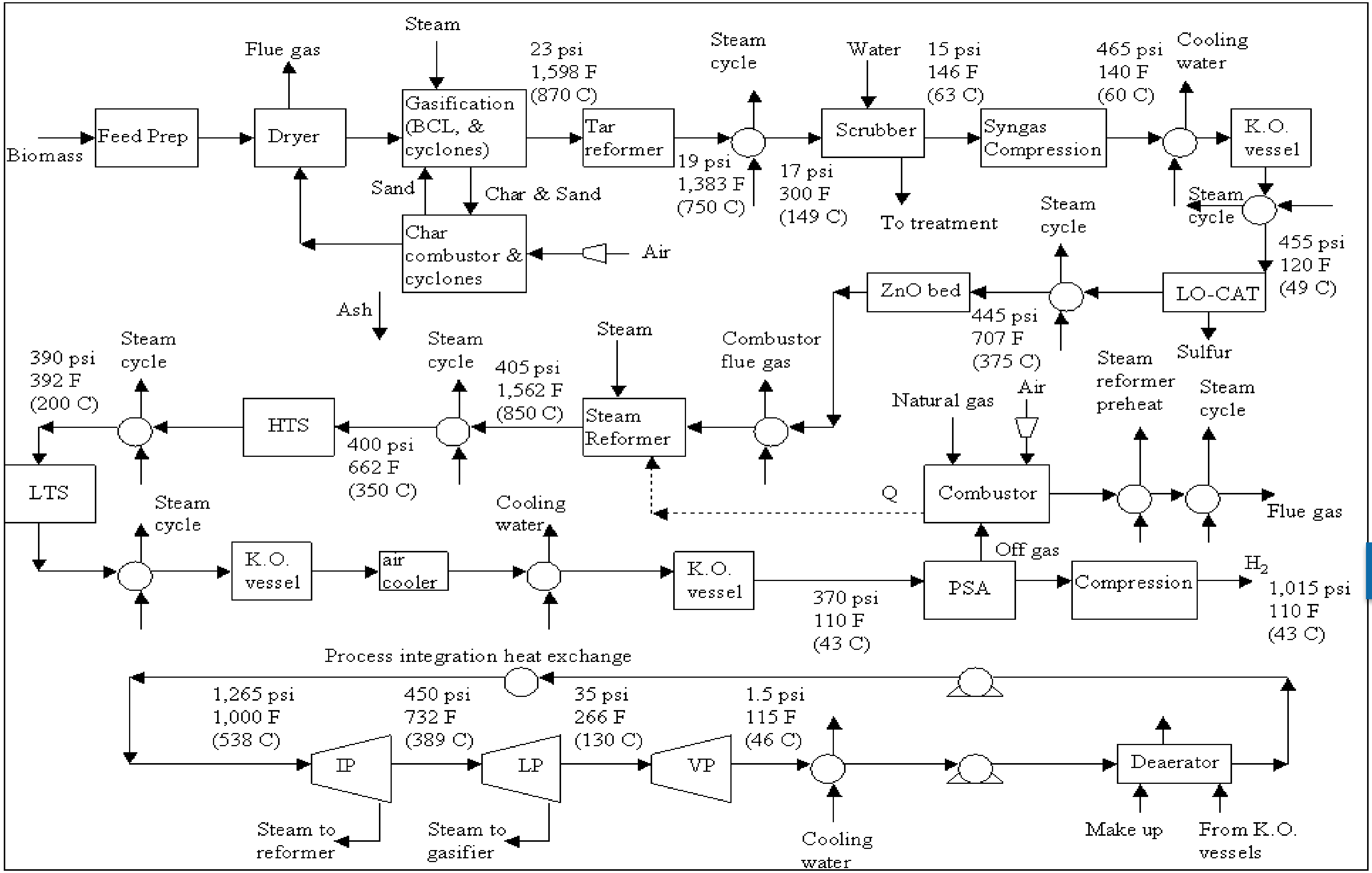
- Central PEM: current & future
- Central SOEC: current & future
- Central biomass: current & future
- Central SMR: current
- Central ATR+CCS: current
- Central coal+CCS: current
- Distributed PEM: current & future
- Distributed SMR: current & future
- User-defined



Note: SMR+CCS was not included based on NETL forecast that it would not be competitive against ATR+CCS. Verification was performed over a range of nameplate capacities.

https://www.nrel.gov/hydrogen/h2a-production-models.html

H2A Model: A Process Flow Diagram for Biomass-Based Hydrogen

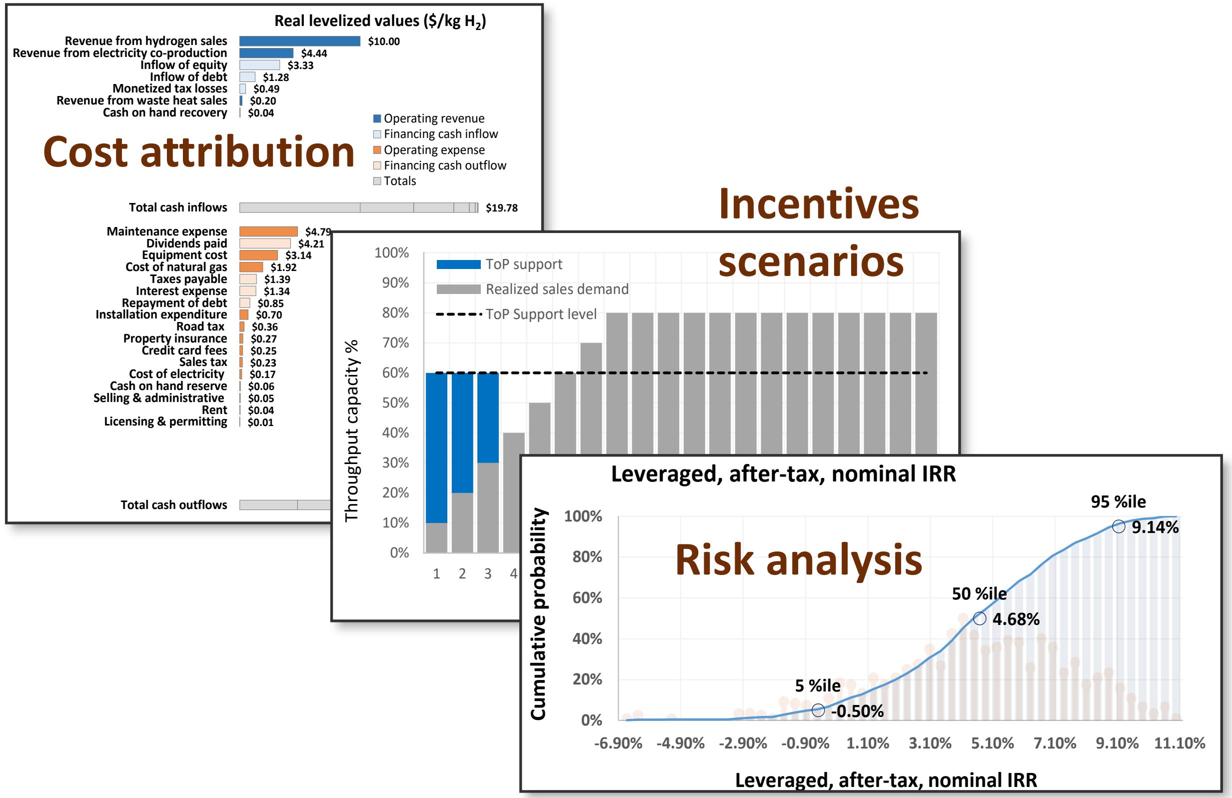


https://www.nrel.gov/hydrogen/h2a-production-models.html

Integrated Hydrogen Production Cost and Financial Analysis: H2A-Lite

Based on Hydrogen Financial Analysis Scenario Tool (H2-FAST)

- Uses Generally Accepted Accounting Principles (GAAP) financial analysis
- Also compatible with International Financial Reporting Standards (IFRS)
- Articulates standard financial reports for duration of analysis
  - Income statements
  - Cash flow statements
  - Balance sheets
- Analysis performed on real 2020$ basis (for consistency with H2A –future methodology)



Case data

Energy cost projections

Financial framework

User overrides

H_2 cost & financials

H2A + AEO 2022 eia + H2FAST → H2A-Lite

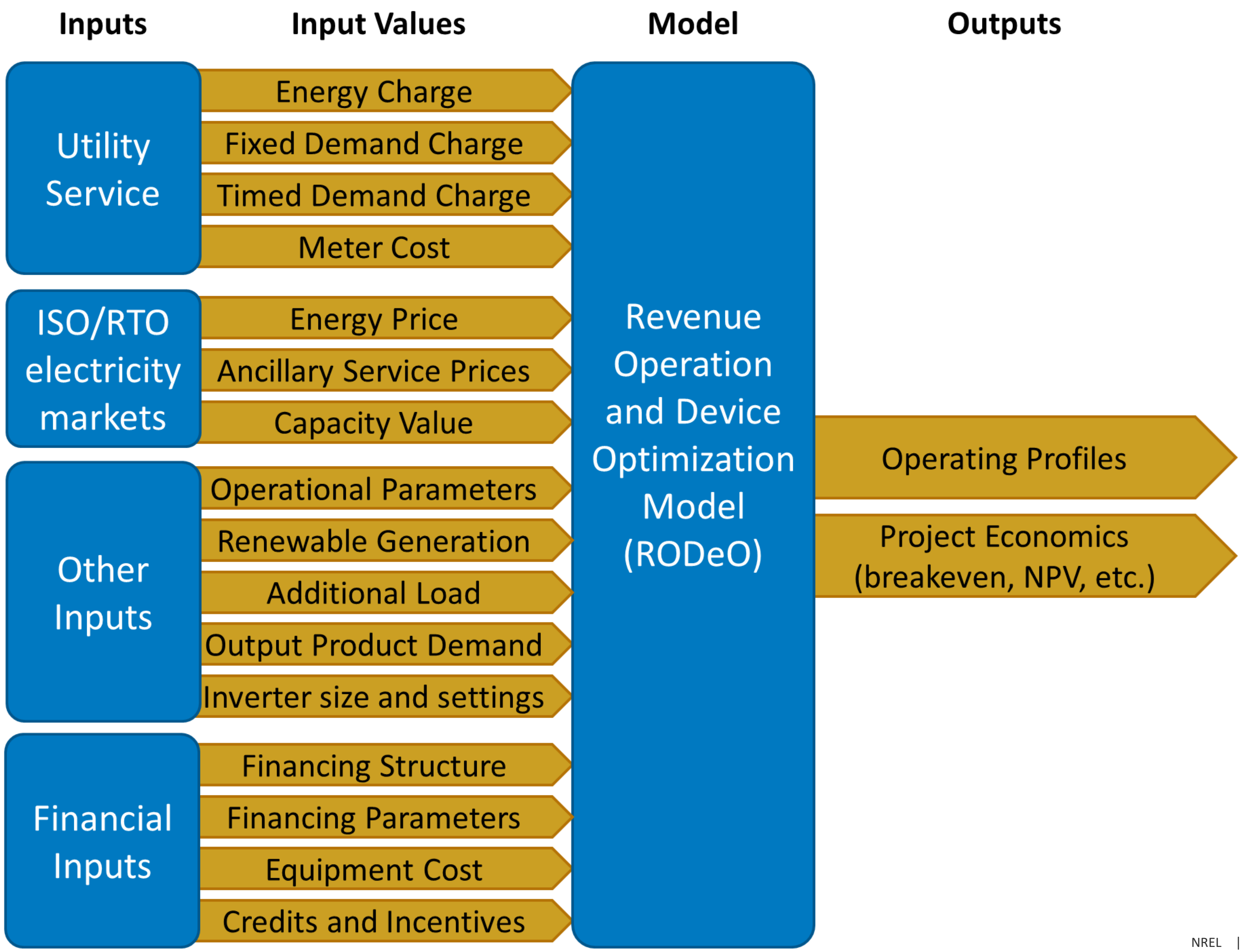
https://www.nrel.gov/hydrogen/h2fast.html
https://www.nrel.gov/hydrogen/h2a-lite.html

Contents

Desing and Operation Optimization of Hydrogen System: RODeO

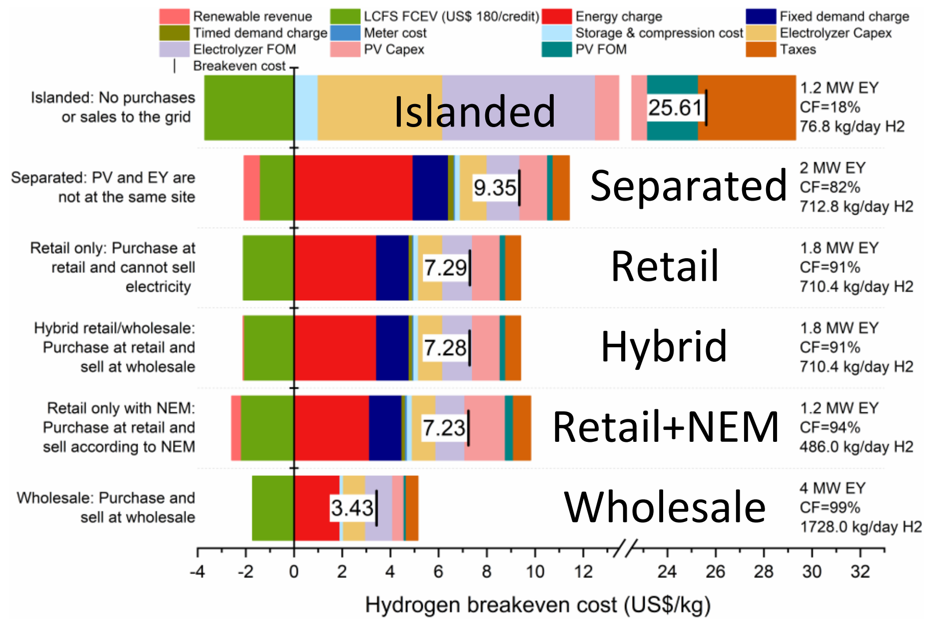
- RODeO is a price-taker model formulated as a mixed-integer linear programming (MILP) model
- Open source; written in GAMS platform
- Objective: maximize net revenue for a collection of equipment at a given site
- Potential equipment
  - Generators (gas turbine, steam turbine, solar, wind, fuel cells, etc.)
  - Storage (batteries, pumped hydro, hydrogen, etc.)
  - Flexible loads (EVs, electrolyzers, buildings)

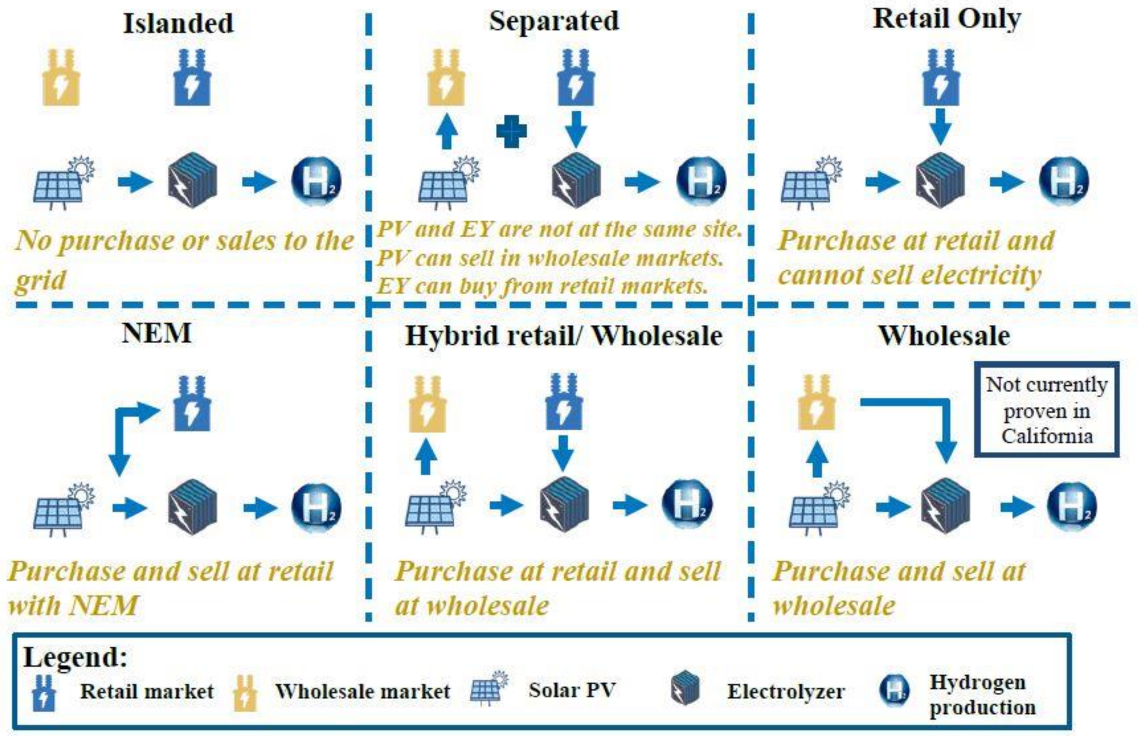
https://github.com/NREL/RODeO

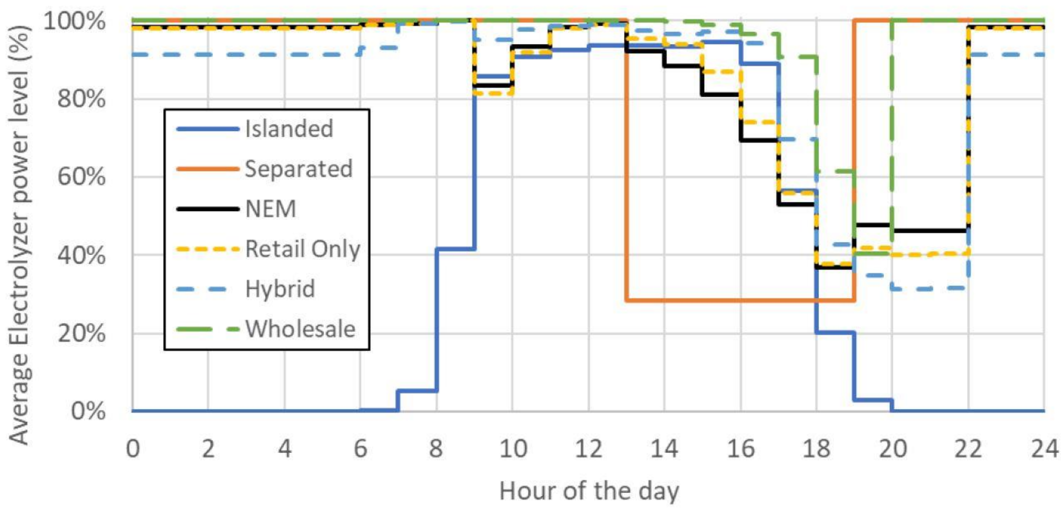


Optimal Desing and Operation of Hydrogen System: RODeO

- RODeO can be used to estimate the break-even price of hydrogen for different energy input scenarios
- It optimizes the hourly dispatch of the electrolyzer based on renewables output and grid electricity costs
- Can also be used to analyze hydrogen energy storage with tanks/geological caverns and fuel cells/H2 turbines







Ref: Eichman et al. "Optimizing an Integrated Renewable-Electrolysis System". NREL/TP-5400-75635. March 2020. https://www.nrel.gov/docs/fy20osti/75635.pdf

Working Together with Public and Private Sectors to Unlock the Potential of Hydrogen Technologies

Public entities

- DOE Hydrogen and Fuel Cell Technologies Office
- DOE Water Power Technologies Office
- California Air Resources Board (CARB)
- California Energy Commission
- University of California, Irvine

RODeO™

Revenue, Operation, and Device Optimization

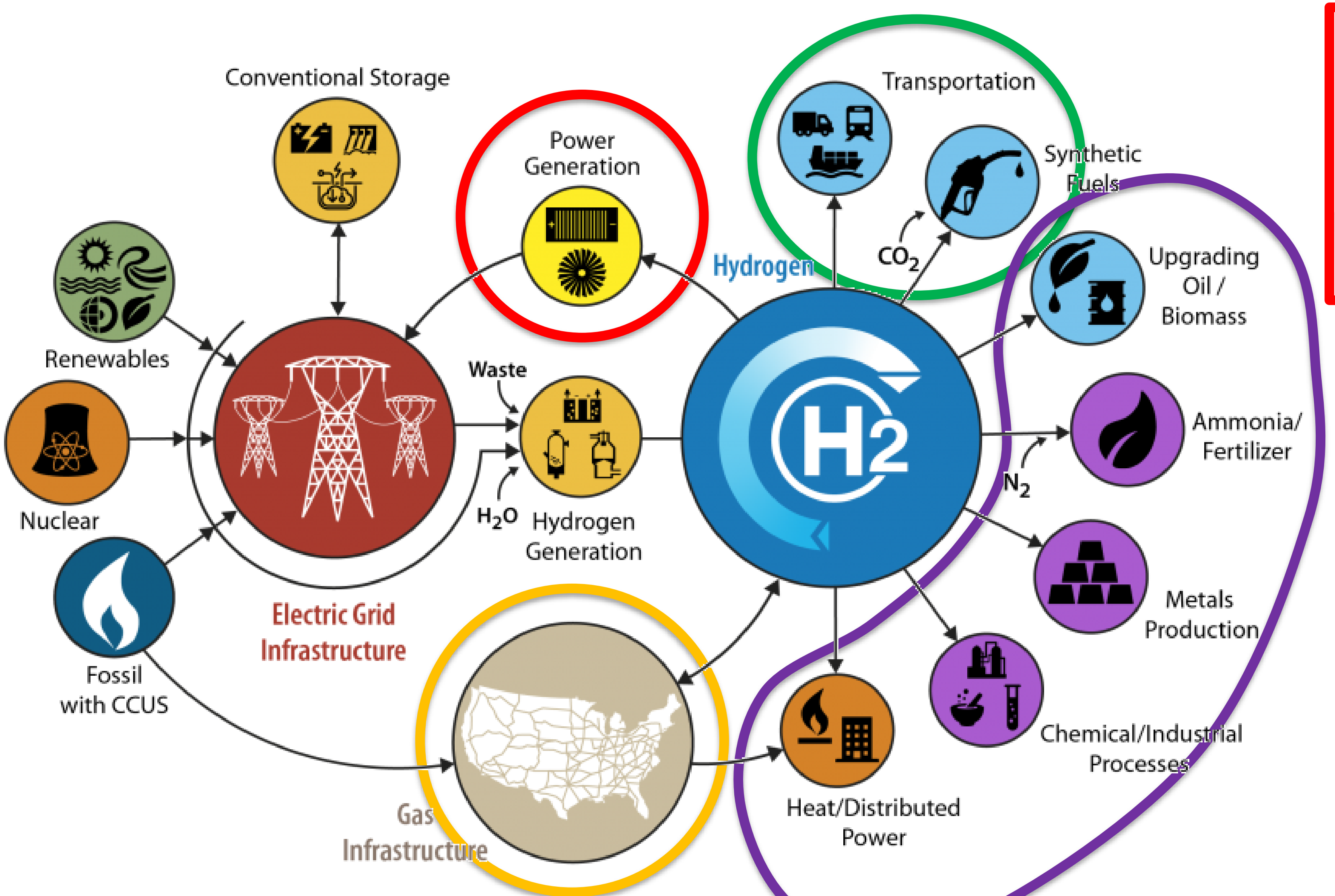
- RODeO has been used in more than 15 projects involving the public and private sectors
- RODeO's project budgets total around $2.5 million dollars

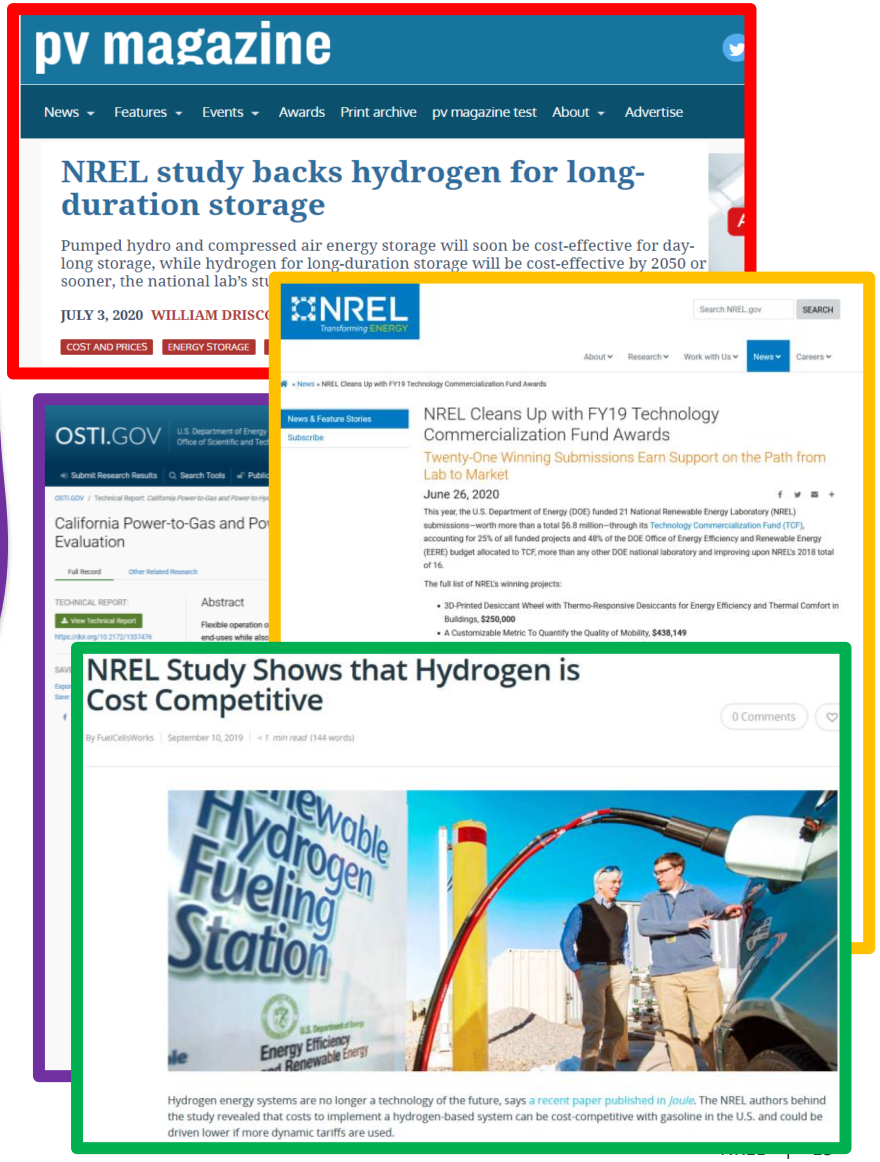
Open-source software: https://github.com/NREL/RODeO

Private entities

- PG&E
- SoCalGas
- EPRI
- Antora Energy
- Woodside
- Statoil
- Versa power
- Valley Transit Authority

RODeO™ identifies opportunities for hydrogen technologies



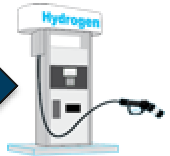


Source: U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office

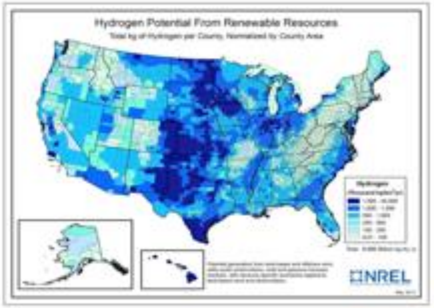
Contents

Hydrogen Supply Chain Modeling: SERA

The SERA model simulates least-cost hydrogen infrastructure supply systems for urban FCEV markets



Energy Resources



- Energy prices (natural gas, electricity, etc.)
- Renewables (biomass, solar, wind)
- Terrain, rights of way, etc.

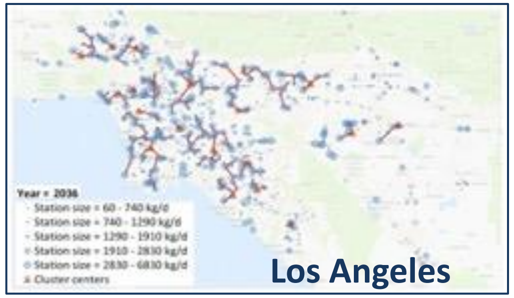
Hydrogen Production

- Central and onsite production facilities
- Capacity sized to meet forecasted demand
- Economies of scale balanced with delivery costs

Storage & Delivery

- Truck delivery, rail, and pipeline.
- Cost is sensitive to volume, distance
- Seasonal and weekly storage
- Networked supply to multiple cities

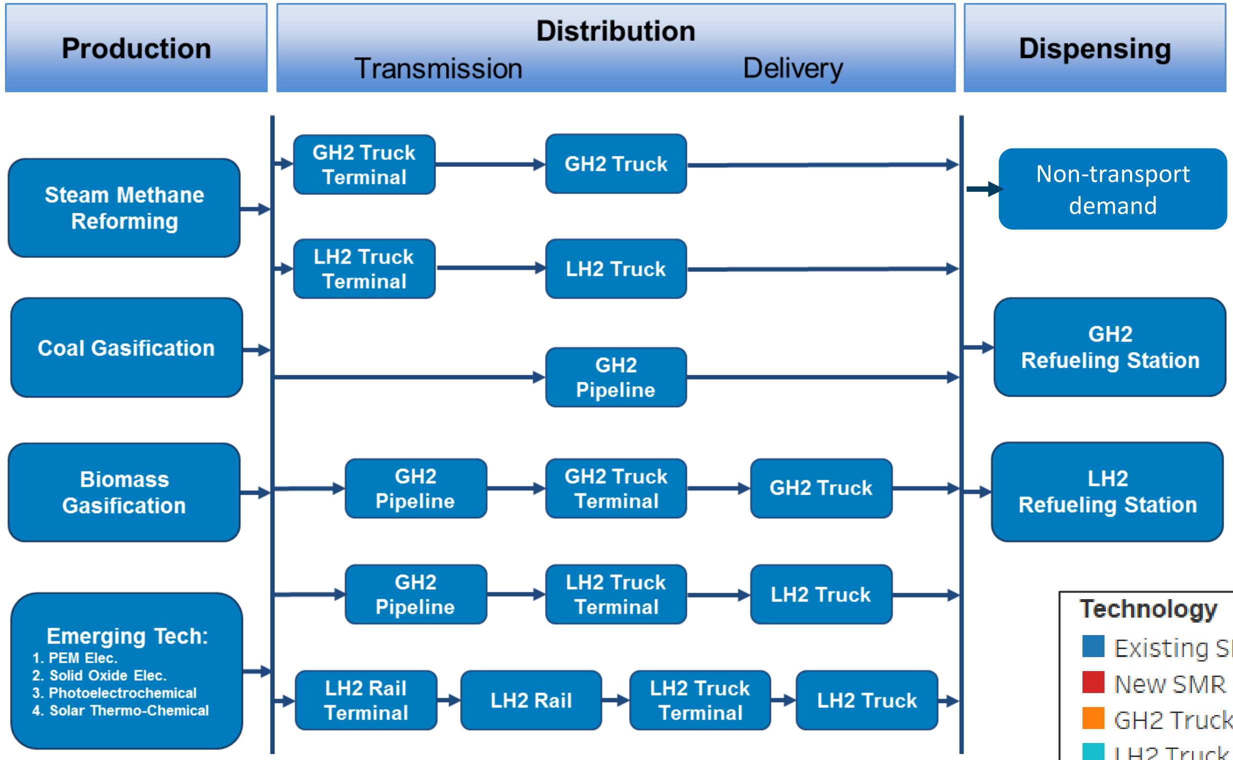
Retail Station Networks



- Coverage stations for FCEV introductions
- Station sizes increase with market growth
- Liquid and pipeline delivery networks compete for large stations

SERA optimizes production, transmission, delivery and dispensing construction technology, timing, and location

SERA



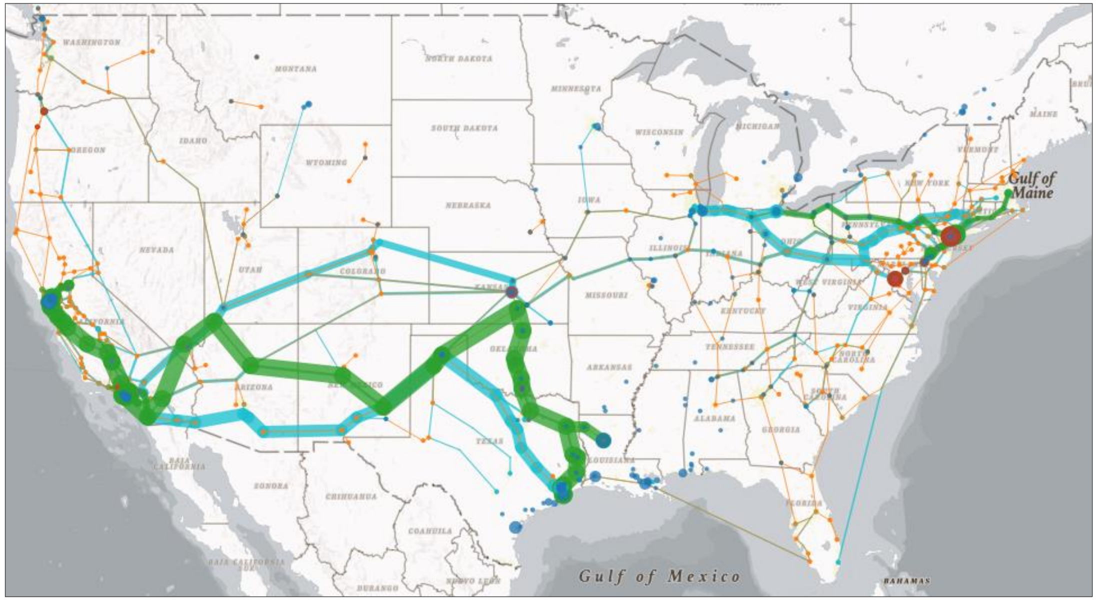
(Above) Example supply chain pathways for SERA to select from

(Right) Visualization of optimized light-duty vehicle hydrogen supply chain in 2050

- **Inputs:** Resource (feedstock) prices, utility prices technology cost and resource data, FCEV demand, non-transport demand
- **Optimization:** SERA finds least-cost infrastructure development to meet demand, technology, and resource constraints
- **Outputs:** "blueprints" for hydrogen supply chain (production, transmission, delivery, dispensing) and levelized cost of dispensed hydrogen

Technology
- Existing SMR
- New SMR
- GH2 Truck
- LH2 Truck
- HyLine

Capacity (kg/yr)
- ≤ 1,000,000
- 20,000,000
- 40,000,000
- 60,000,000
- 80,000,000
- ≥ 100,000,000



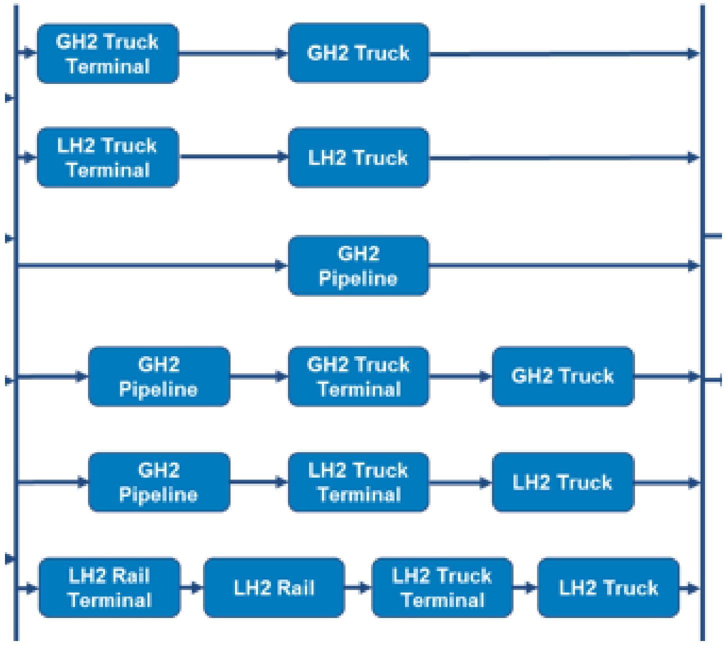
Note:
GH2: Gaseous H2
LH2: Liquid H2

Supply, Demand and Prices over time with SERA (*Illustrative Examples Only*)

SERA

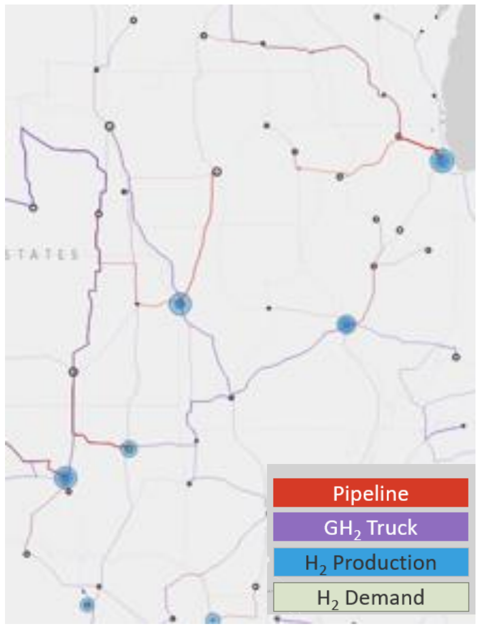
Given pre-defined pathways, SERA rolls out infrastructure on a least-cost basis to meet demand. Hydrogen prices are levelized cost and can be broken out by supply-chain component

Pre-Defined Pathways

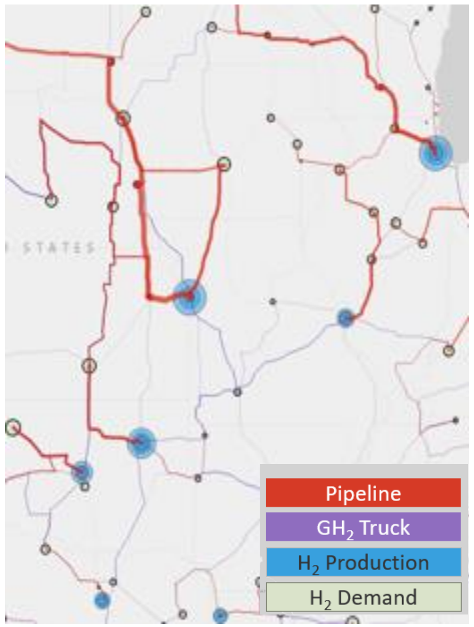


Transmission Infrastructure Rollout over time

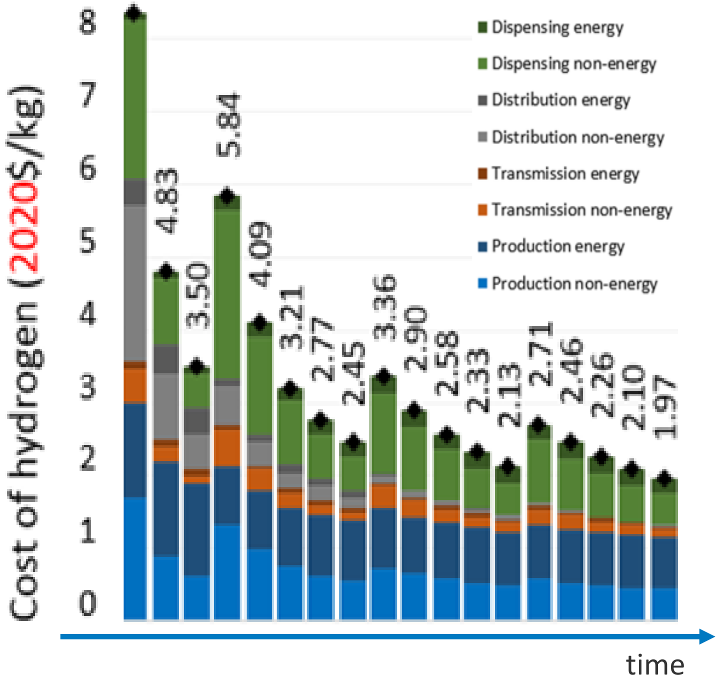
2030



2040



Hydrogen Prices by Supply-Chain Component



Contents

Summary

Models	Strengths	Opportunities for Enhancement	Time Scale	Source Code/ Open or Close-sourced	Inputs	Outputs	Point of Contact
H2A/ H2FAST	Intuitive, model any supply chain component	Representing renewable-coupled electrolyzer systems	Annual	Excel / Open	Financial assumptions, nameplate capacity, utilization rate	Levelized cost of hydrogen	**Michael Penev** (michael.penev@nrel.gov)
RODeO	Optimizes system design and operation for a hybrid system to maximize revenue	Integration of greenhouse gas emissions analysis	Hourly	Python, Matlab, GAMS / Open	Energy and demand charges, electrical demand, output demand, tech assumptions, operational and financial parameters	Optimal system configuration and operation on hourly timescale.	**Omar J. Guerra** (omarjose.guerrafernandez@nrel.gov)
SERA	Flexible, optimizes over time and space	Increased model customization	Annual	Julia, Excel, Python / Closed	Demand, network, electricity and fuel prices, production technologies, delivery pathways	Infrastructure deployment, supply-chain component costs and delivered hydrogen price	**Mark Chun** (Mark.Chung@nrel.gov)

!Gracias!

Omar José Guerra Fernández

e-mail: omarjose.guerrafernandez@nrel.gov

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