ENERGY TECHNOLOGIES AREA

LAWRENCE BERKELEY NATIONAL LABORATORY

Energy Analysis &
Environmental Impacts Division

Emerging Applications for H2: Iron/Steel, Combined Heat and Power, Grid Support

Shell/ EBI H2 Economy Workshop
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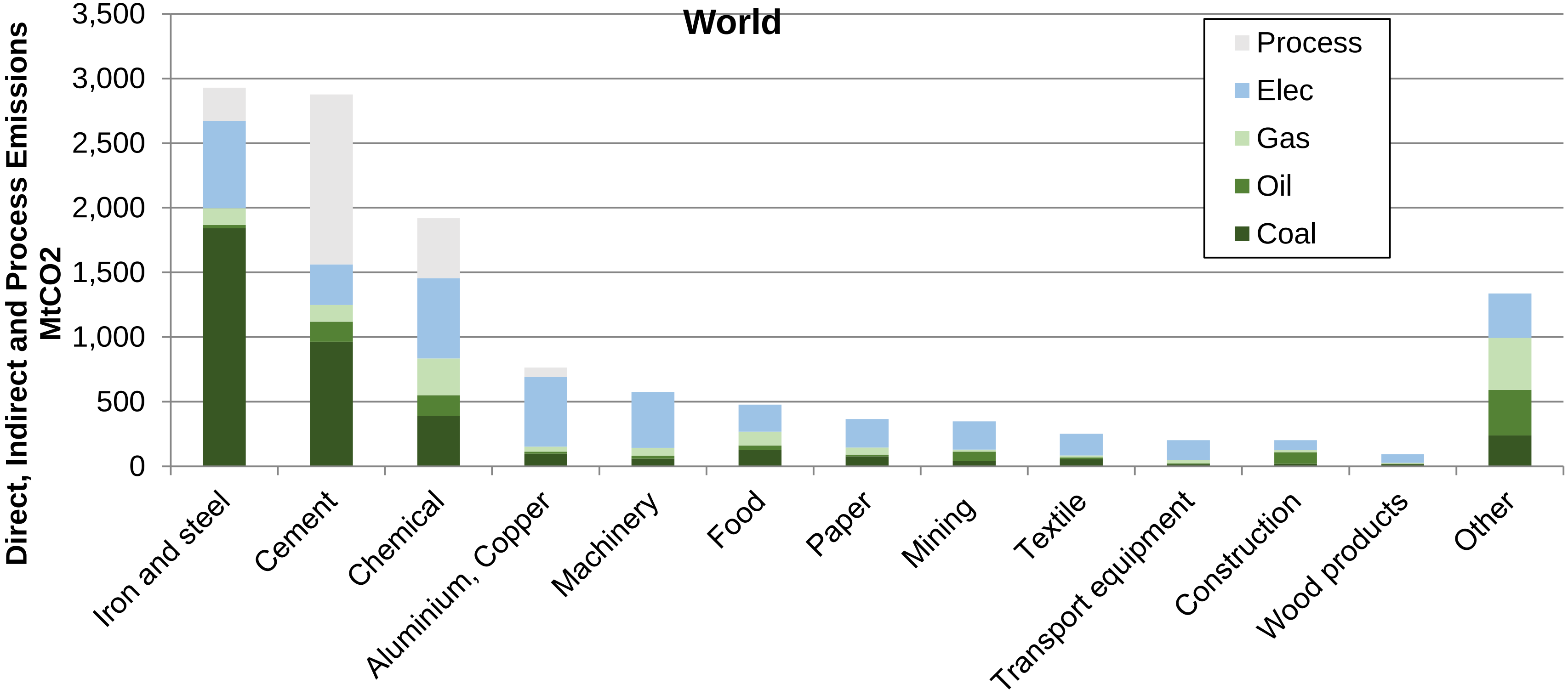
Emerging (stationary) H2 applications

- Iron / steel
- Combined heat and power
- Grid support
  - Grid support from flexible electrolysis
  - H2 storage opportunity and technology development

2015 Industry CO_2 Emissions
1/3 of global GHG

Only 3 sectors represent 2/3 of global industry GHG emissions



Source: IEA World Statistics, 2018

Iron & Steel Making

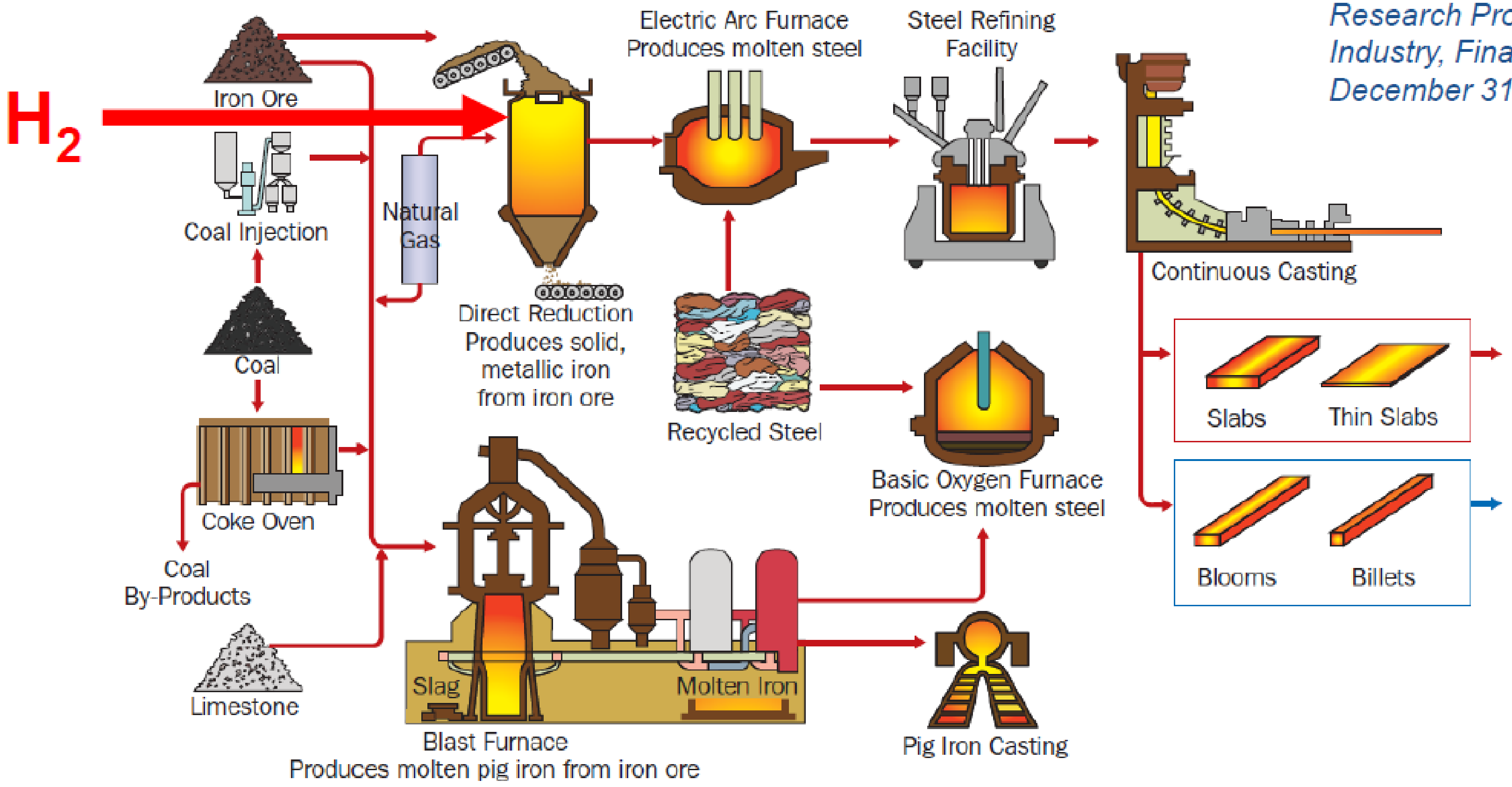


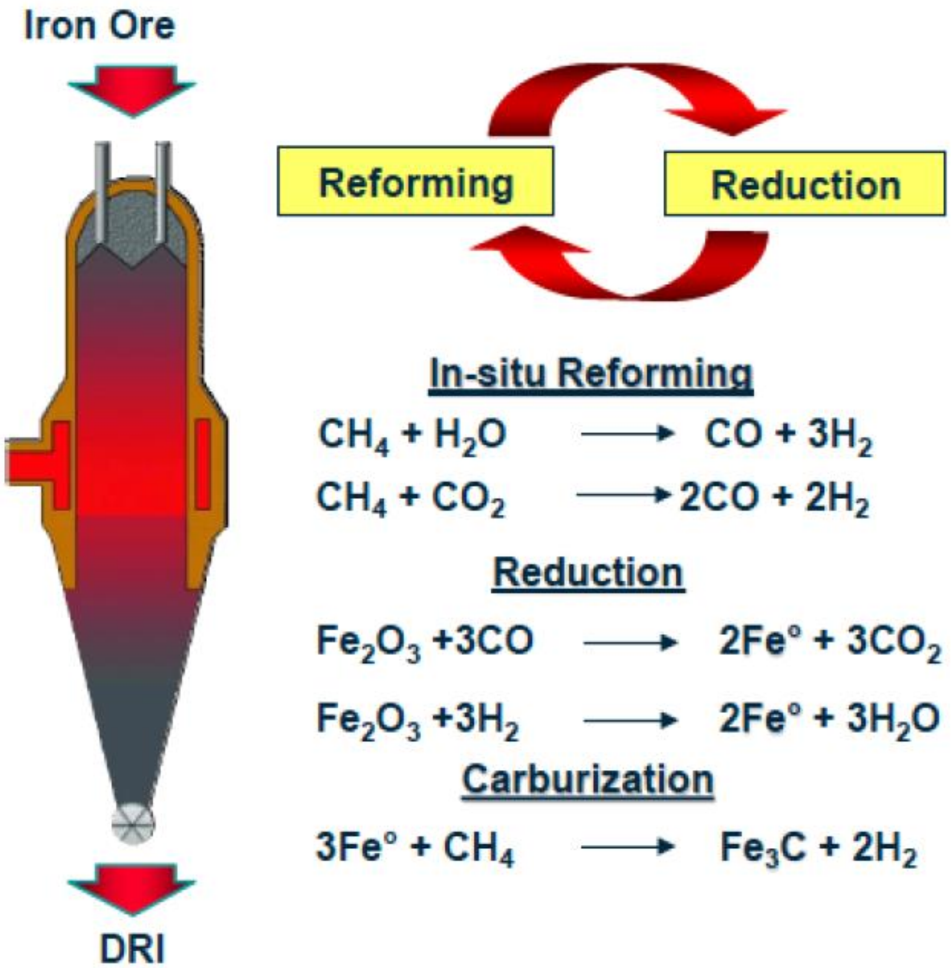
Figure Source:
ANSI, Technology Roadmap Research Program for the Steel Industry, Final Report, December 31, 2010

Iron and steel making employs two interrelated processes:

1) Molten pig iron is produced from iron ore with coke in a **Blast Furnace (BF)**. The Pig Iron is mixed with scrap metal and refined in a **Basic Oxygen Furnace (BOF)**.
2) Solid metallic iron is produced in a **Direct Reduction Iron (DRI).** This iron is processed with scrap metal in an **Electric Arc Furnace (EAF)** to produce molten steel.

Direct reduction of iron ore with CH4

- Total reduction with hydrogen is endothermic; reduction with carbon monoxide is exothermic.
- Note C source for carburization or hardening



In-situ Reforming

$CH_4 + H_2O \longrightarrow CO + 3H_2$

$CH_4 + CO_2 \longrightarrow 2CO + 2H_2$

Reduction

$Fe_2O_3 + 3CO \longrightarrow 2Fe^{\circ} + 3CO_2$

$Fe_2O_3 + 3H_2 \longrightarrow 2Fe^{\circ} + 3H_2O$

Carburization

$3Fe^{\circ} + CH_4 \longrightarrow Fe_3C + 2H_2$

Direct Recovery Iron

DRI Process Development Examples

- MIDREX™
- U.S. CO_2 Breakthrough Program
- Europe: ULCOS
- Japan: COURSE 50
- Korea: POSCO
- University of Utah **(FIT)**

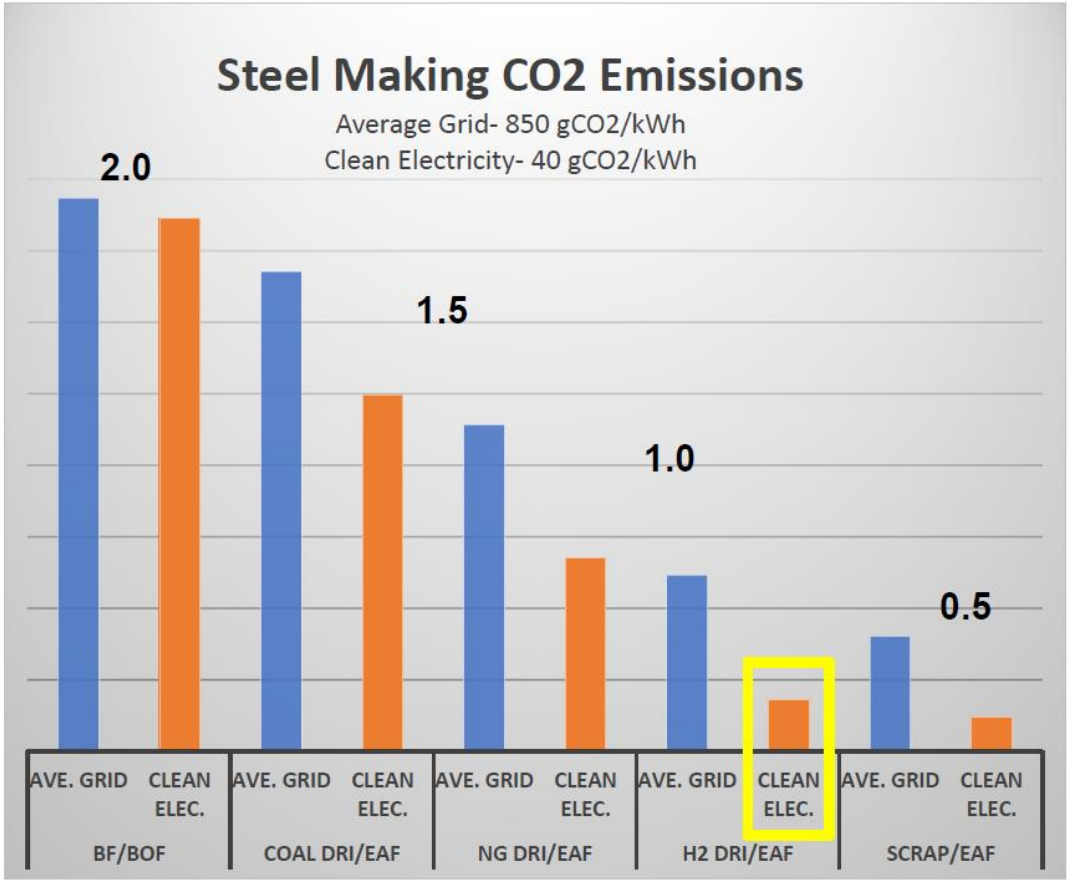
Current U.S. DRI steel industry hydrogen potential is: > 6 million tonnes-$H_2 \bullet yr^{-1}$

BELOW: The ZR Process accepts any reducing gas source – direct natural gas, syngas from a coal gasifier, coke oven gas or H_2/CO mixtures.

LEFT: MIDREX™ DRI shaft furnaces are being installed around the world to use various reducing gases and solids

- DRI process technology is no longer considered nascent
- Benefits include: Process intensification; Reduced capital; Increased energy efficiency: Reduced GHG emissions; Iron ore concentrates processing`

Steel Making Options CO_2 Emissions Comparison



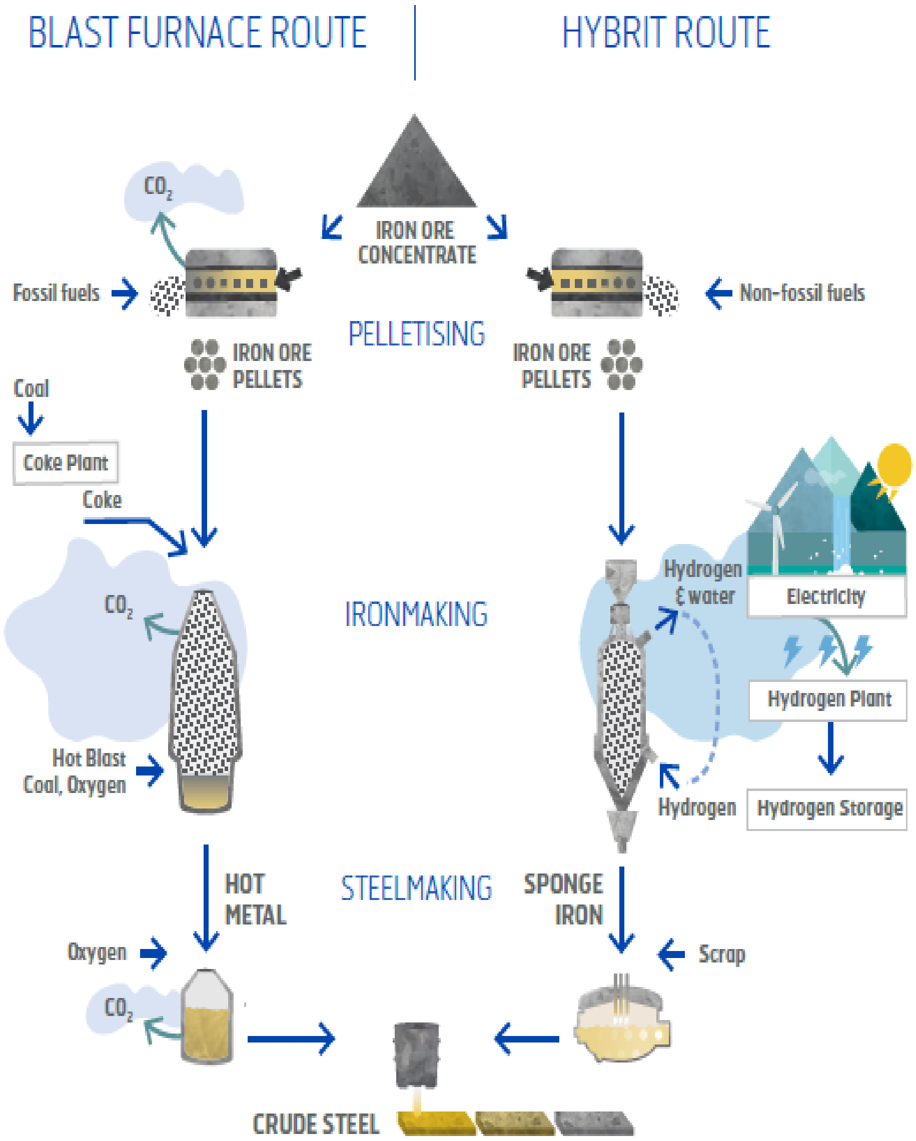
Low-emissions electricity and hydrogen from electrolysis yield 50-90% reduction in CO_2 emissions for finished steel products

Ref: Boardman, Industry Energy Hubs, 1/14/20

Some Pilots -1

HYBRIT Sweden

- HYBRIT Development AB pilot plant began construction during summer 2018 at the SSAB site in Luleå, Sweden, with SEK 500 million **($51.88 million**) in funding assistance from the Swedish Energy Agency.
- **Pilot phase until 2024, followed by a demonstration phase from 2025 to 2035**



DRI Pilot 2 - Hamburg

- Germany: Arcelor Mittal Hamburg steel production plant
  - In mid-Sept.’19, Arcelor Mittal announced that it had commissioned Midrex to design a demonstration plant to produce steel with hydrogen at the steelmaker’s Hamburg site
- The first of these projects is to **demonstrate the large-scale production and use of DRI (direct reduced iron) made with 100% hydrogen** as the reductant.
- Due to produce about **100,000 tonnes per year** of DRI. Initially the hydrogen used will be made from natural gas

Pilots - 3

- Austria: Primetals Technologies Limited, the joint venture of Siemens VAI Metals Technologies and Mitsubishi Hitachi Metals Machinery has developed technology for hydrogen reduction of iron ore.
- Planning a pilot plant for testing to be constructed at the Voestalpin steel plant in Stahl Donawitz, Austria.
- Commissioned Q2’20.
- Modular design & capacity of **250,000 tons of steel** per year.

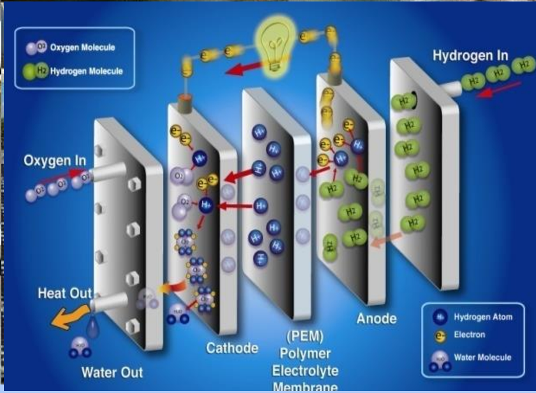
Some key considerations

- Process issues
    - Energy requirements
    - H2 embrittlement
- Cost
    - Cost and sourcing of (green) H2
    - Cost of equipment
- Product quality

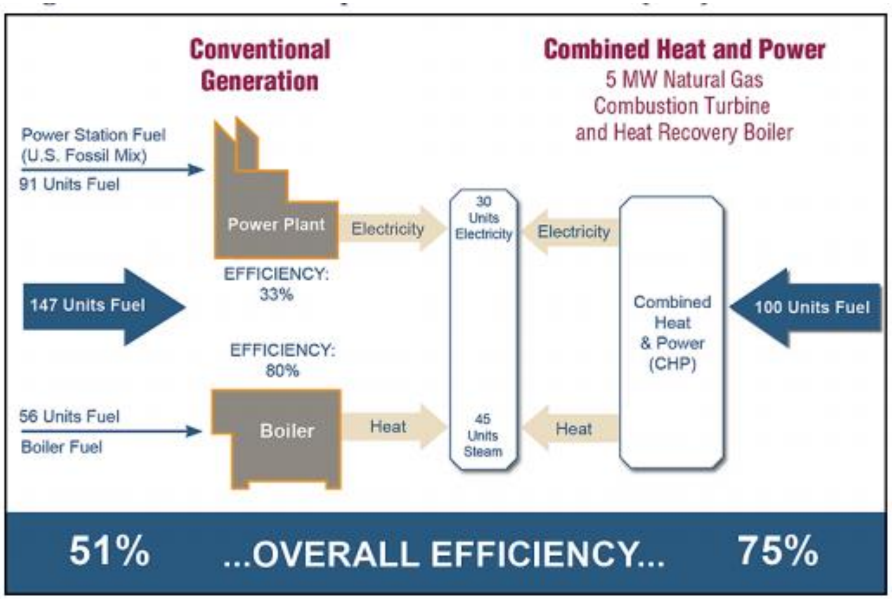
Key question & challenges, DRI with pure H2

- Product quality: physical properties and its melting performance are two key DRI characteristics to be tested.
- Energy requirements: the pure hydrogen process will need additional energy input (i.e. heat) to perform the reduction.
  - Existing reduction process have been held in balance exothermic iron oxide reduction by carbon monoxide and endothermic reduction by hydrogen.
- Cost reductions needed: capital and operating costs need to be three to four times lower than they are now
- Other:
  - Carbon incorporation: Other means will need to be found to add carbon to the steel melt.
  - How fast can a DRI plant react to rapidly changing levels of hydrogen availability.
  - H2 storage technologies/implementation

Total Cost of Ownership Modeling for Stationary Fuel Cell Systems



Combined heat and power



Fuel cell-based CHP (natural gas based) nominally 2-3x more expensive than gas-based CHP –
What are cost reductions from scaling up production and ancillary benefits?

Table 1-3. Comparison of CHP Technology Sizing, Cost, and Performance Parameters

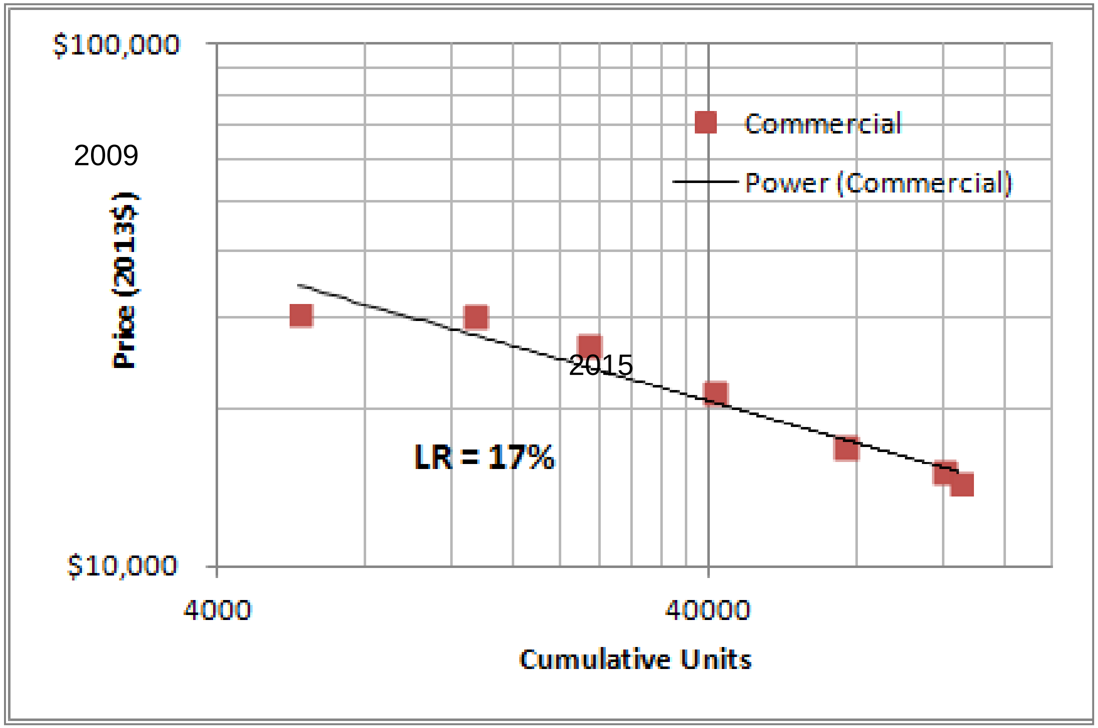
Technology	Recip. Engine	Steam Turbine	Gas Turbine	Microturbine	Fuel Cell
Electric efficiency (HHV)	27-41%	5-40+%[2]	24-36%	22-28%	30-63%
Overall CHP efficiency (HHV)	77-80%	near 80%	66-71%	63-70%	55-80%
Effective electrical efficiency	75-80%	75-77%	50-62%	49-57%	55-80%
Typical capacity (MW$_e$)	.005-10	0.5-several hundred MW	0.5-300	0.03-1.0	200-2.8 commercial CHP
Typical power to heat ratio	0.5-1.2	0.07-0.1	0.6-1.1	0.5-0.7	1-2
Part-load	ok	ok	poor	ok	good
CHP Installed costs ($/kW$_e$)	1,500-2,900	$670-1,100	1,200-3,300 (5-40 MW)	2,500-4,300	5,000-6,500

Ref: EPA Catalog of CHP Technologies 2015

One reference point: Japan Micro CHP (LT PEM) – 50% cost reduction in 5 yrs

- 17% Learning curve from 2009-2014, nominal 0.7kW system
- 50% cost reduction observed from 2009 to 2014

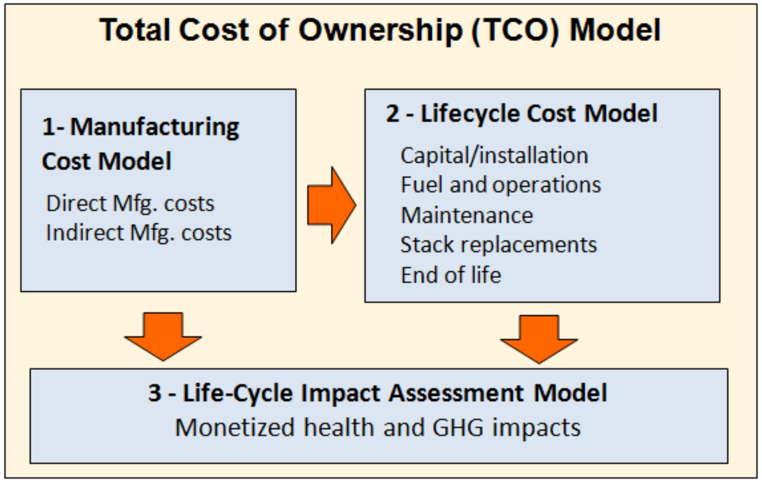
LEARNING CURVE (2009-2015)



Max Wei, Sarah J. Smith, Michael D. Sohn, Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US, Applied Energy, Volume 191, 1 April 2017, Pages 346-357, ISSN 0306-2619,

Total Cost of Ownership Modeling of Fuel Cell Systems

- Total cost modeling capability for stationary fuel cell systems (power and CHP, material handling units, backup and auxiliary power)
  - Bottom-up direct manufacturing costing vs. annual production volume
  - Life-cycle cost modeling
  - Total cost modeling including valuation of externalities (CO_2, health, environmental)
- Key Results
  - Total cost of ownership on a levelized-cost basis by location
  - Key cost sensitivities e.g. materials, stack components;
  - Favorable geographies and commercial building types identified

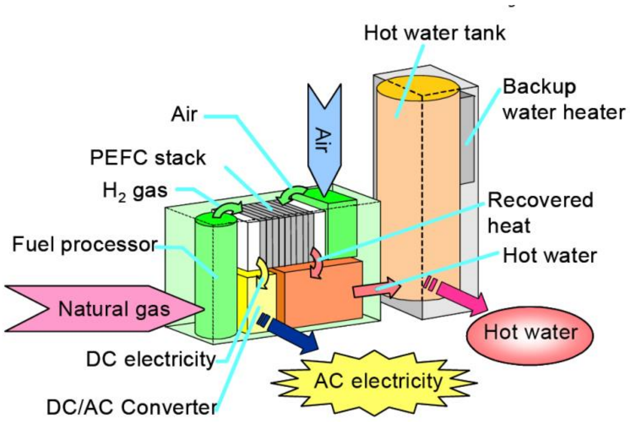


Total Cost of Ownership (TCO) Model

1- Manufacturing Cost Model
Direct Mfg. costs
Indirect Mfg. costs

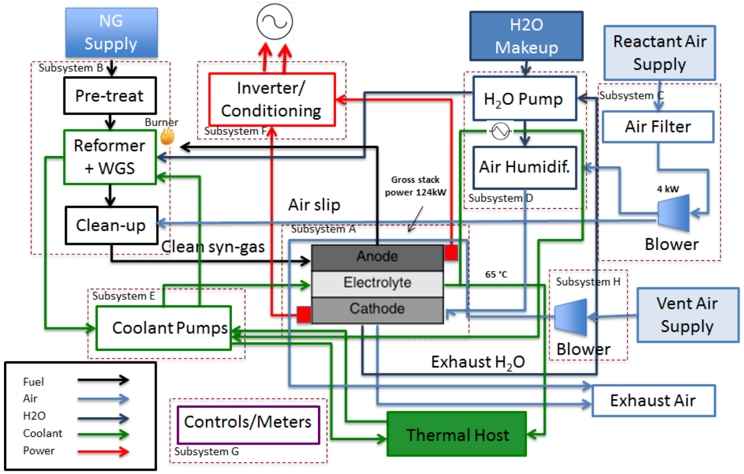
2 - Lifecycle Cost Model
Capital/installation
Fuel and operations
Maintenance
Stack replacements
End of life

3 - Life-Cycle Impact Assessment Model
Monetized health and GHG impacts



Direct cost modeling approach

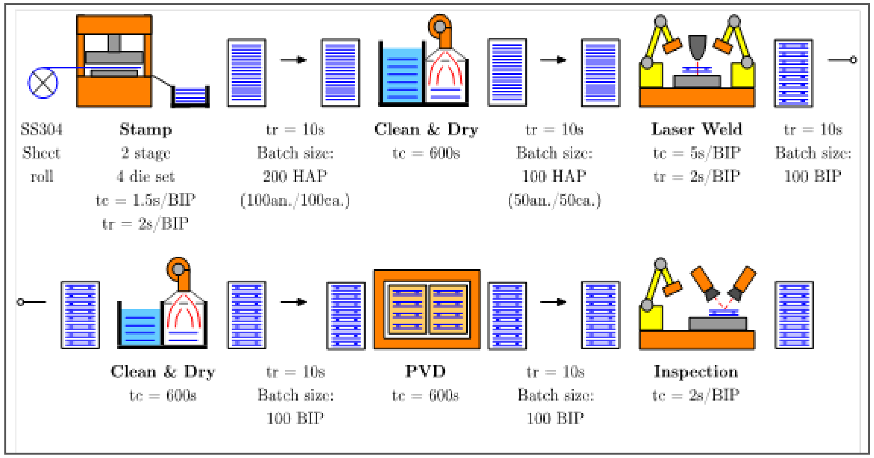
1. System Schematic/BOP (100kW CHP shown)



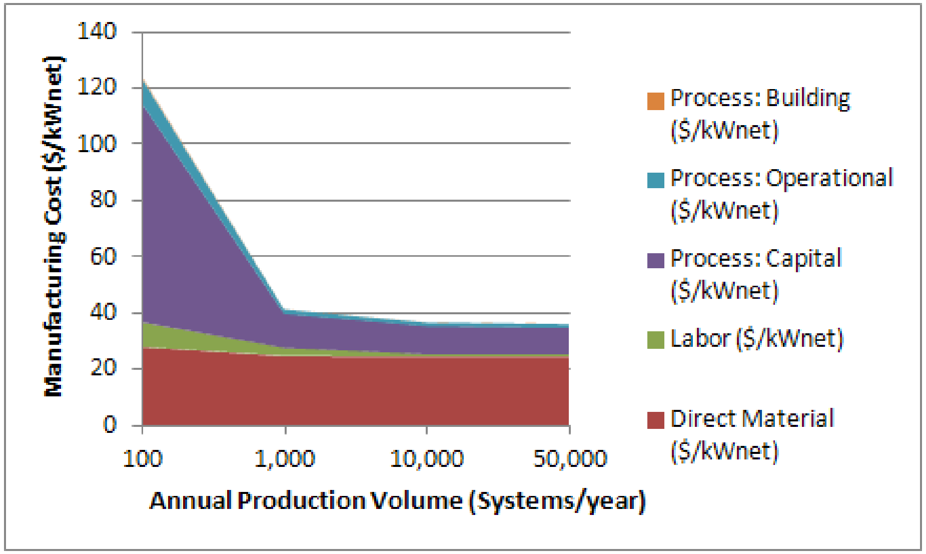
2. Functional Specifications (100kW CHP)

Parameter	Value	Unit
Gross, Net syst. power	124, 100	kW
Waste heat grade	65	Temp. °C
Fuel utilization	80-95	%
Net Electrical efficiency	32	% LHV
Thermal efficiency	51	% LHV
Total efficiency	83	Elect.+thermal (%)
Stack power	9.5	kW
CCM coated area	232	cm^2
Single cell active area	198	cm^2
Current density	0.56	A/cm^2
Reference voltage	0.7	V
Power density	0.392	W/cm^2
Cells per stack	122	Cells
Stacks per system	13	Stacks

3. FC stack module process flow (metal plates shown)



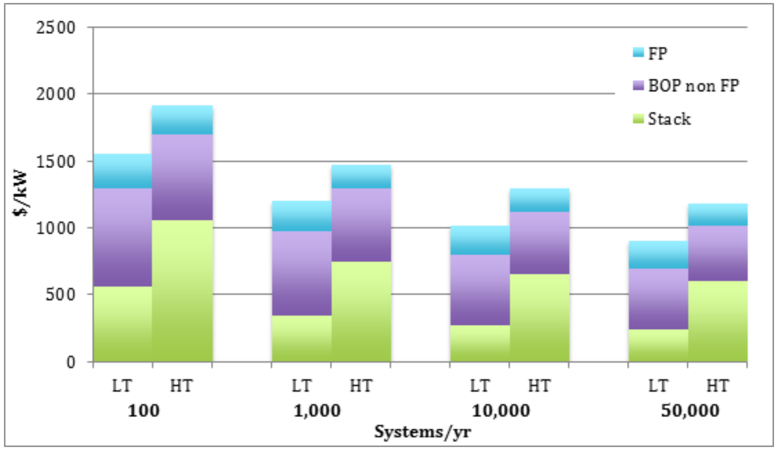
4. Process Costing vs. Volume (metal plates)



Direct Cost Modeling Results

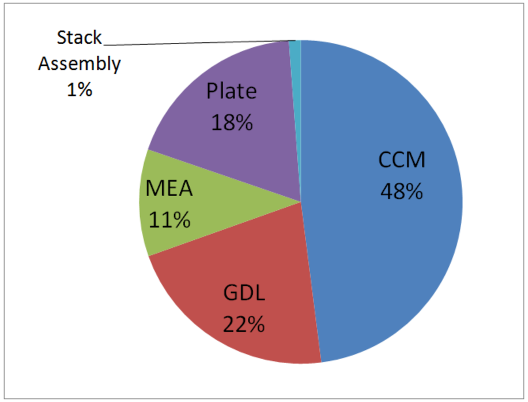
- Key Output
  - System cost by volume and technology (LT = low temp. PEM; HT = hi-temp PEM)
  - PEM direct manufacturing cost ~$1000/kW at high volumes (250kW system)
  - Fuel cell stack and Balance-of-Plant component cost break-out
  - Key Cost sensitivities, cost reduction opportunities

1. System Cost: Low-temp. vs Hi-temp. PEM



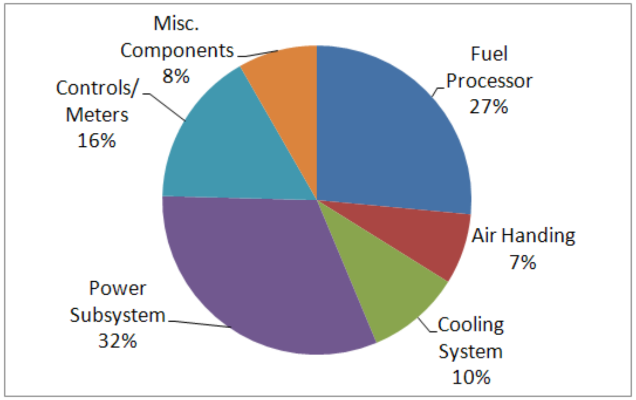
PEM= polymer electrolyte membrane; FP= fuel processor; BOP = balance of plant

2. Fuel Cell Stack Cost (LT PEM)

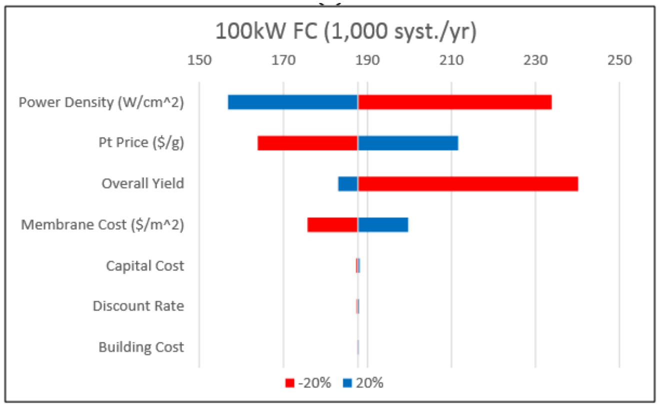


CCM= catalyst coated membrane; GDL = gas diffusion layer; MEA=membrane electrode assembly

3. Balance of Plant Cost (LT PEM)

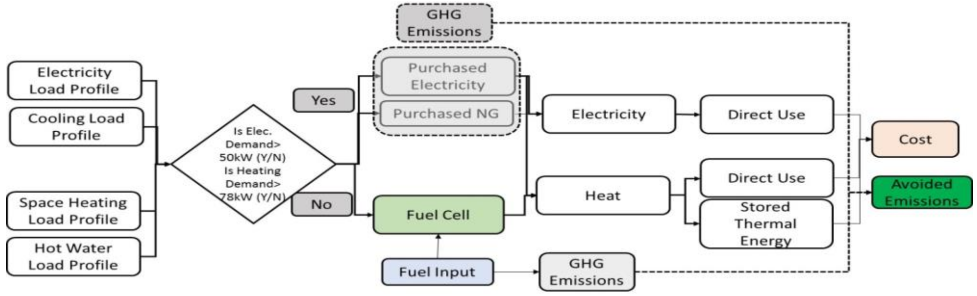


4. Cost Sensitivity (LT PEM)

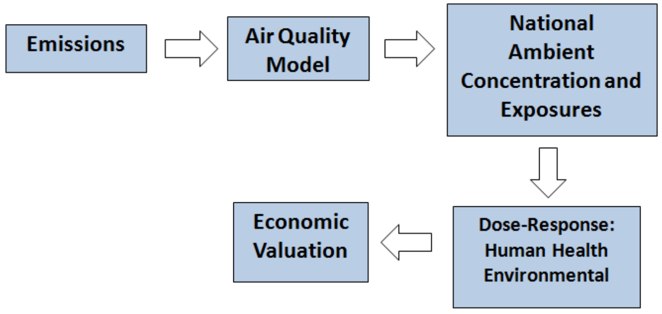


Total Cost of Ownership Modeling

1. Life-cycle cost model



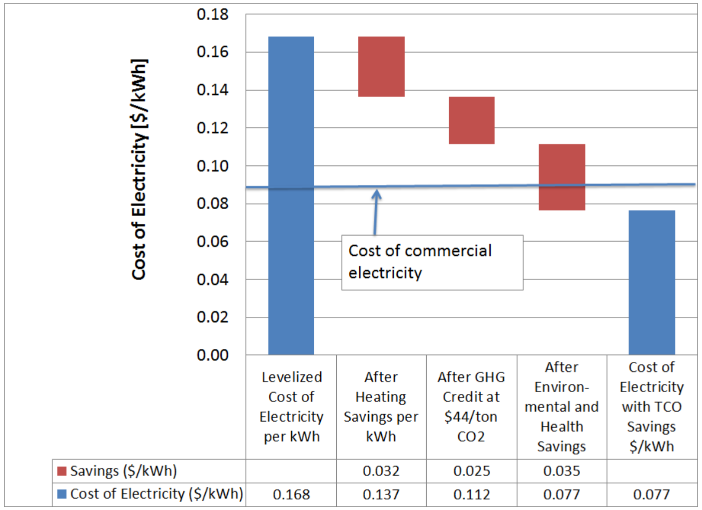
2. Air Pollution Emissions Experiments and Policy Analysis Model (APEEP)



Nicholas Muller

3. TCO model includes six cities with various commercial buildings

FC CHP is most favorable in regions with higher carbon intensity electricity (e.g. Midwest)



	Levelized Cost of Electricity per kWh	After Heating Savings per kWh	After GHG Credit at $44/ton CO2	After Environ-mental and Health Savings	Cost of Electricity with TCO Savings $/kWh
🟥 Savings ($/kWh)		0.032	0.025	0.035	
🟦 Cost of Electricity ($/kWh)	0.168	0.137	0.112	0.077	0.077

Example - 10 kW Small Hotel in Chicago LT PEM system with offset water heating Installed cost $3,900/kWe

CHP potential in commercial buildings

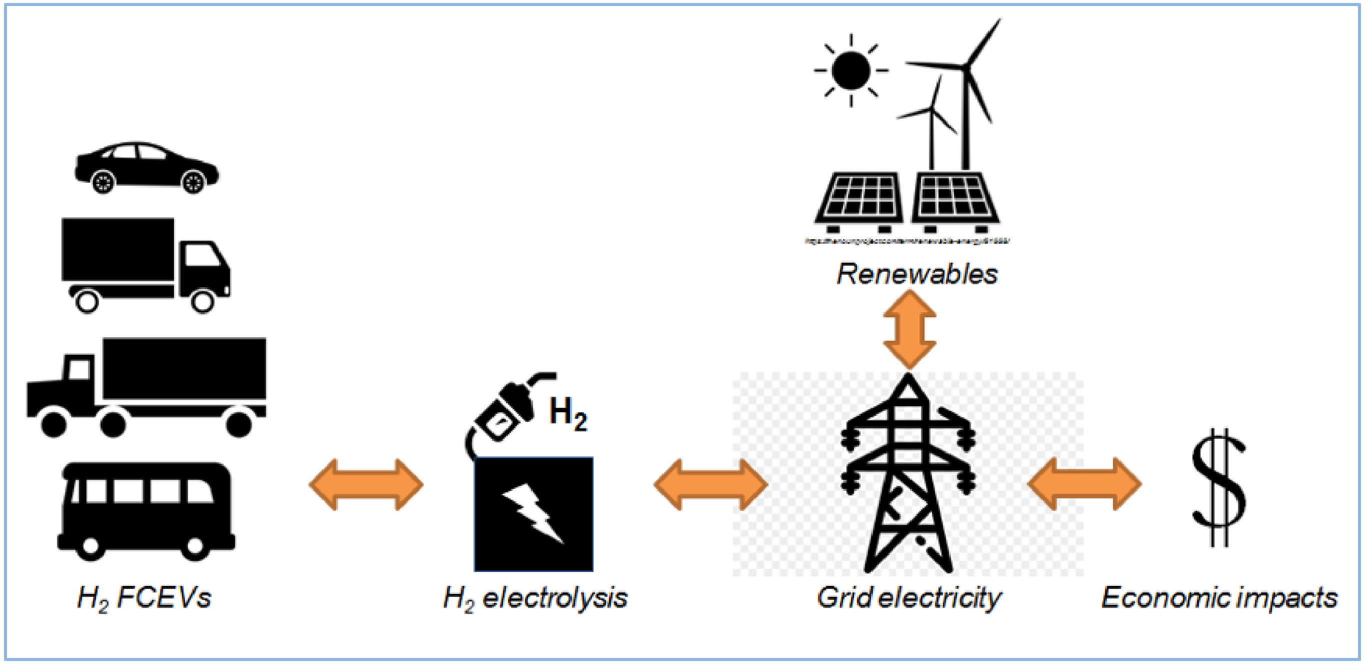
- From 2016 DOE CHP Technical Potential study:
  - CHP technical potential in commercial buildings: 76 GW
  - 16% of states w/ ‘high carbon intensity electricity’: ~12 GW
- But note that the GHG and heath benefits of fuel cell CHP will be lower as the electricity grid becomes lower carbon intensity.

Integrated H_2 Systems for Transportation and Grid Support

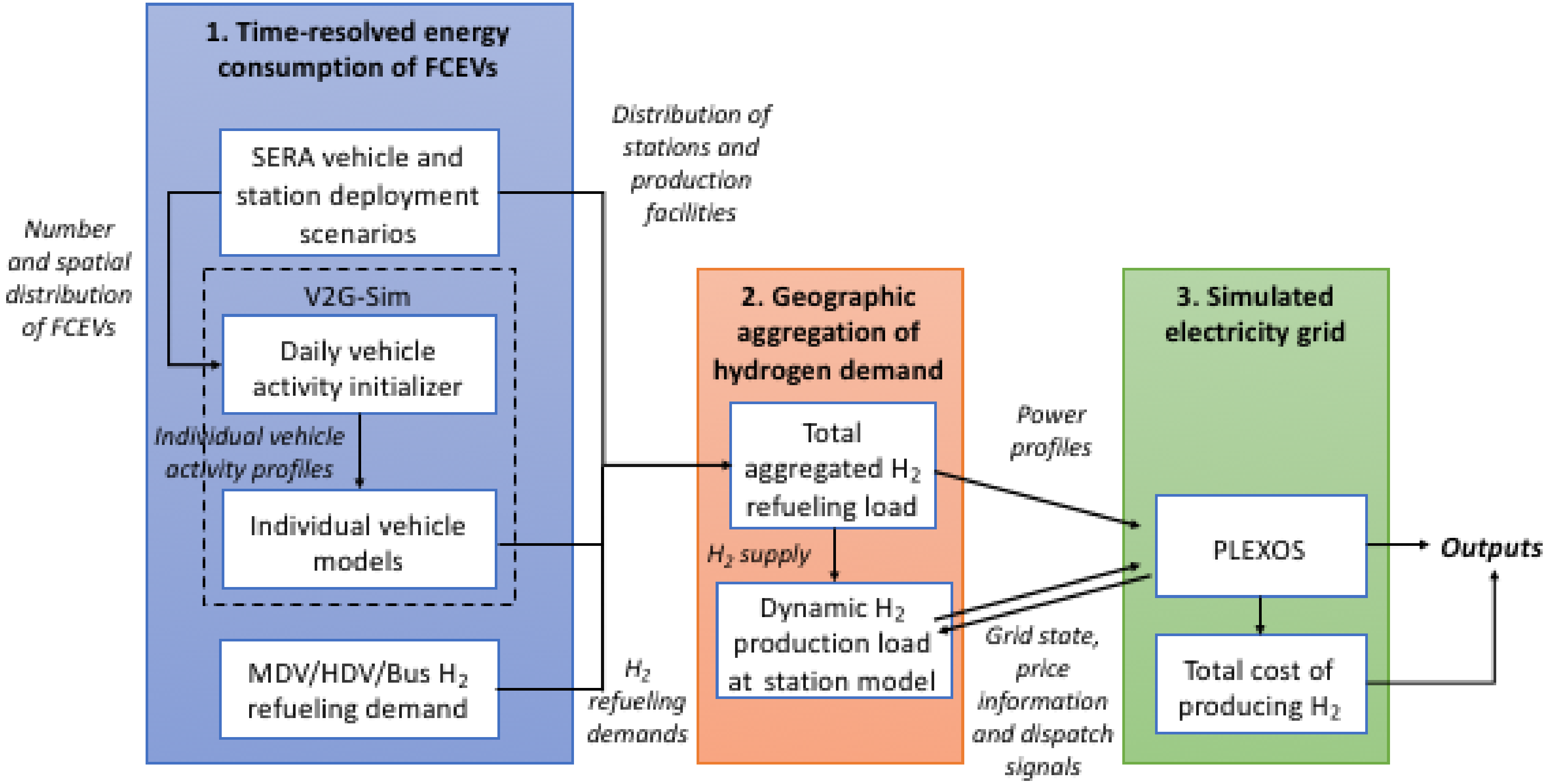
Project objectives:

- **Develop an integrated modeling capability ("H2VGI Model")** to quantify the interactions between stationary H_2 generation, fuel cell vehicles, and grid support resources
- **Quantify potential grid support** from flexible H_2 production
- **Assess ability to support integration** of renewable generation

Conceptual Overview



Approach: H2VGI Model Structure



1. Time-resolved energy consumption of FCEVs

SERA vehicle and station deployment scenarios

Number and spatial distribution of FCEVs

V2G-Sim

Daily vehicle activity initializer

Individual vehicle activity profiles

Individual vehicle models

MDV/HDV/Bus H_2 refueling demand

Distribution of stations and production facilities

H_2 refueling demands

2. Geographic aggregation of hydrogen demand

Total aggregated H_2 refueling load

H_2 supply

Dynamic H_2 production load at station model

Power profiles

Grid state, price information and dispatch signals

3. Simulated electricity grid

PLEXOS

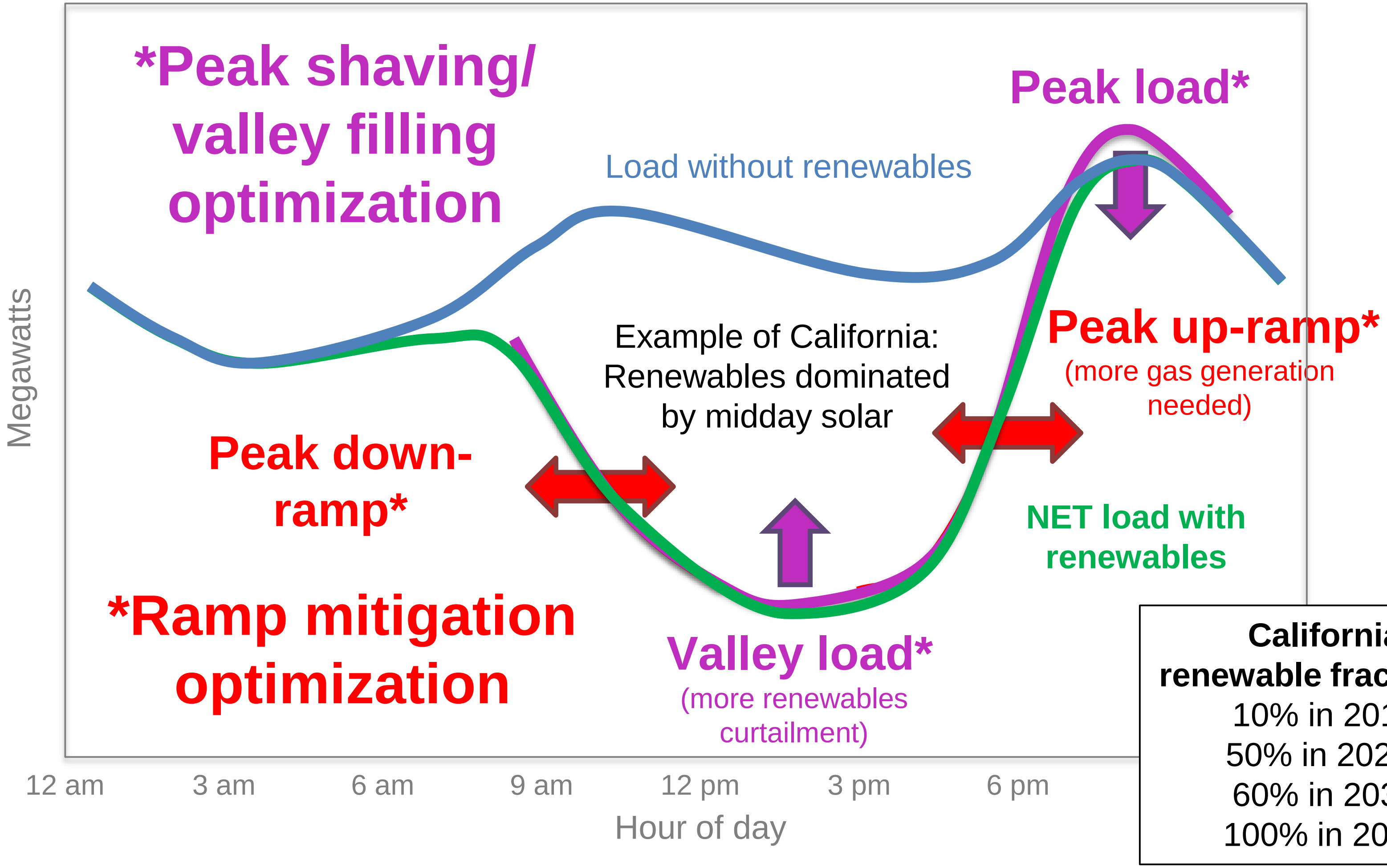
Total cost of producing H_2

Outputs

The H2VGI model integrates multiple operational and deployment models for FCEVs and H_2 generation resources with external grid models across various time scales

Renewable Integration Challenge in California

Four important problems highlighted by the daily load or “Duck” curve:



*Peak shaving/ valley filling optimization

Example of California: Renewables dominated by midday solar

Peak load*

Peak up-ramp*

(more gas generation needed)

Peak down-ramp*

Valley load*

(more renewables curtailment)

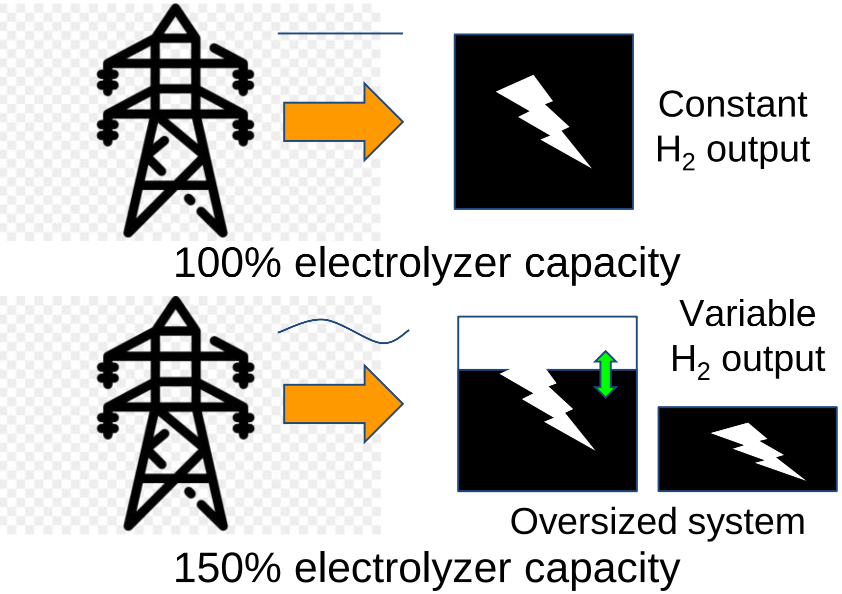
*Ramp mitigation optimization

California renewable fractions:
10% in 2014
50% in 2026*
60% in 2030
100% in 2045

*50% by 2020 on track in 3 IOUs—several yrs. ahead!

Electrolyzer H_2 generation can support greater renewable integration by reducing ramp rates

2025 California Net Load Impact for 5 FCEV Scenarios - Ramp Up Rates are restored to 2014 levels with Flexible Electrolyzer Generation for 0.8-1.5M FCEVs



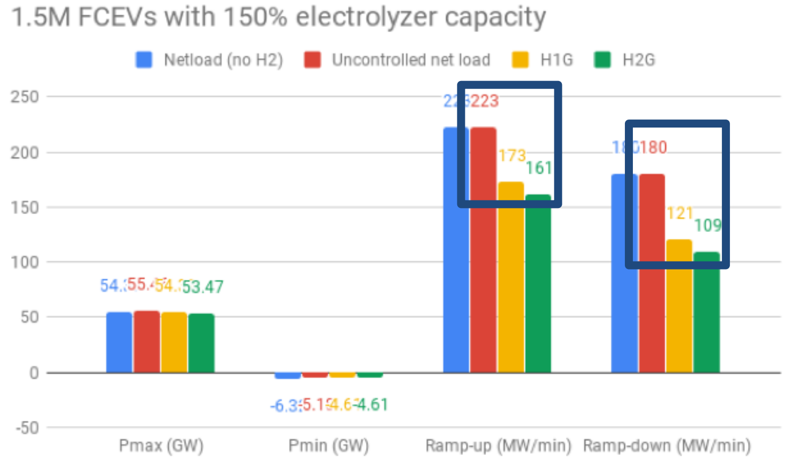
Constant H_2 output

100% electrolyzer capacity

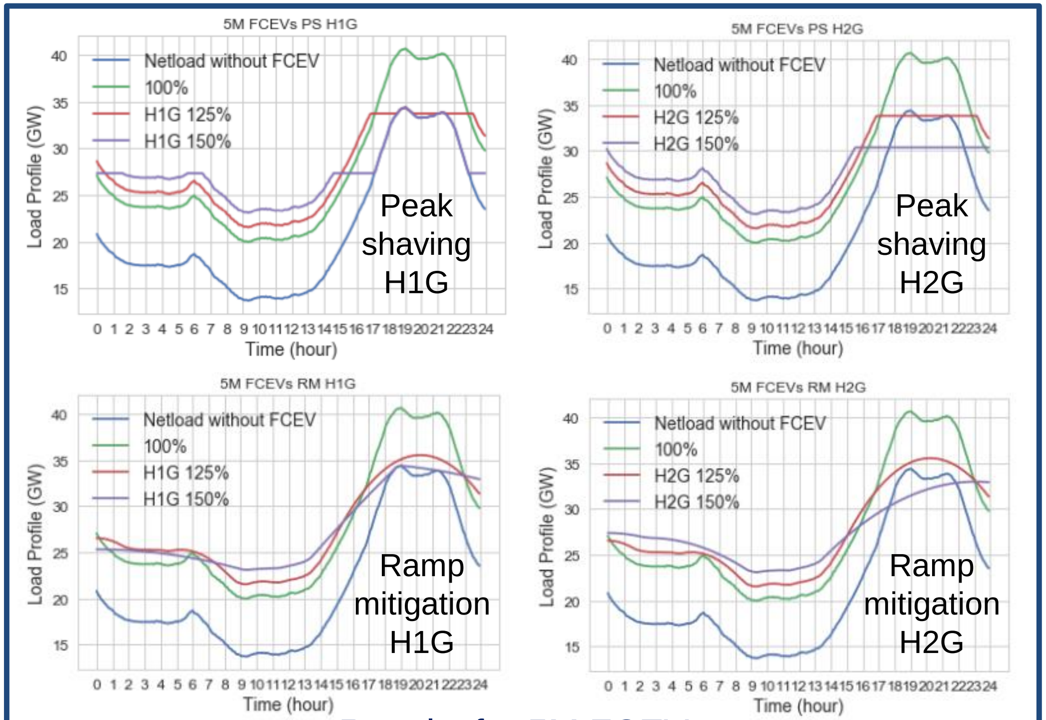
Variable H_2 output

Oversized system

150% electrolyzer capacity



1.5M FCEVs with 150% electrolyzer capacity



Results for 5M FCEVs

Summary results

- FCEVs can provide peak shaving/valley filling and ramp mitigation benefits, but **ramp mitigation benefits have much larger proportional reductions**
- **Ramp-up rates in 2025 can be reduced to 2014 levels** at 800k-1.5M FCEVs and 125-150% electrolyzer capacity
- **Ramp-up rates can be reduced to ~zero** at 10M FCEVs and 150% capacity
- **H1G alone can deliver sizable benefits**, though H2G enhances impacts

Economic modeling: electricity production cost modeling for Western North America, 2030 (PLEXOS)

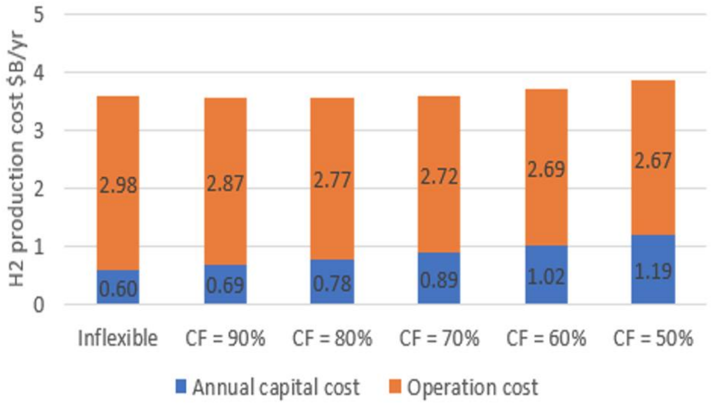
Vehicle class	Abbre-viation	Definition	Gross vehicle weight (GVW) [52]	Projected number of FCEVs (see text)
Light-duty vehicle	LDV	Passenger cars and light trucks (class 2a)	≤3,853 kg (≤8,500 lbs.)	5.0 million (18%)*
Medium-duty vehicles	MDV	All class 2b-6 vehicles	3,854-11,786 kg (8,501-26,000 lbs.)	274,000 (23%)*
Heavy-duty vehicles	HDV	All class 7 and 8 vehicles except buses	>11,786 kg (>26,000 lbs.)	33,500 (9%)*
Buses	BUS	Urban, school and other buses		19,400 (26%)*

* The fraction of vehicle stock in 2030 for California

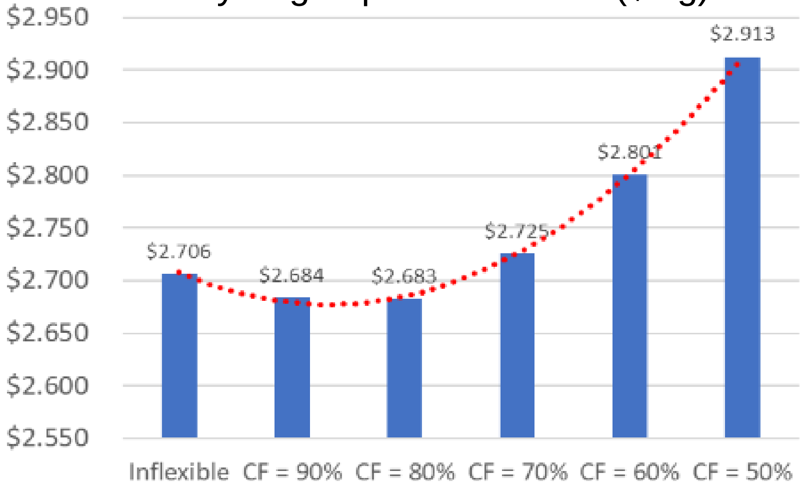
5M fuel cell LDV; ~0.33M fuel cell MDV, HDV, buses
LDVs represent ~90% of the total hydrogen demand
Storage tank capital cost: $30/kWh
2020 Target electrolyzer capital cost: $300/kW

Oversizing electrolyzer increases load flexibility and can reduce overall system cost with future electrolyzer capital cost

Total System Cost (Operating and Capital Cost)



Hydrogen production cost($/kg)

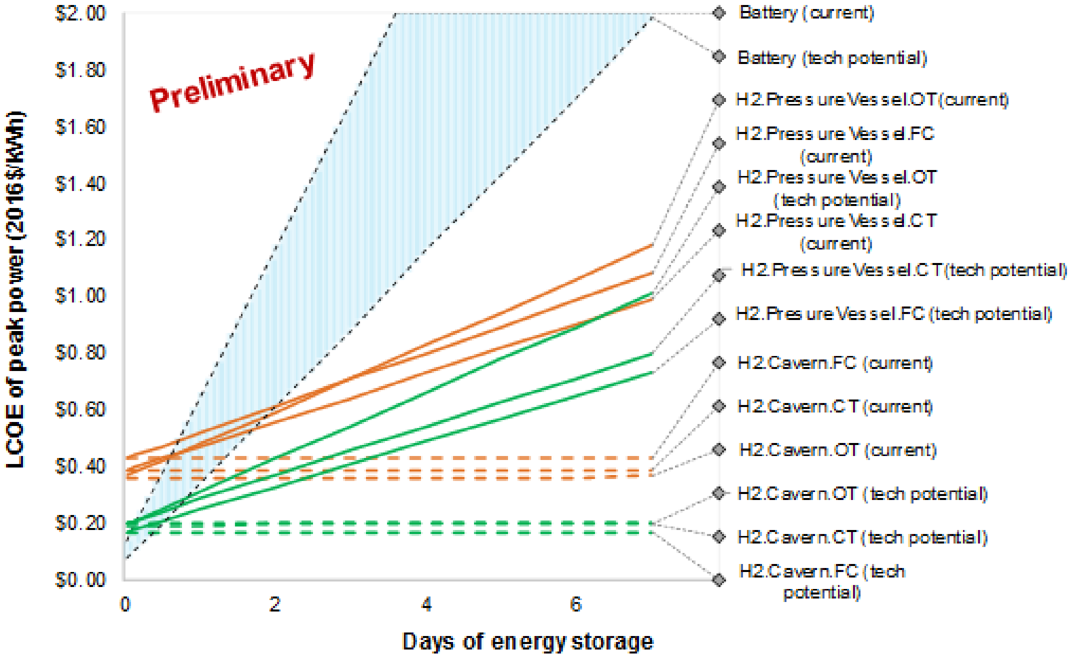


Scenarios	Inflexible	CF=90%	CF=80%	CF=70%	CF=60%	CF=50%
Electrolyzer size/GW	5.6	6.3	7.1	8.1	9.5	11.5

Long duration storage cost reduction

At ~10h of storage, hydrogen technologies are more cost competitive than batteries

Ref: H2FAST Benchmark vs. Storage Days (NREL Penev et al., 2019)



OT: Oxy-combustion turbines
FC: Fuel Cells
CT: Combustion Turbines

Round trip efficiency limitations are surpassed by **lower cost storage** benefits:
At ~10h of storage, hydrogen technologies are more cost competitive than batteries.

Motivation – Chemical storage can have very low energy storage costs ($/kWh) compared to other approaches

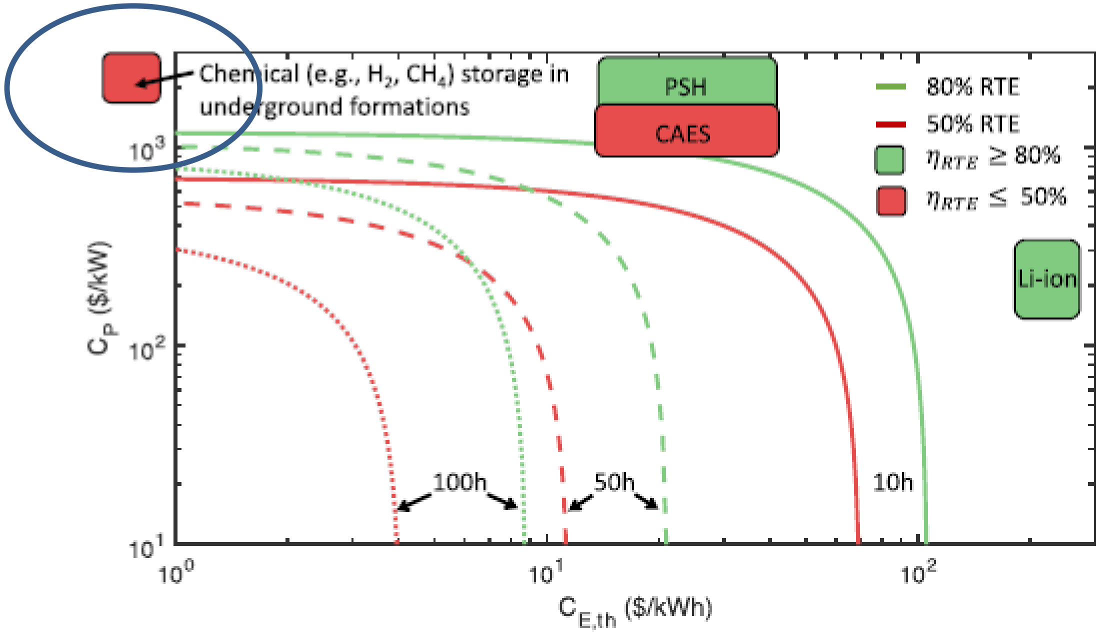


Figure 3. Relationship between Power and Energy Capital Costs Derived from Figure 2

Albertus et al 2020

Motivation – how to sharply reduce capital cost for power conversion units ($/kW) for chemical storage (H2)?

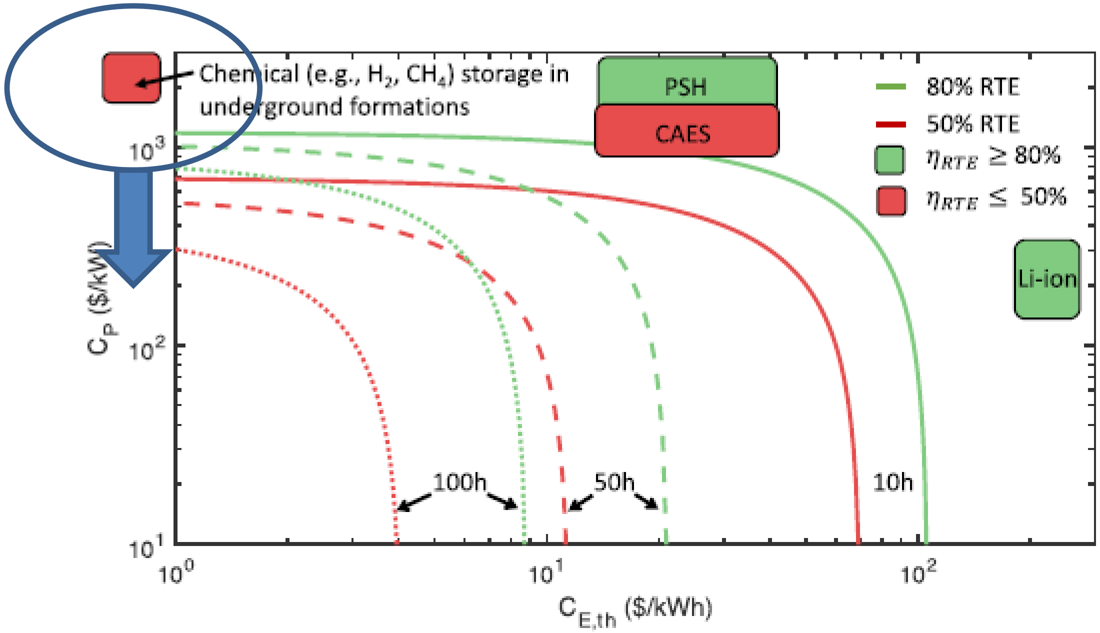
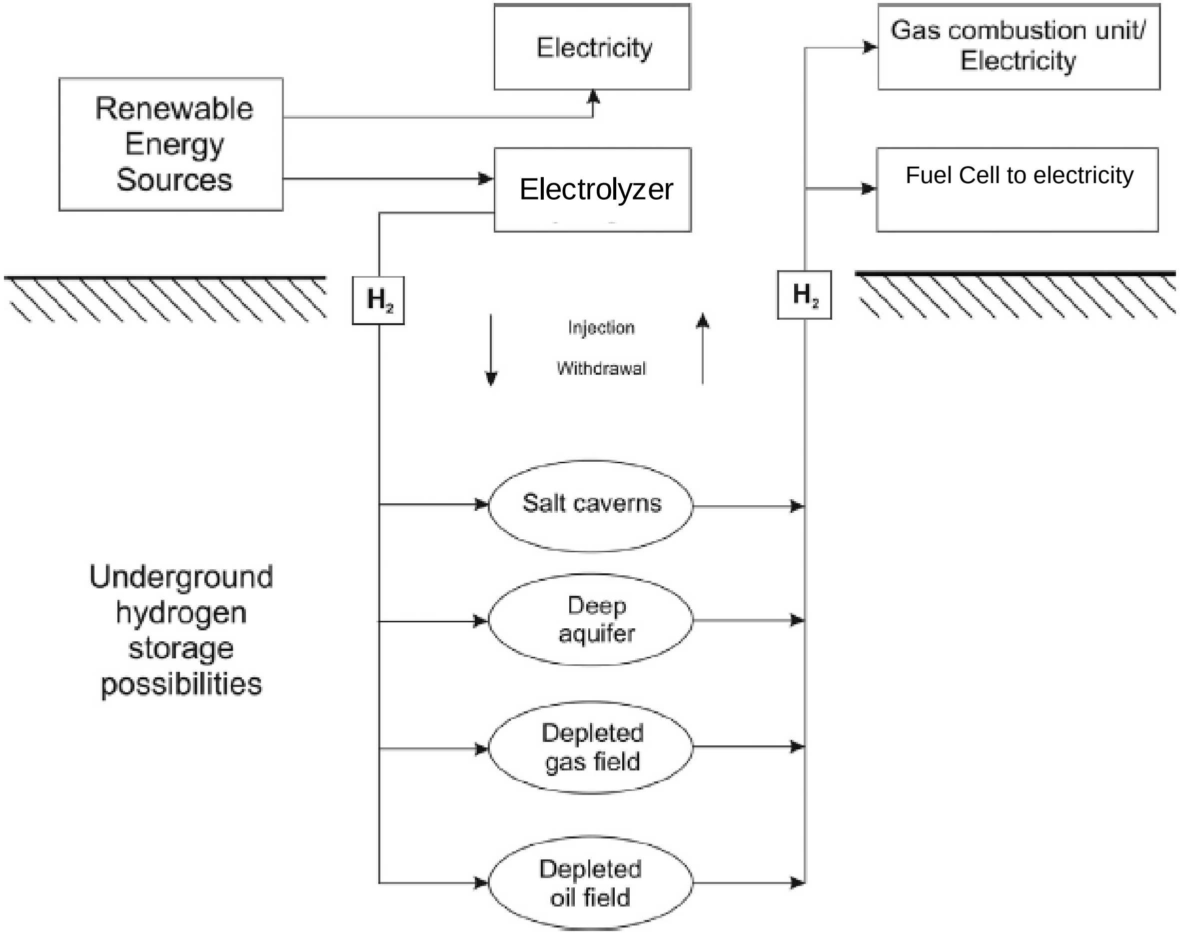


Figure 3. Relationship between Power and Energy Capital Costs Derived from Figure 2

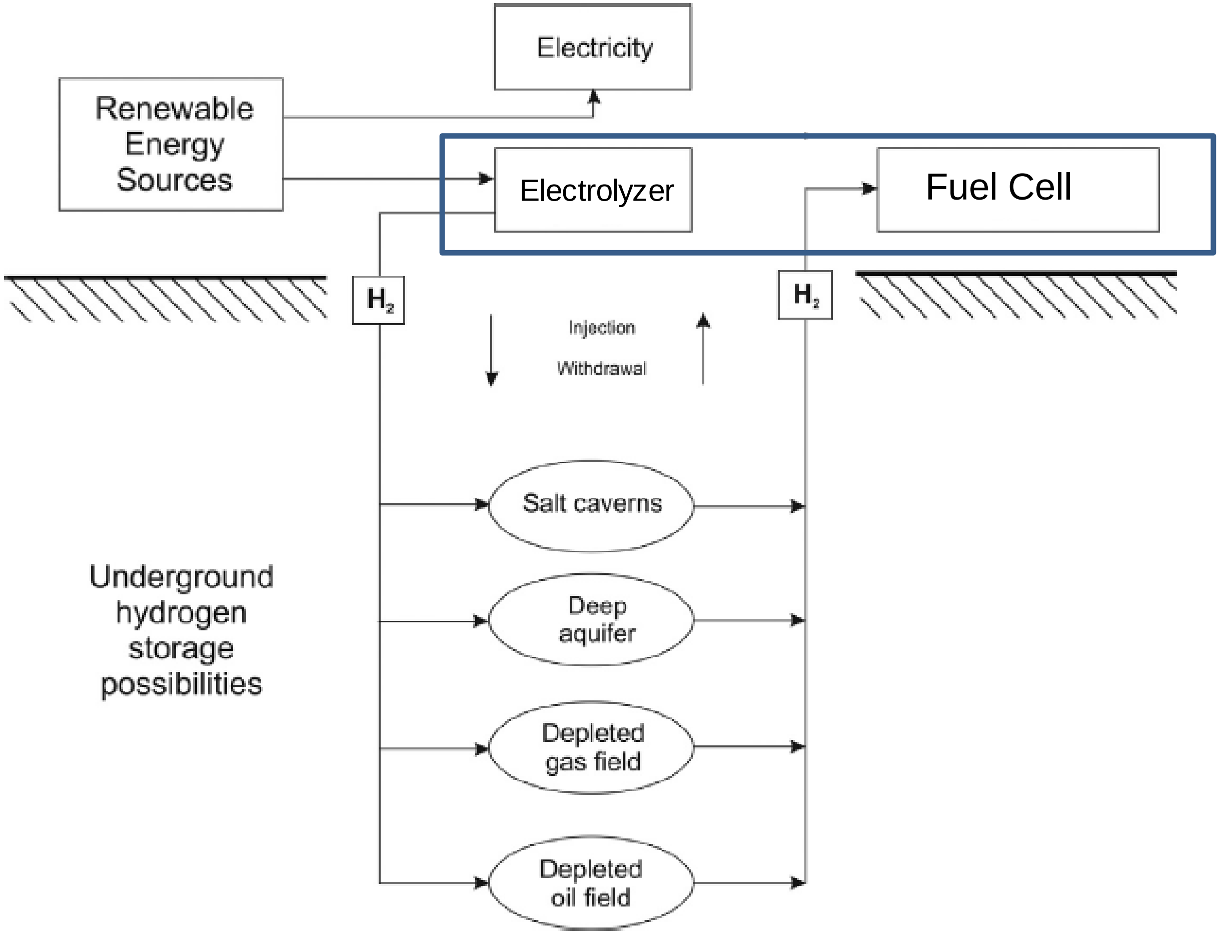
Albertus et al 2020

Grid-scale H2 Storage system schematic

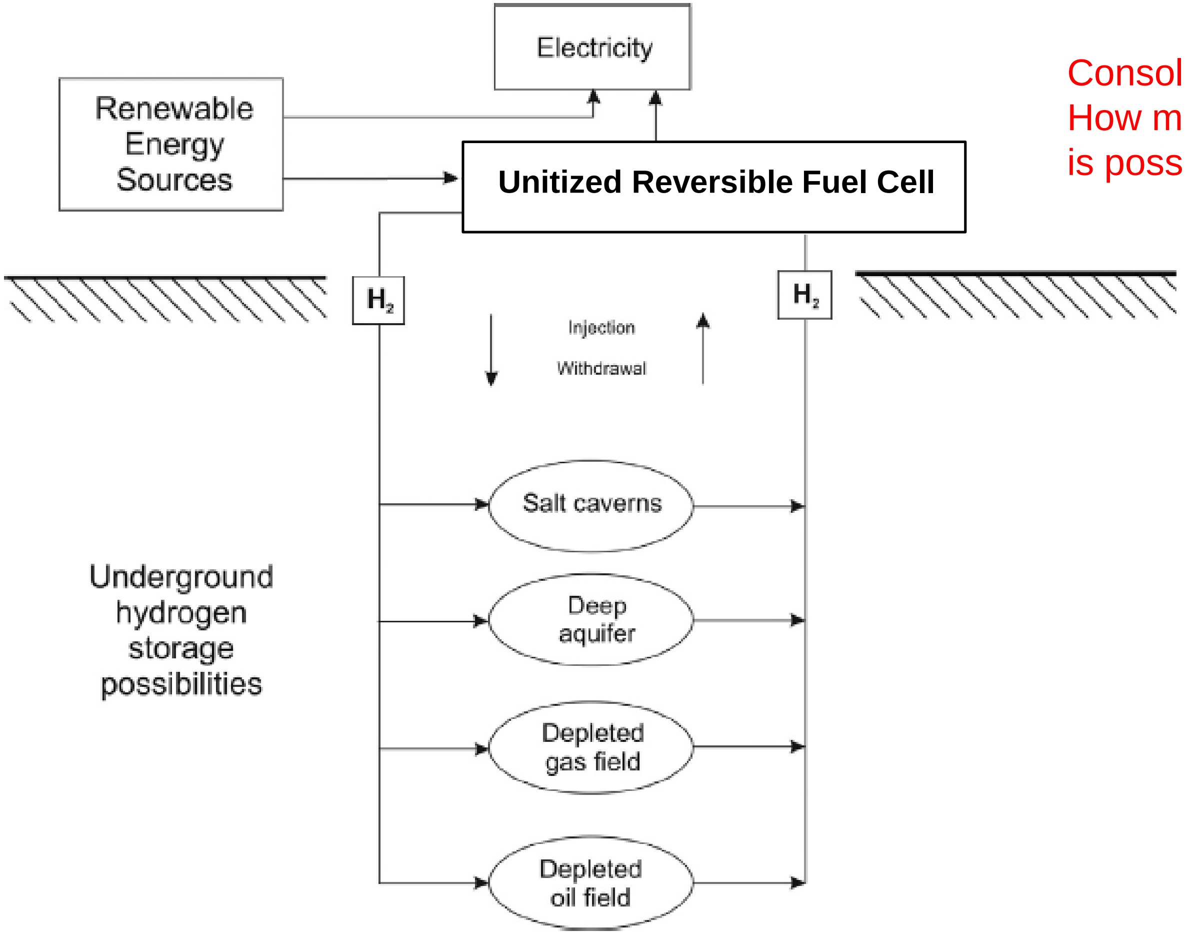


:
How much capital cost reduction is possible e.g. grid-scale Fuel Cell system with reduced hours of operation?

Consolidate Electrolyzer and Fuel Cell to unitized stack for capital cost reduction



Consolidate Electrolyzer and Fuel Cell to unitized stack for capital cost reduction



Consolidate electrolyzer & fuel cell:
How much capital cost reduction
is possible?

Summary

- Iron and steel – Commercial hydrogen-based DRI production may be just 5-10 years away where power is already cheap; and with Green H2 could reduce emissions by up to 90%
- Fuel cell CHP in commercial buildings are most competitive in areas of country with high CO2-intensity electricity, but is still an expensive option without much higher volumes and externality valuation
- Grid support of California duck curve modeling has been demonstrated with large-scale controllable electrolysis H2 vehicle fleet and economic benefits quantified for ~2030 scenario with high FC vehicle adoption
- H2-based storage can offer grid-scale storage at low cost with subsurface storage, but further characterization and demonstration of geologic storage needed
  - Capital reduction of power conversion equipment, e.g. low cost MW-scale PEM fuel cells or lower cost reversible fuel cells is critical

Emerging H2 applications – topics/pubs

H2 CHP Cost Analysis

Max Wei, Sarah J. Smith, Michael D. Sohn, Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US, Applied Energy, Volume 191, 1 April 2017, Pages 346-357, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2017.01.056.

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FCEV Cost Analysis

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Thank you

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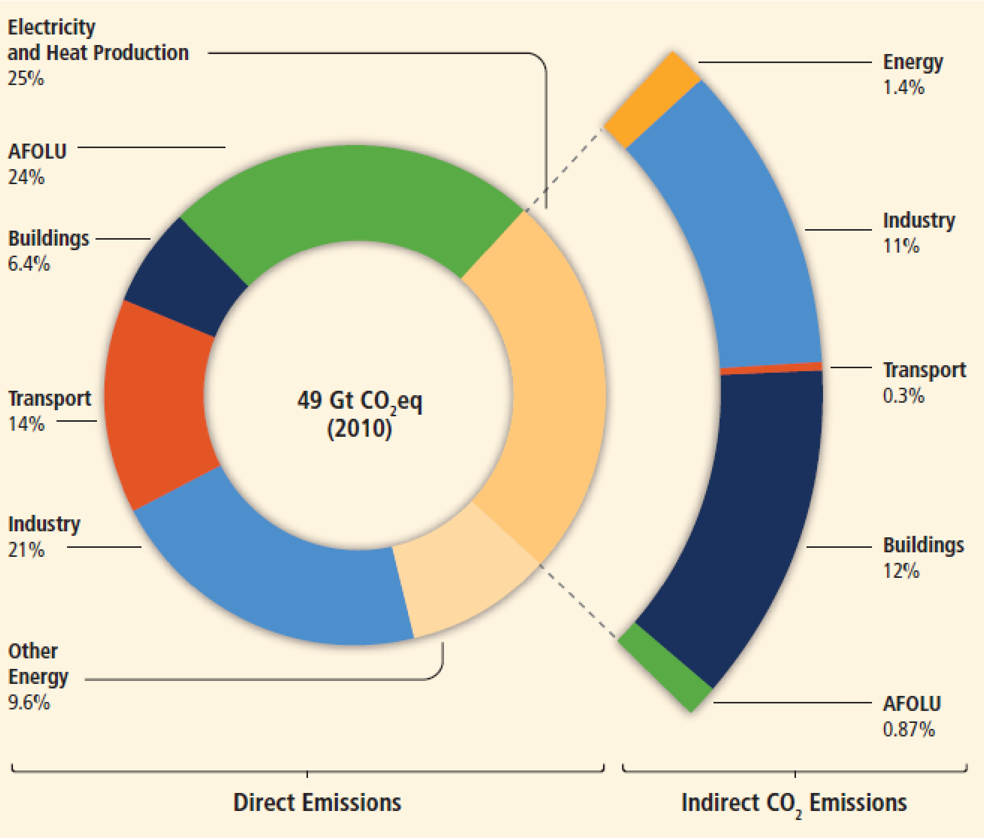
Global Greenhouse Gas Emissions

Industry represent 1/3 of global GHG emissions



Source: de la Rue du Can et al. Applied Energy 159 (2015) 548-559 – Inputs to IPCC AR5