How to Transition to a Hydrogen Powered Regional Fleet

A Case Study

SOUTHWEST RESEARCH INSTITUTE®

09-25-2025

How Hydrogen Projects are Born

How can I decarbonize my fleet?

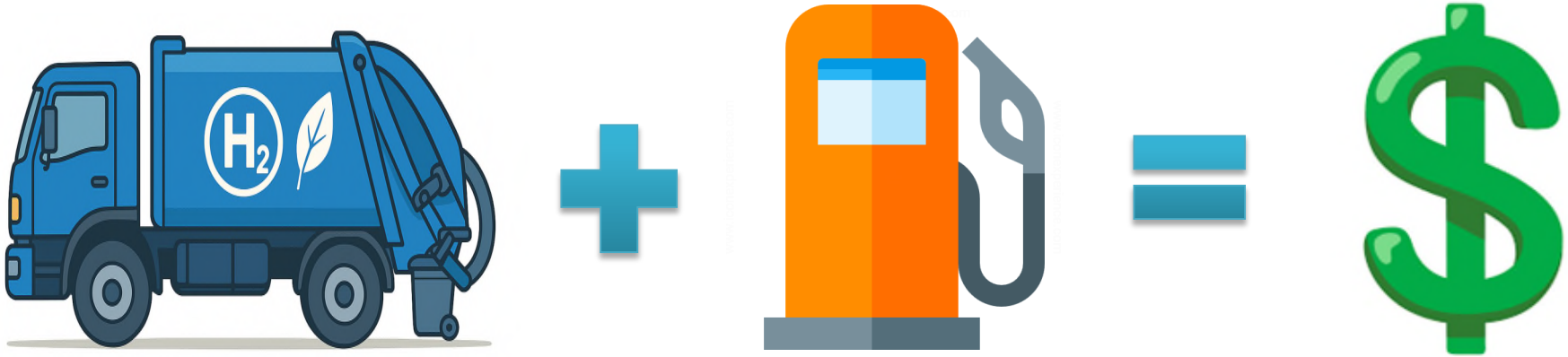
Electric Vehicles?

- ✗ Slow recharge time (2X inventory required)
- ✗ I can't upgrade my power on-site

Hydrogen Vehicles?

- ✓ Fast refill times
- ✓ Refueling on-site

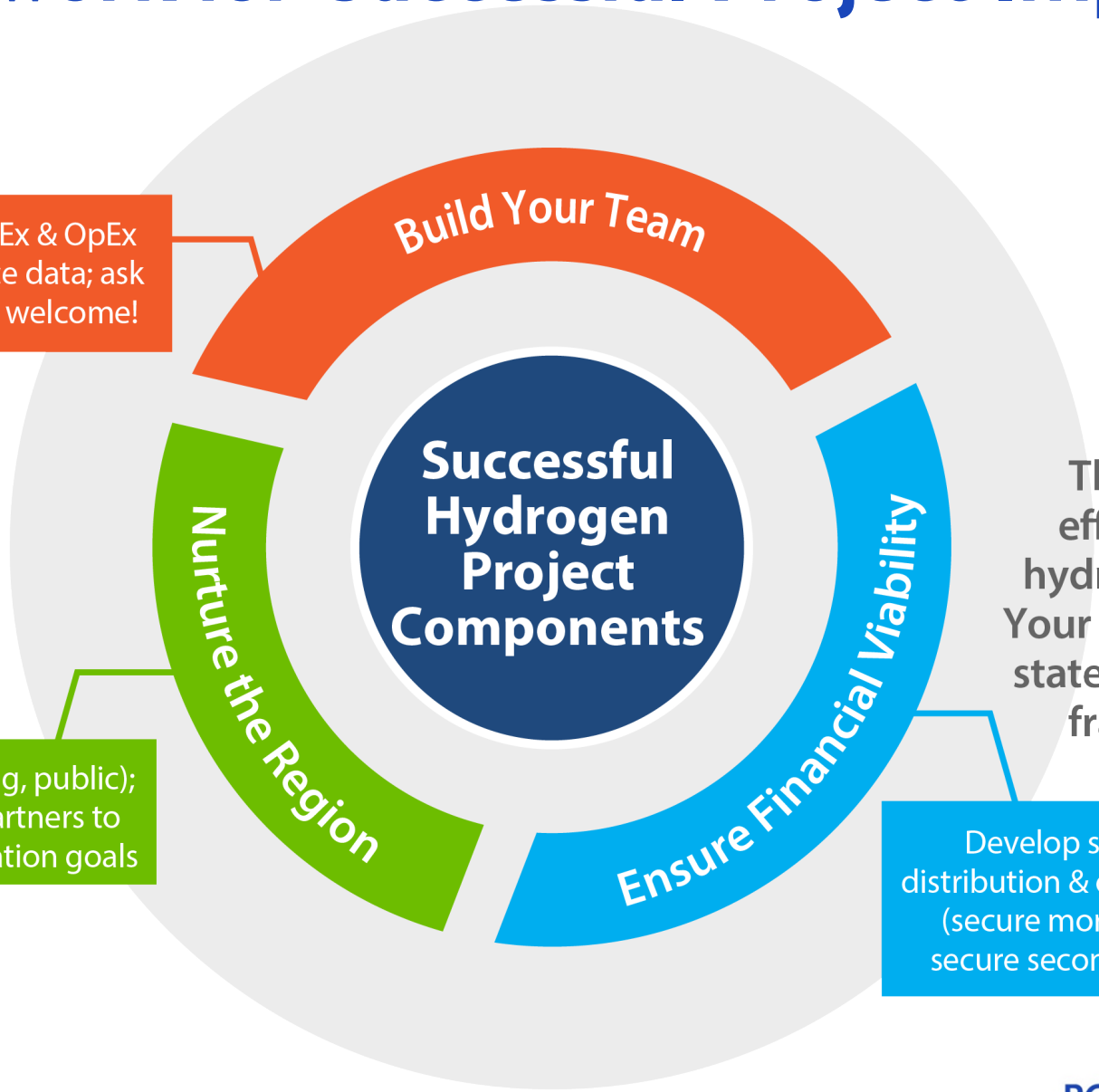
From Feasibility to Implementation Logistics



- Successful Project Implementation:
  - Ensure financial viability
  - Build your team
  - Nurture the region

- Total Cost of Ownership Variables:
  - Geographical region
  - Costs along the value chain: production, distribution, end use equipment (CapEx + OpEx)
  - Implementation scale

SwRI's Framework for Successful Project Implementation



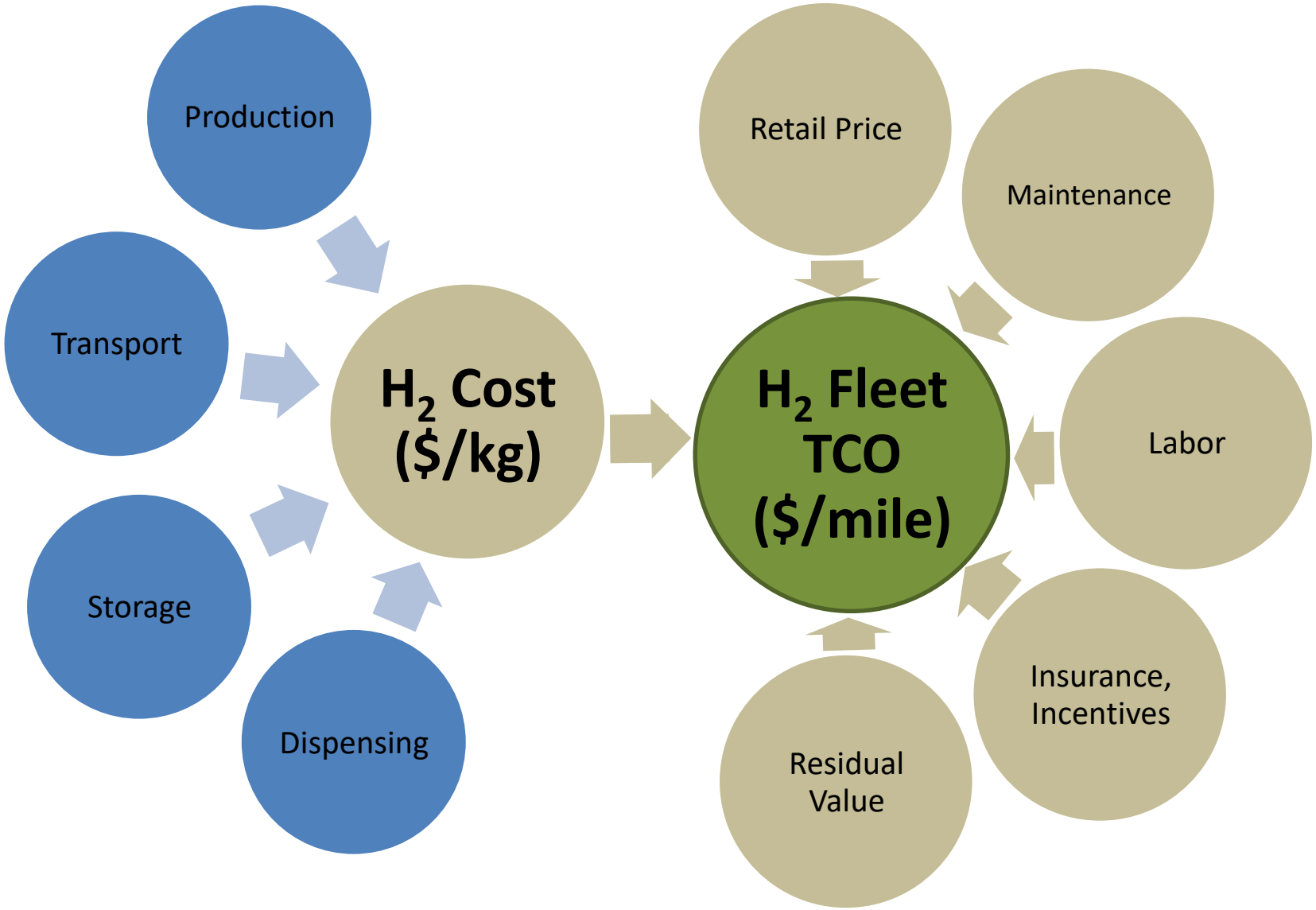
Personal relationships; clear CapEx & OpEx expectations; shared performance data; ask for references; teams of partners welcome!

Educate locals (fire marshal, permitting, public); create unbiased tools for financial partners to use; tailor project to local decarbonization goals

Develop stability and balance for supply, distribution & off-takers; line up the H2 ecosystem (secure more than one financial advantage); secure second opinion on the project viability

The hub model is the most effective way to introduce a hydrogen economy to a region. Your project doesn't have to span states to be effective. Follow this framework to find success!

Calculating TCO of a Hydrogen Truck



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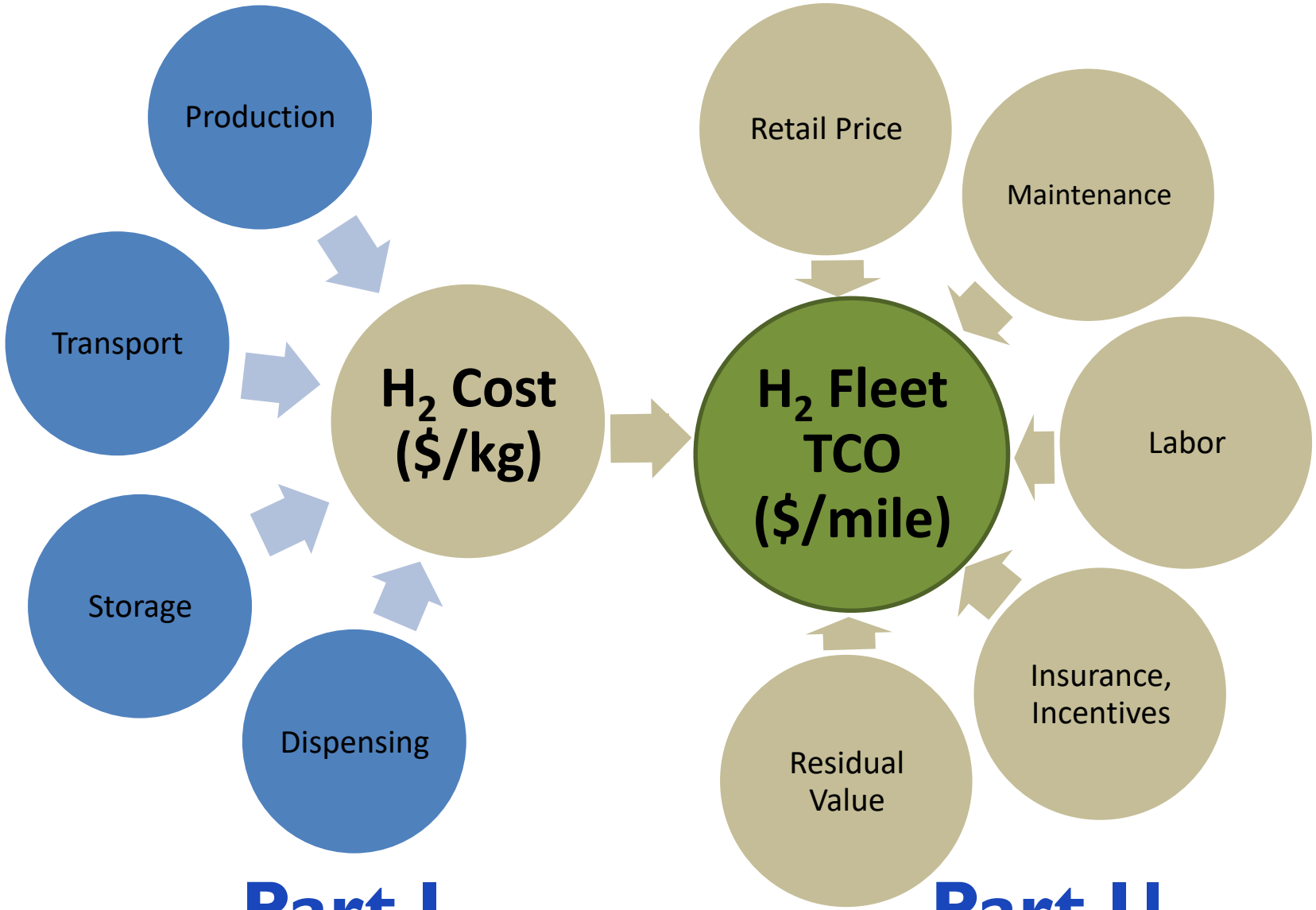


Part I: H2 Cost Estimation

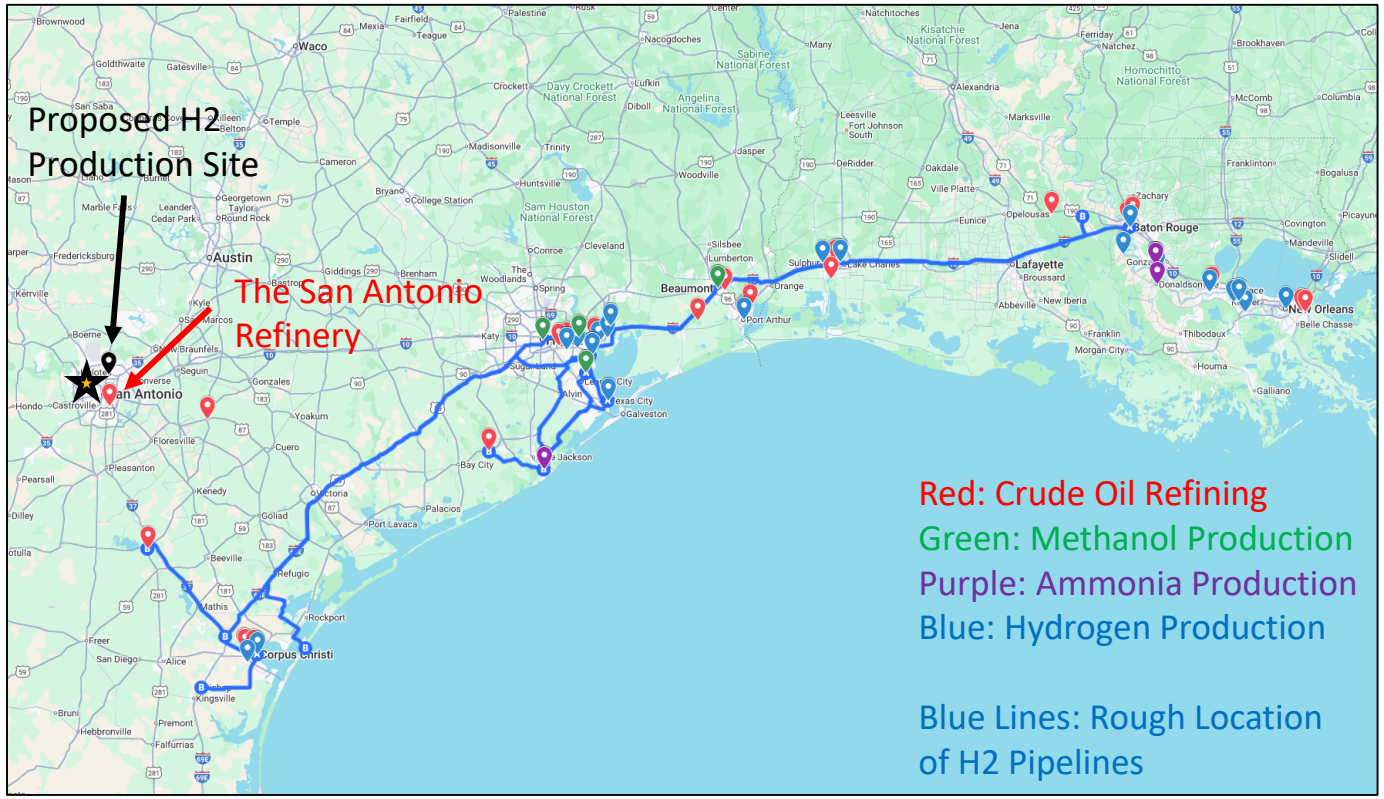
Onsite Production or Delivery?

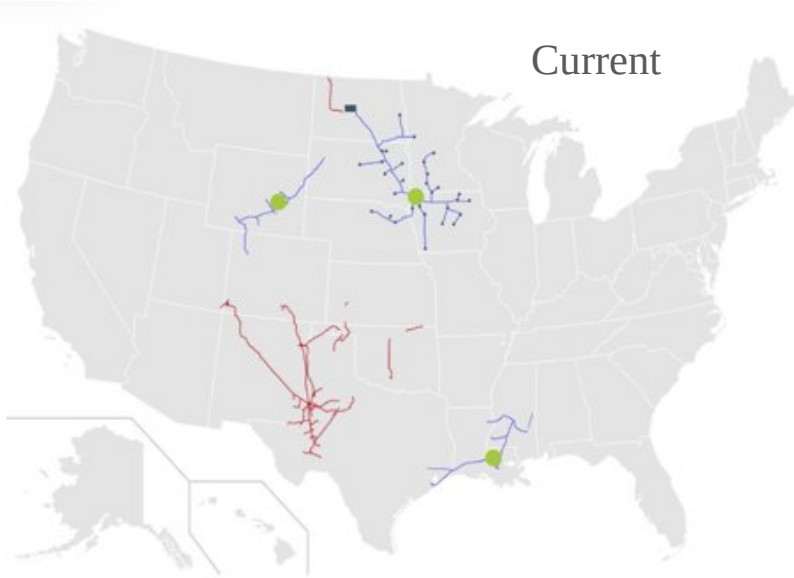
Deliver
Indus

Onsite
with Hy
Ref

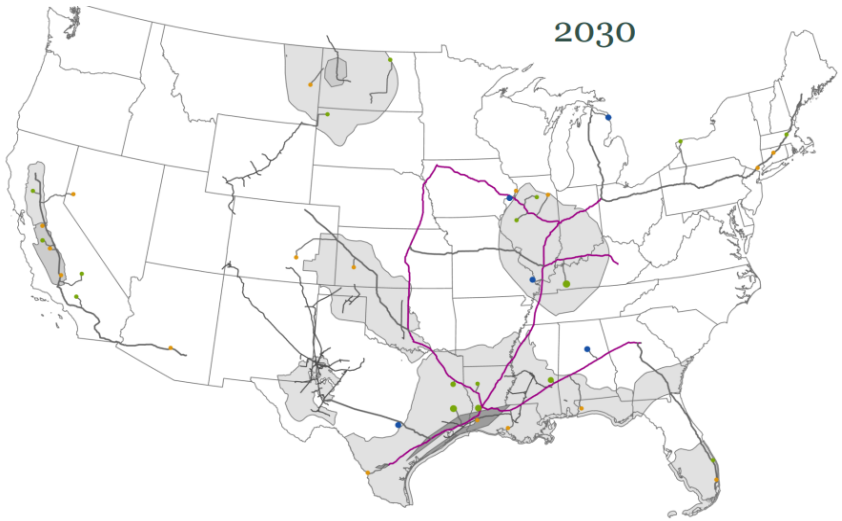
Hydrogen Cost are Region Specific

- Assumed the hydrogen refueling station (RFS) has a capacity of 1 MT/day - demonstration of 10-13 trucks
- The remainder of produced hydrogen is sold to The San Antonio Refinery (TSAR)
- For carbon capture scenarios, assumed a CO2 pipeline exists between San Antonio and Houston (plant doesn't become fully operational until 2030)





Map of Carbon Pipelines - American Carbon Alliance. (2025, January 9). American Carbon Alliance. https://americancarbonalliance.org/map-of-us-pipelines/



Larson, E., et al. *Net-Zero America: Potential Pathways, Infrastructure, and Impacts Final Report*. Princeton University, Princeton, NJ. October 2021.

Cost Estimating Assumptions and Methodology

Assumptions

- Existing land at CoSA's mulch grinding site can be used to host a hydrogen production plant
- Some biomass pretreating equipment is already owned (front end loaders, grinder, metals screener, truck scales)
- No taxes
- No internal rate of return (IRR)
- If pursued, capital investment is solely through debt financing (bonds, or other)
- The maximum size of a production plant is 20,000 kg H2/day (limited by the annual biomass processed by the site)

$$LCO"X" = \frac{(capital\ cost\ x\ CRF) + annual\ O\&M\ costs + annual\ energy\ costs}{average\ annual\ hydrogen\ yield\ in\ kg}$$

$$where\ CRF = \frac{r(1+r)^n}{[(1+r)^n]-1}; n = useful\ life\ (in\ years); r = discount\ rate$$

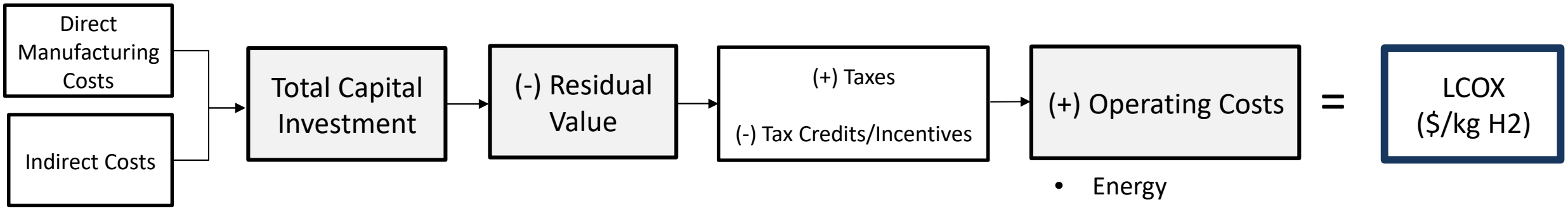
What is the actual cost of hydrogen?

- Actual cost of hydrogen (LCOH) is the sum of the following,
  - Levelized Cost of Production (LCOP)
  - Levelized Cost of Liquefaction and Terminal (LCOL+T), when applicable
  - Levelized Cost of Transport (LCOT), when applicable
  - Levelized Cost of Dispensing (LCOD)

- Information was collected from multiple sources,
  - City of San Antonio WMD
  - Vendor discussions/quotes
  - Equipment correlations
  - Literature trends

- Equipment cost
- Maintenance
- Catalyst cost/replacement

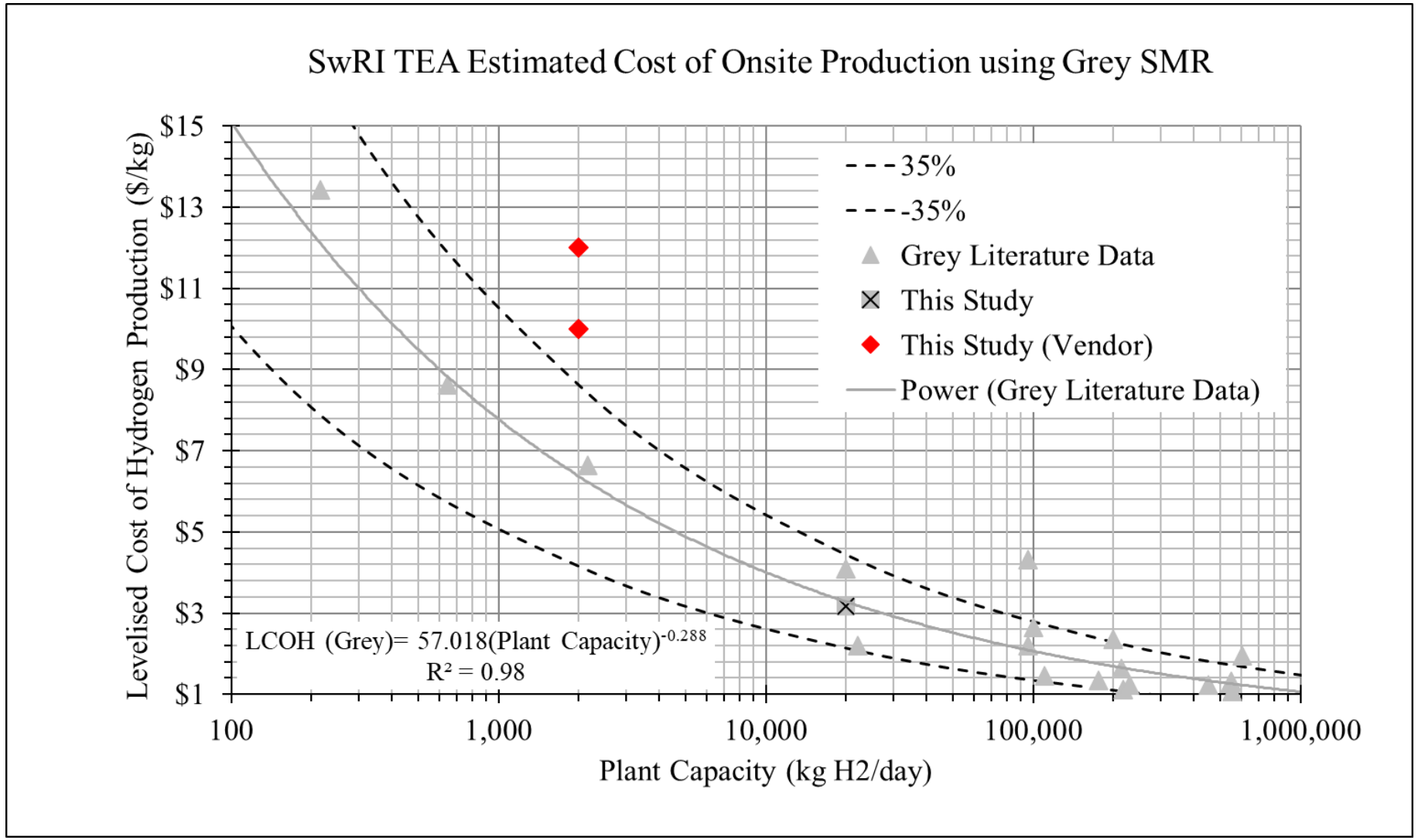
Equation for levelized cost of "X"



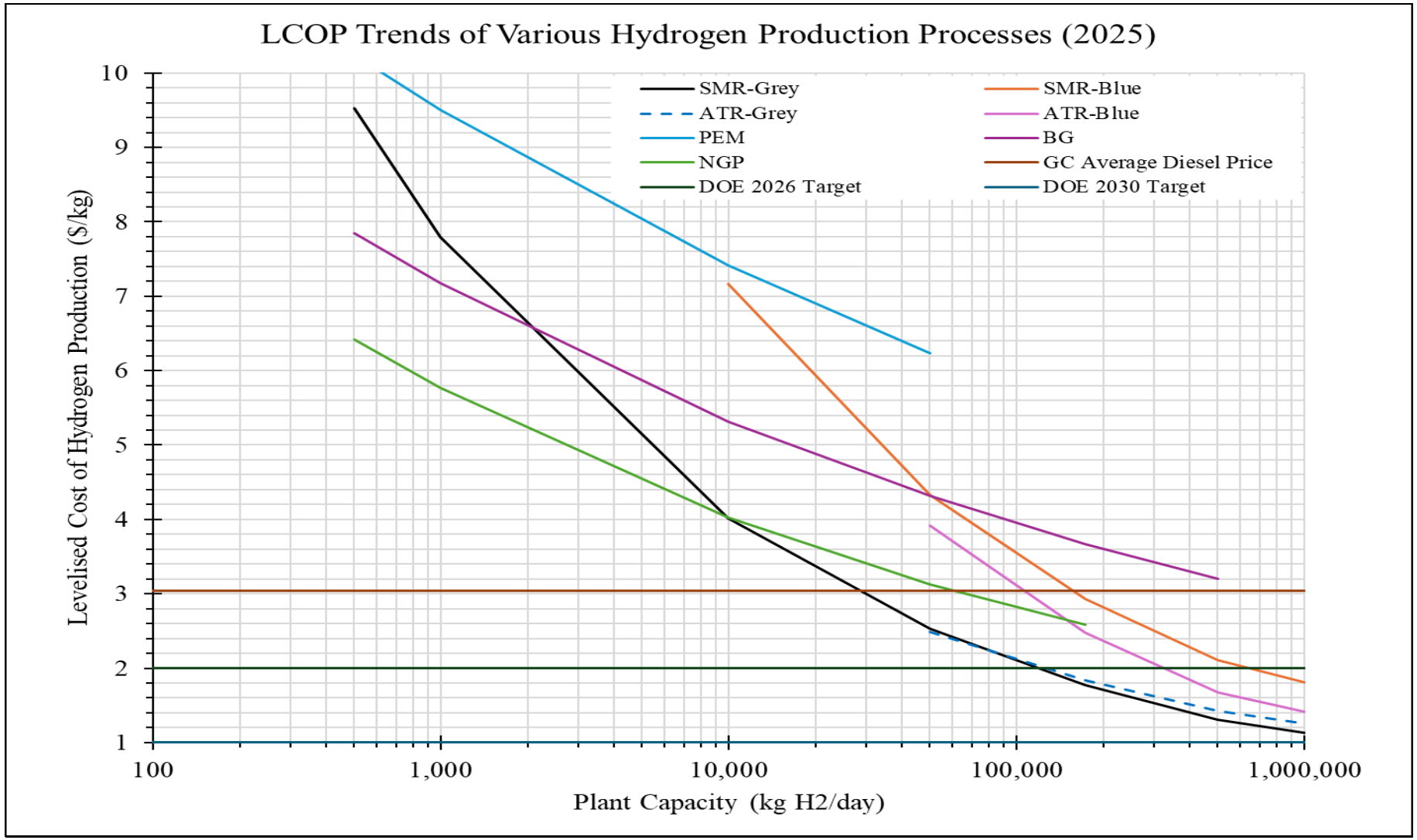
- R&D
- Overhead
- Marketing / distribution
- Warranty
- Markups

- Energy
- Maintenance
- Labor
- Insurance
- Financing

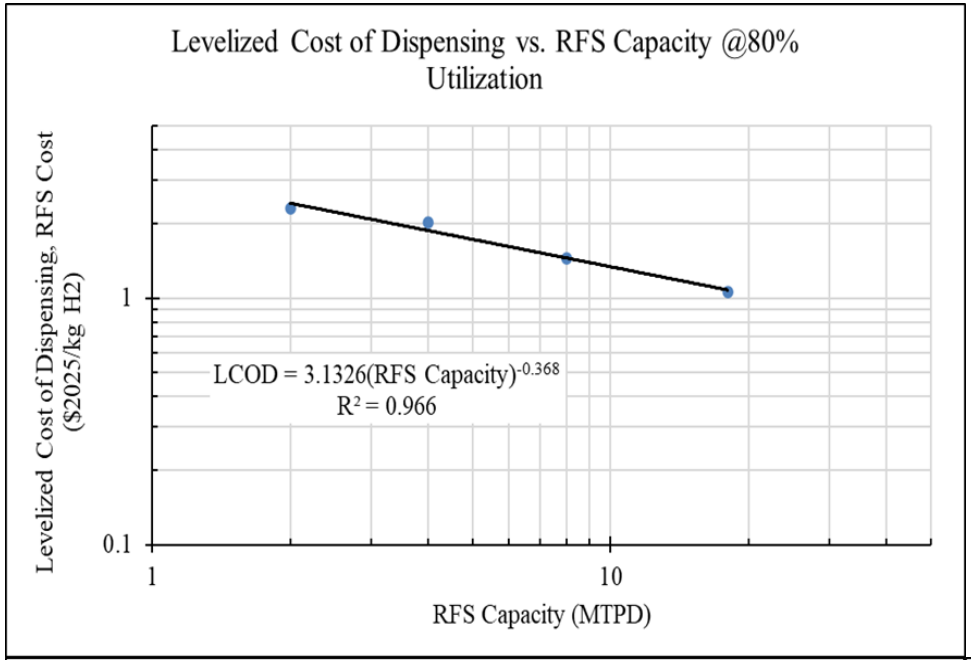
Detailed Example of Hydrogen Production Results



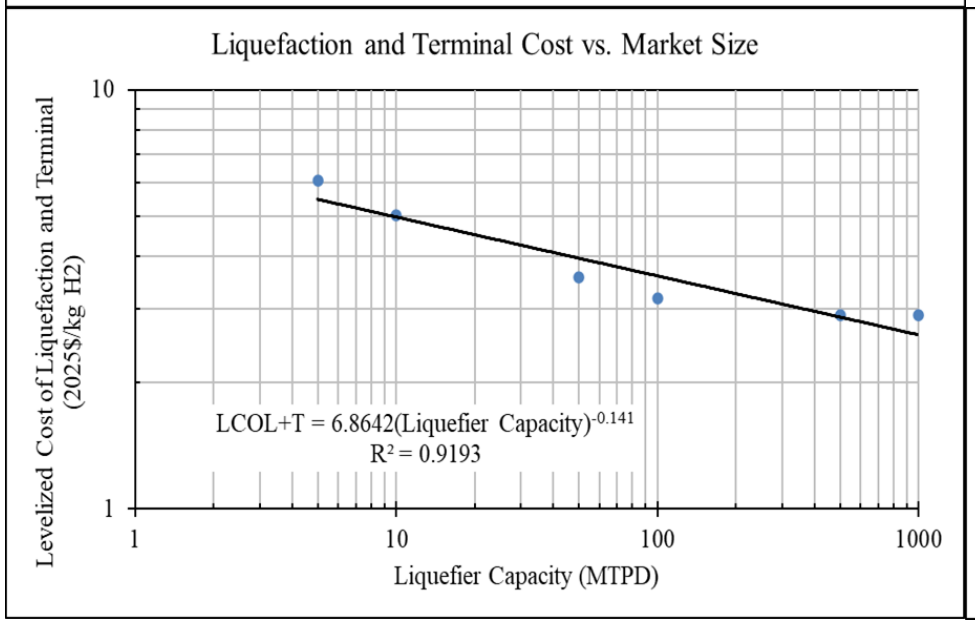
Hydrogen Production Results

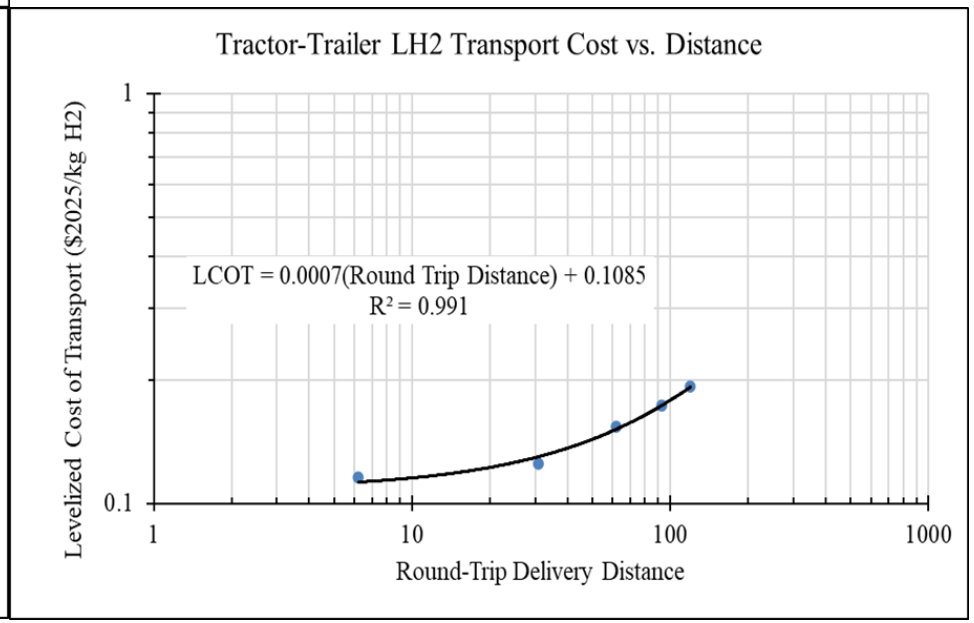


GH2 or LH2 Delivery



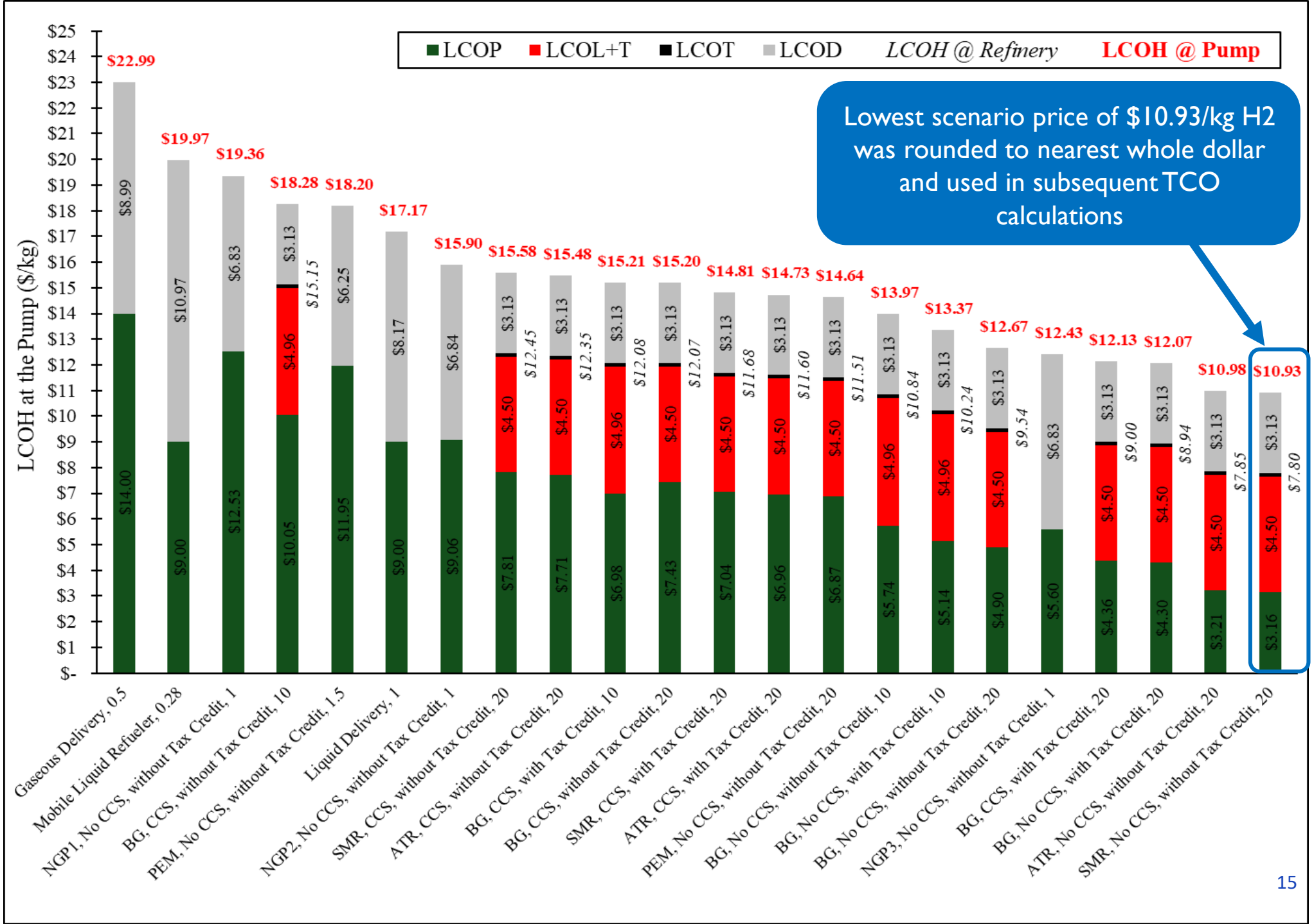
Process	Daily Hydrogen Capacity (kg/day)	TCI ($/kg/day)	LCOH ($/kg)
Liquid Delivery	1,000	2,000	$17.17
Gaseous Delivery	500	10,000	$30.82
Mobile Gas Refueler	280	8,928	$19.83



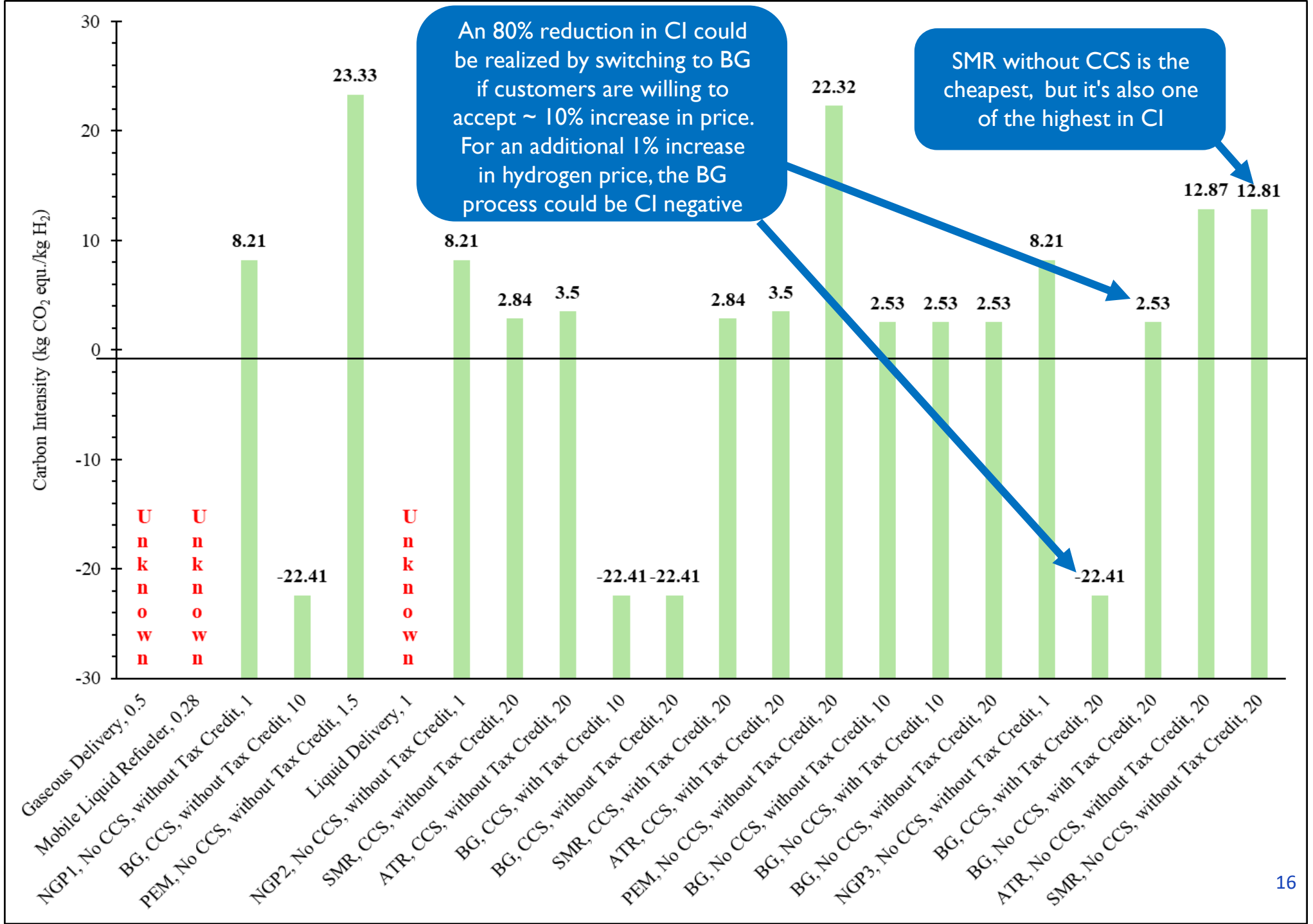


Data from Bracci et al., *Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles.* NREL Technical Report TP-5400-88818. March 2024.

Levelized Cost of Hydrogen at the Pump



Estimated Carbon Intensity

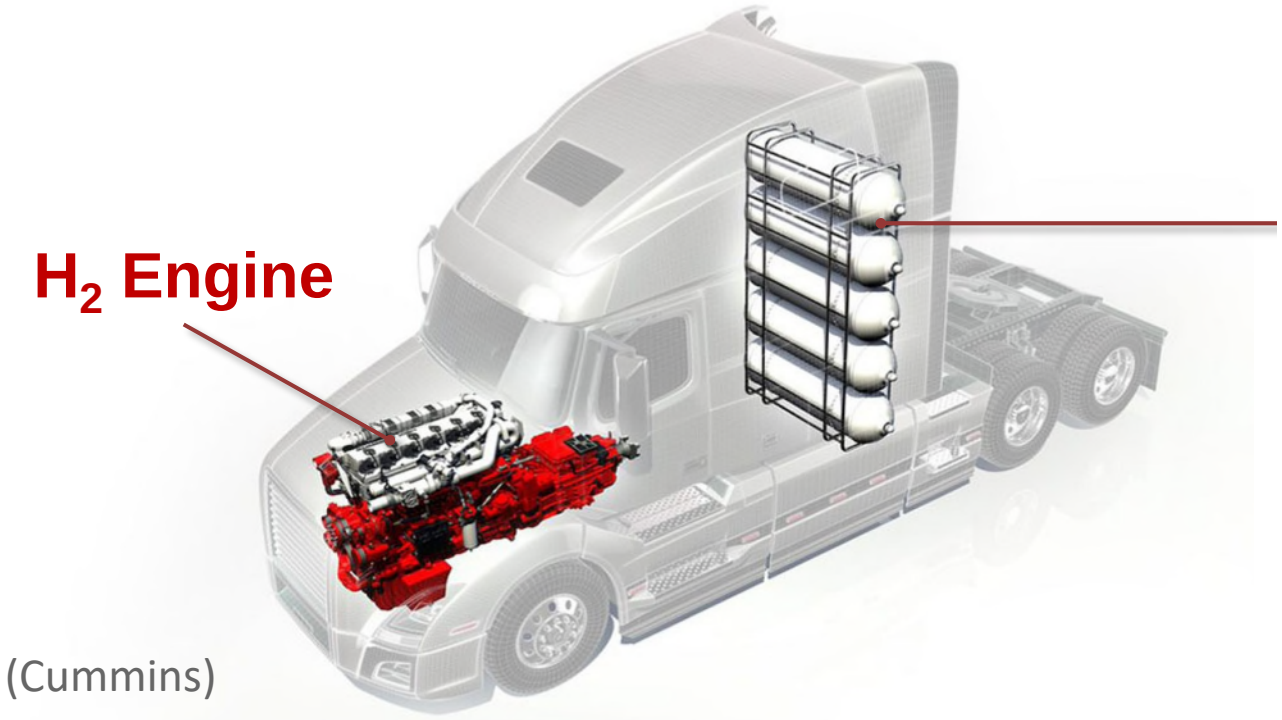


Conclusion

- Low-cost hydrogen requires very large plants to take advantage of economy of scale
  - By increasing production capacity by 100x, the LCOP can be reduced by roughly 75%
- Large plants normally are in rural areas, requiring transportation over longer distances to reach customers
- Transportation over long distances is typically cheaper to accomplish in the liquid phase
- Liquefaction of hydrogen adds additional $3-$5 to dispensed hydrogen (dependent on liquefier scale)
- The hydrogen landscape cannot currently support CoSA's decarbonization efforts while remaining on par with diesel prices

Part II: H_2 Refuse Truck Fleet TCO Estimation

H_2 Propulsion Systems



(Cummins)

(Nikola)

H_2 ICE
(Internal Combustion Engine)

H_2 FC
(Fuel Cell)

H_2 FC or H_2 ICE Trucks?

Both are technically viable, have been demonstrated on a limited scale, and present unique benefits and challenges

SwRI Class-8 H_2 ICE truck

JCB H_2 ICE digger

WM / Hyzon H_2 FC refuse truck

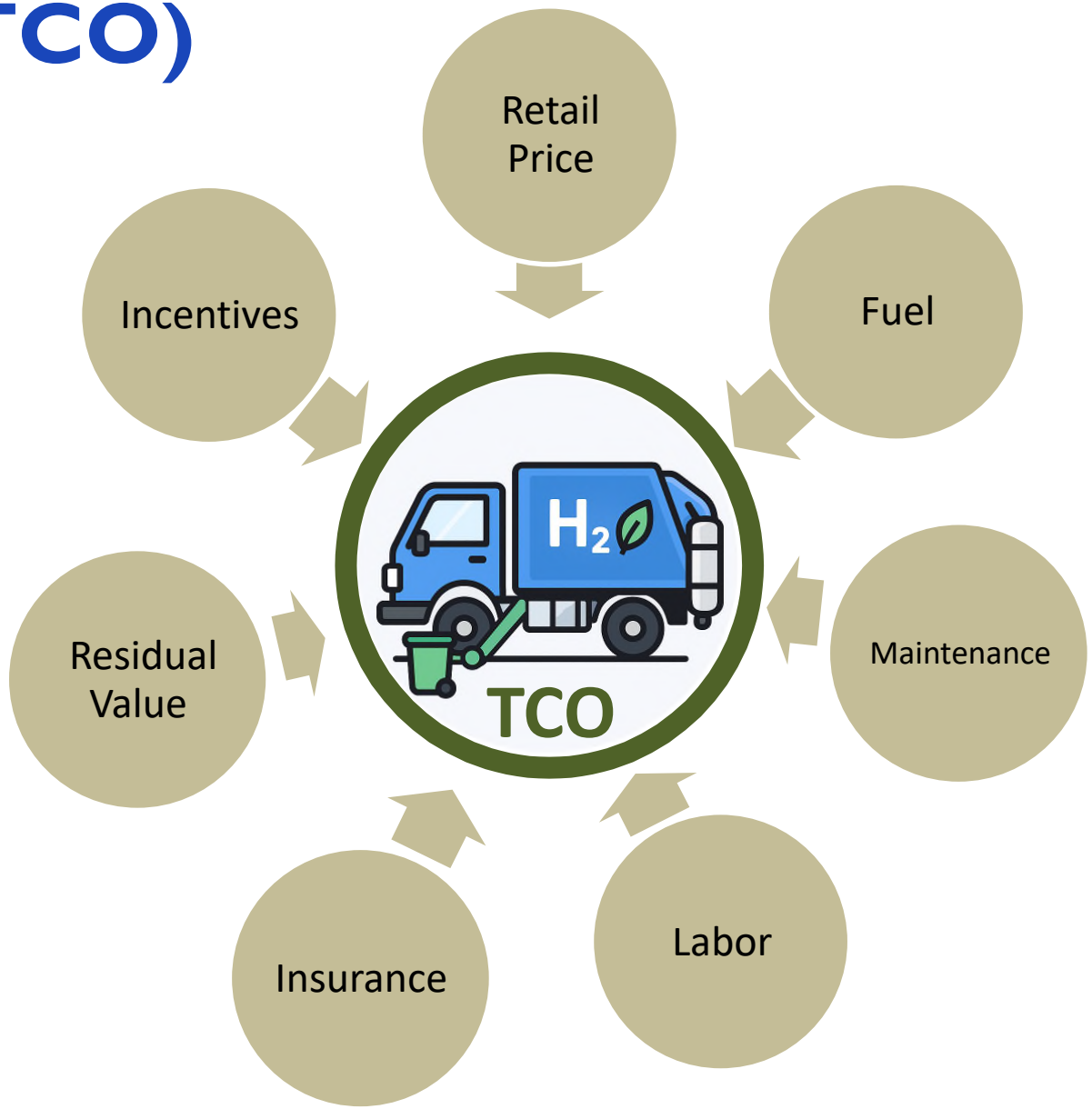
Hyundai Xcient H_2 FC truck

Are H_2 refuse trucks economically viable?

Total Cost of Ownership (TCO)

- The levelized cost of owning a vehicle
- Accounts for all major capital and operational costs incurred over the vehicle's life
- Typically represented in $\frac{\$_{NPV}}{mile}$

TCO will be used to assess the economic viability of H_2 refuse trucks

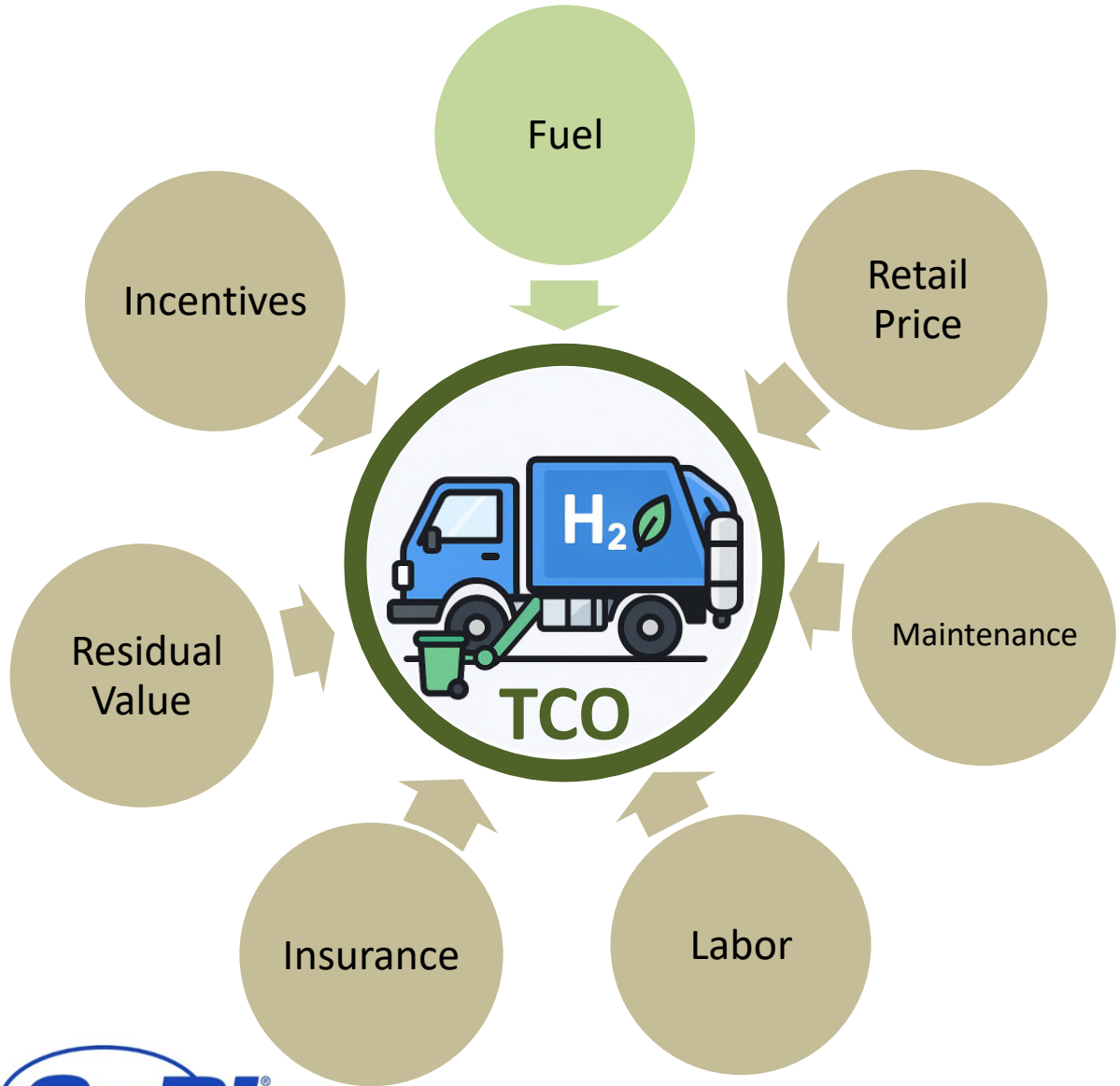


Baseline Truck for Case Study Analysis

- Fuel: Diesel
- Range: 150 miles/trip
- Fuel consumption: 2.5 mpg
- Useful life: 8 years
- Retail price (MSRP): $475,000

TCO of H_2 trucks will be compared to that of a CoSA diesel truck

Fuel Cost



Price:

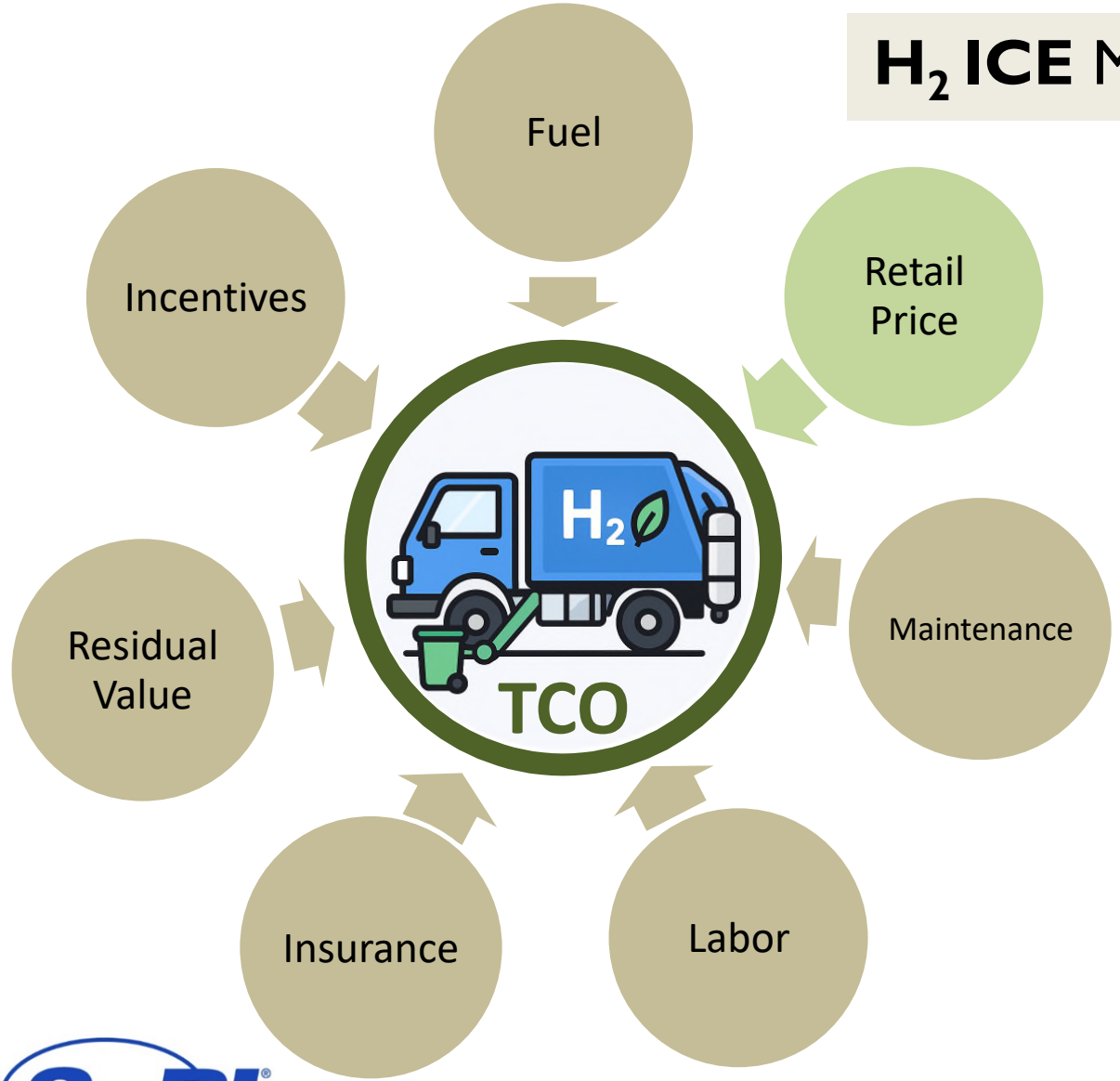
- H_2: 11 $/kg [from H_2 supply model]
- Diesel: 2.70 $/gal [pre-tax, bulk price]

Fuel Quantity:

- H_2 trucks have the same range as baseline (diesel)
- Assumed drive cycle fuel conversion efficiencies:

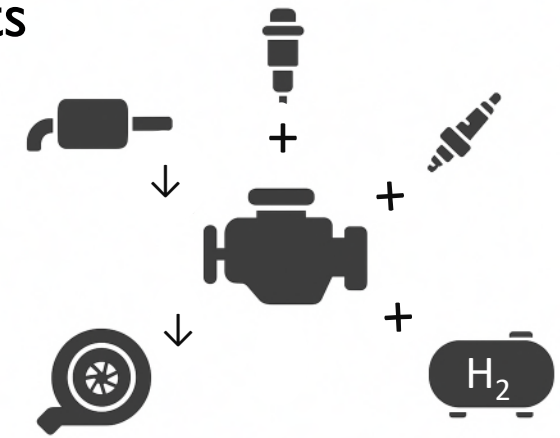
Diesel	H_2 ICE	H_2 FC
35%	33.6% (↓4%)	42% (↑20%)

Retail Price = Manufacturing Cost + Indirect Cost



H_2 ICE MSPR estimated using bottom-up approach

1. Calculated baseline truck manufacturing cost from MSRP (assuming 42% indirect costs)
2. Estimated H_2 ICE truck manufacturing cost by accounting for vehicle systems changes
3. Estimated H_2 ICE truck MSRP by assuming 53% indirect costs



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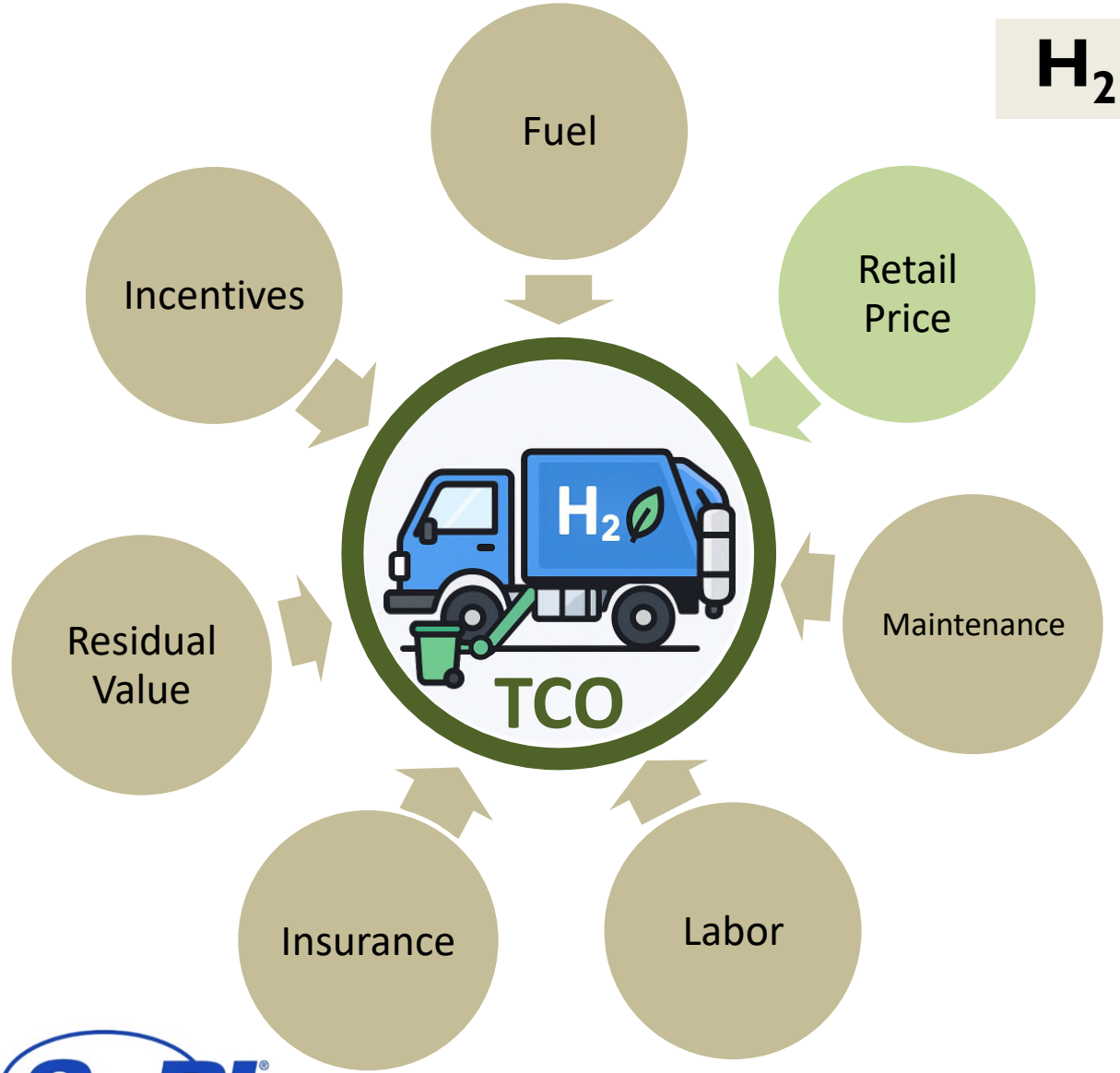
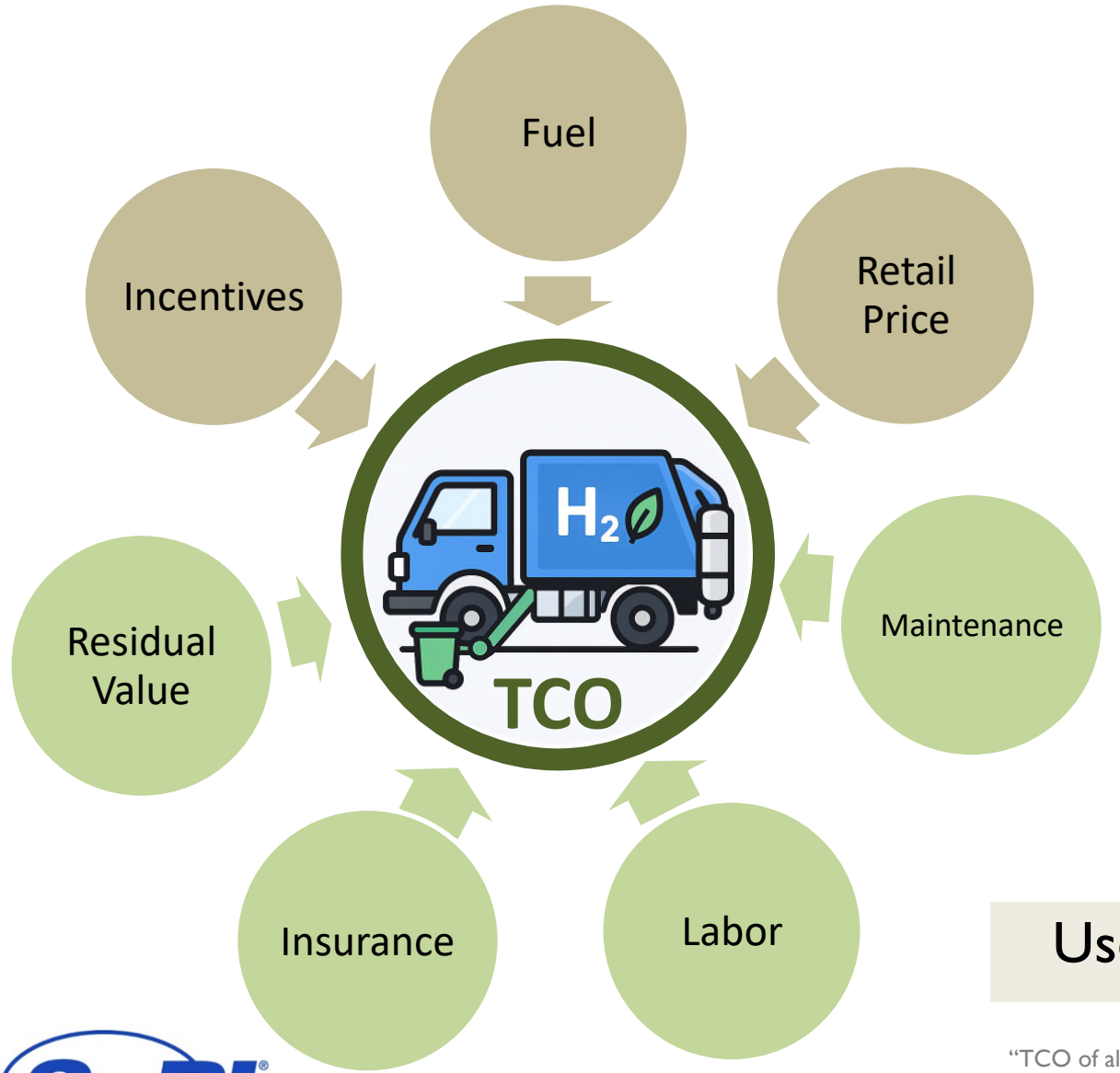


H_2 FC MSPR = 2.5 x Diesel Truck MSRP

- H_2 FC truck MSRP is assumed to be 2.5 times the baseline truck's MSRP
  - based on discussions with stakeholders and literature survey

> A spokesperson for New Way said the difference between manufacturing a hydrogen vs a diesel truck is a few hundred thousand dollars. While a diesel side loader would cost around 300,000, a hydrogen side loader would cost approximately 700,000 and could extend up to a million dollars. The cost for both could also be higher or lower depending on the model, type of truck, and systems installed.

Kaur, S. (2024, September 13). *North America's first hydrogen-powered garbage truck debuts in Redwood Shores: Cleaner, but costly*. Mountain View Voice.



Maintenance Cost

- $475,000 over lifetime

Labor Cost

- 32 $/hr, 10 hrs/day, 1 person/vehicle

Insurance Cost

- [3% of Vehicle Price] + [$0.065∗Miles/Year]*

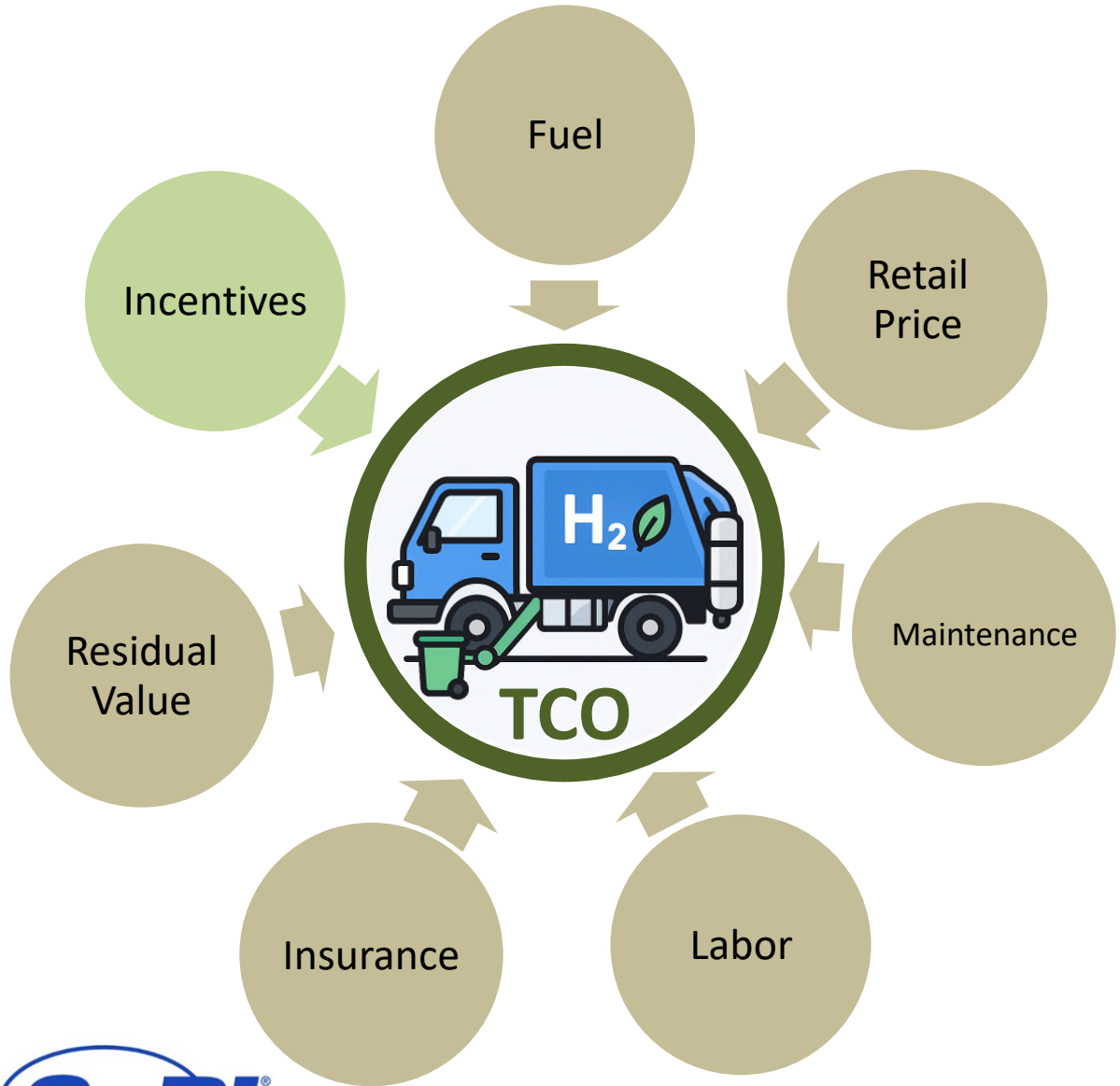
Residual Value

- 5% of retail price at end-of-life (year 8)

Used same assumptions for H_2 FC and H_2 ICE

"TCO of alternative powertrain technologies for Class 8 long-haul trucks in the United States." *ICCT* (2023).

Incentives



- IRA's "Clean Commercial Vehicle Credits" [Discontinued] — Nominal Incentive Scenario
  - Up to **40,000 $/truck** for FC trucks
  - H_2 ICE trucks not eligible

North Central Texas Council of Governments

- North Texas Zero Emissions Vehicles Project [$60 million] — High Incentive Scenario
  - H_2 FC Class 6 and 7 trucks
  - **Lower of $600,000 or 70% of MSRP** / truck
  - Call launch in Fall 2025

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

- Texas Hydrogen Infrastructure, Vehicle, & Equipment (THIVE) [$16 million]
  - H_2 FC / ICE trucks with 25% lower NO_x
  - Up to **100%** of incremental cost
  - Projected Opening: January 2026

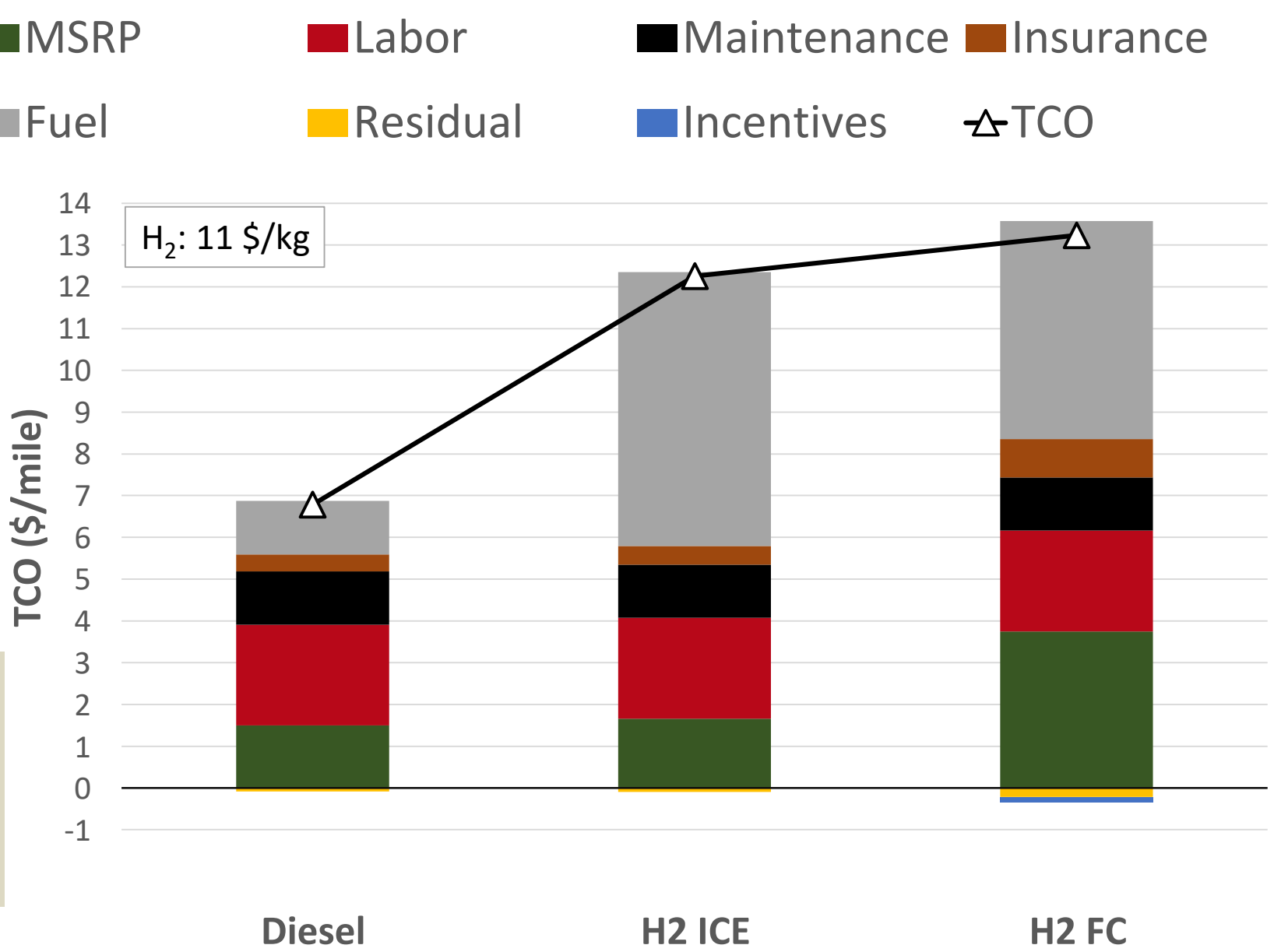
City of San Antonio Refuse Truck TCO Case Study Results

Important Assumptions

- H_2 price: 11 $/kg
- H_2 FC incentive: 40,000 $/truck
- H_2 ICE incentive: 0 $/truck

TCO Results

- MSRP, labor and fuel costs are the largest costs
- Fuel cost is the largest cost for the H_2 trucks



TCO Comparison

H_2 ICE: 1.81X baseline truck

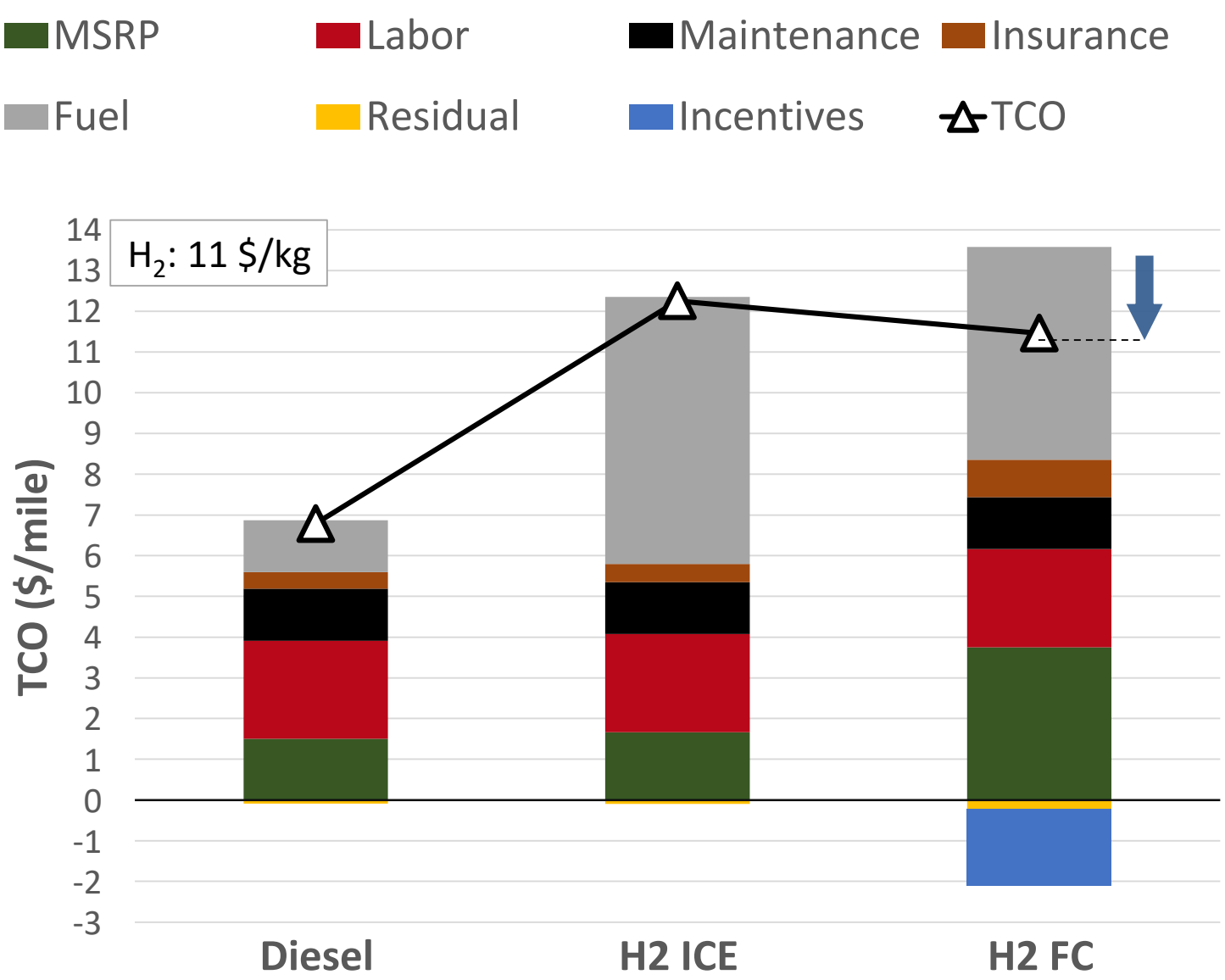
H_2 FC : 1.95X baseline truck

"High" Incentive Scenario

Incentive Scenario : **Nominal** **High**

	H_2 ICE 0 $/truck	H_2 FC 40 k$/truck	H_2 FC 600 k$/truck
TCO	1.81X	1.95X	1.69X (7%↓)
TCO (Non-Fuel)	1.04X	1.46X	1.13X (10%↑)

TCO results relative to diesel truck

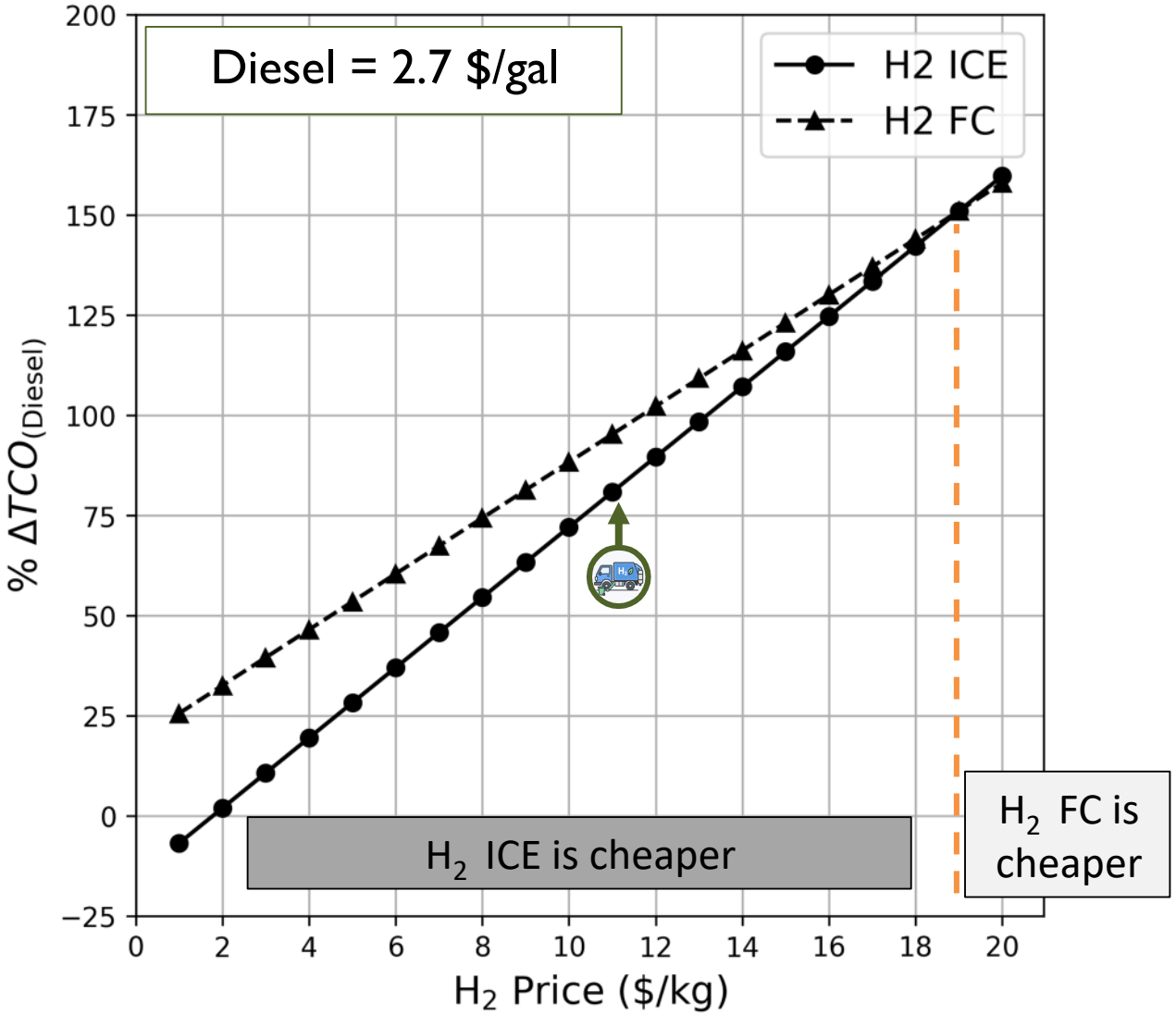


H_2 Price Sensitivity

$$\Delta TCO_{(Diesel)} = \frac{TCO_{H_2\ Truck} - TCO_{Diesel}}{TCO_{Diesel}}$$

When to Use H_2 ICE and H_2 FC?

- H_2 ICE has lower TCO below 19 $/kg_{H2}$ because of its lower retail price
- Above this, H_2 FC has lower TCO because of its higher efficiency



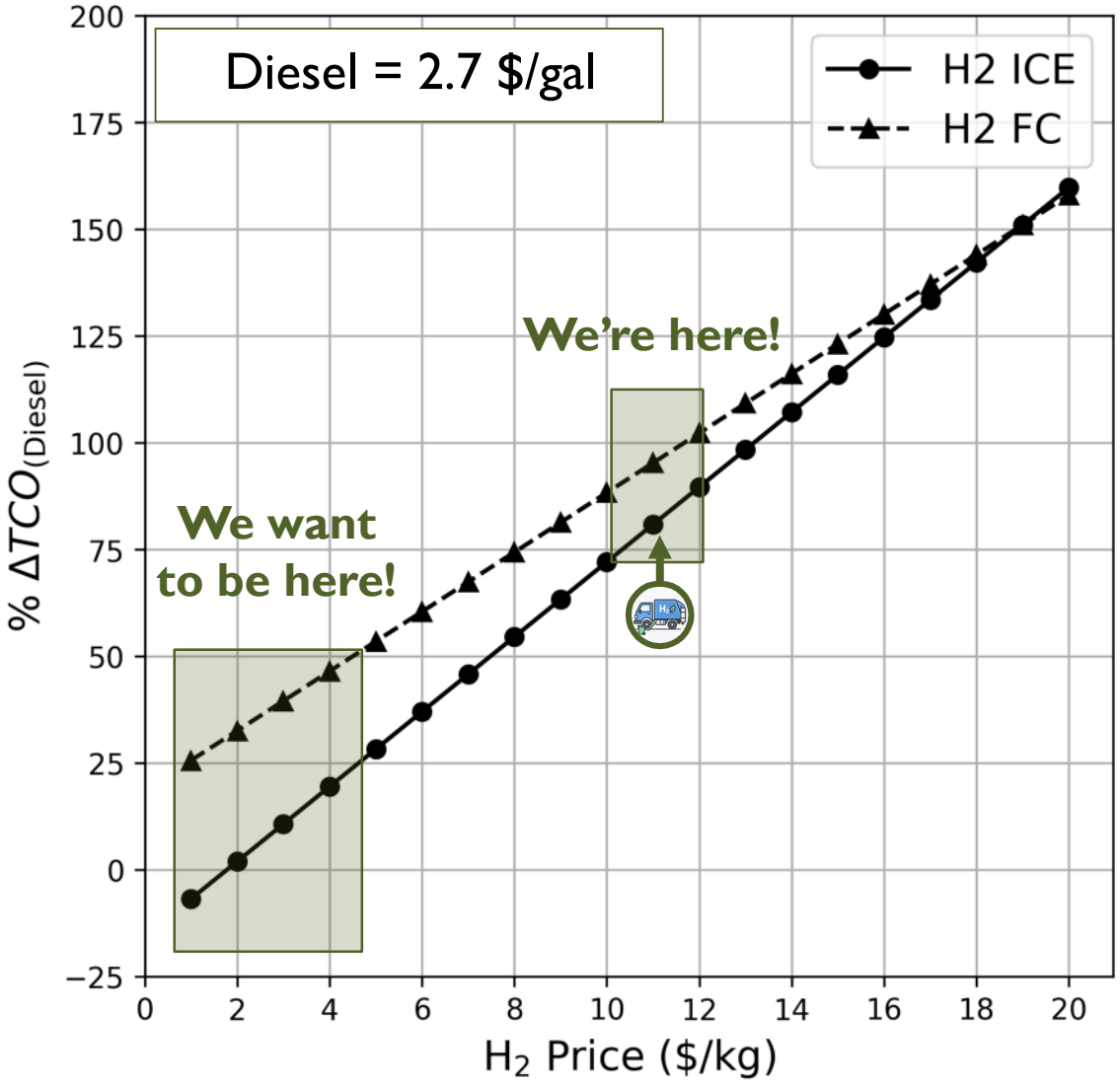
TCO Takeaways

- At H_2 supply price of 11 \$/kg, H_2 refuse truck TCO is roughly twice that of a diesel truck

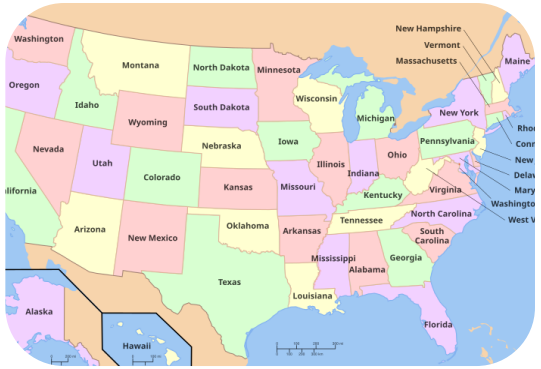
1 H_2 truck costs as much as 2 diesel trucks

- However, if H_2 is sourced at **lower costs**, H_2 trucks can become economically viable,
  - H_2 ICE trucks have lower TCO than H_2 FC because of lower vehicle costs

- **Substantial government incentives** will be needed to make H_2 trucks economically viable



TCO Model Conclusions



TCO costs are region specific and depend on many factors

H_2 Costs depend drastically on scale.

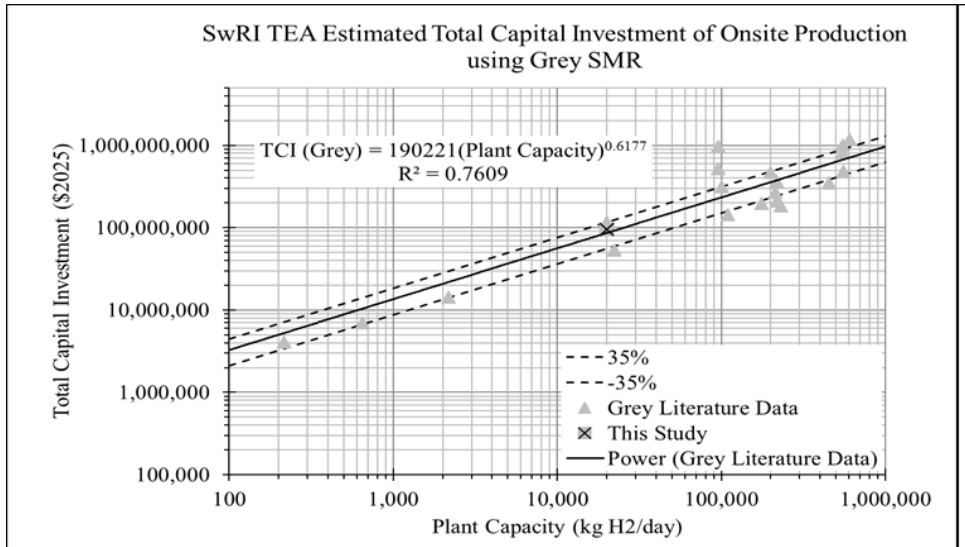
Distribution methods heavily affect H_2 cost

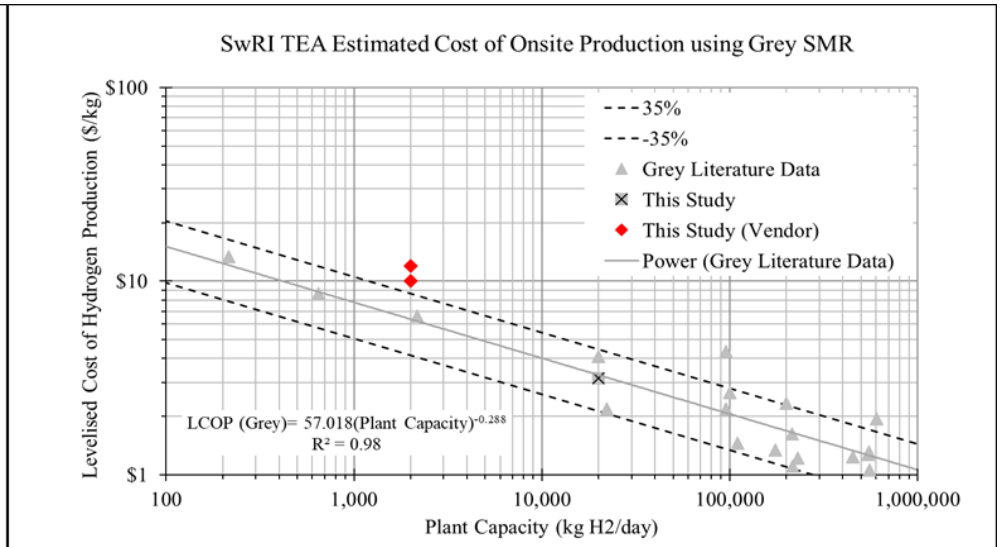
H_2ICE vs. FCEV choice depends strongly on cost of H_2

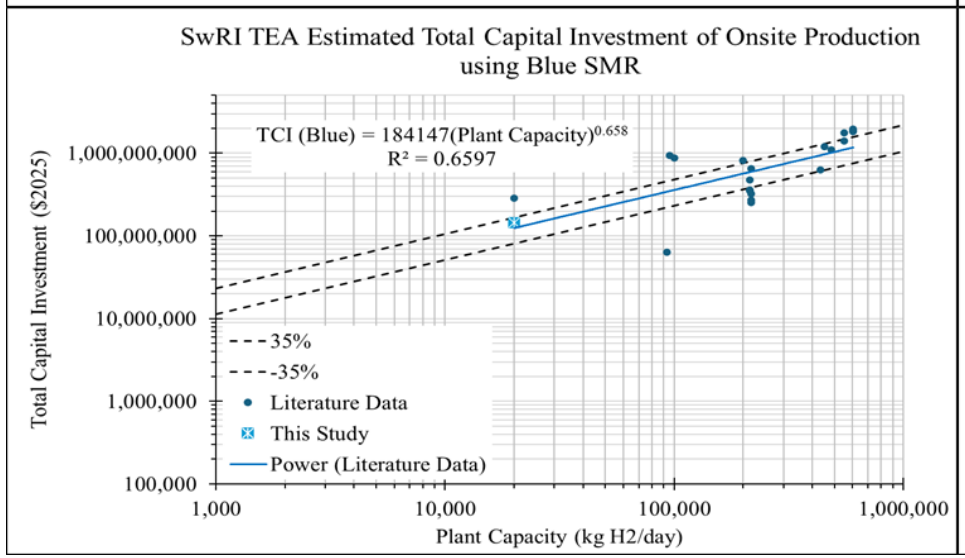
Each region could follow the HUB model:
It just needs to be designed.

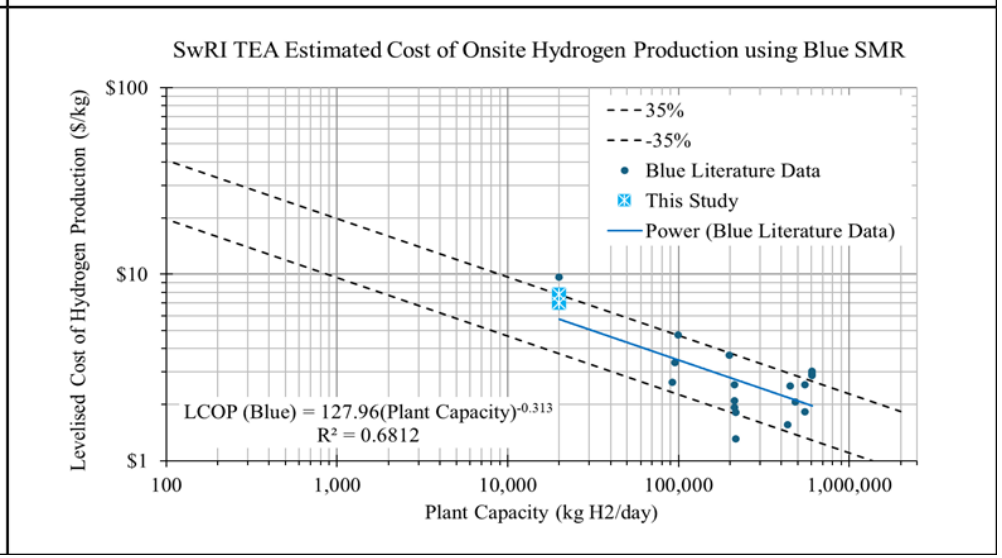
Appendix

Steam Methane Reforming (SMR)

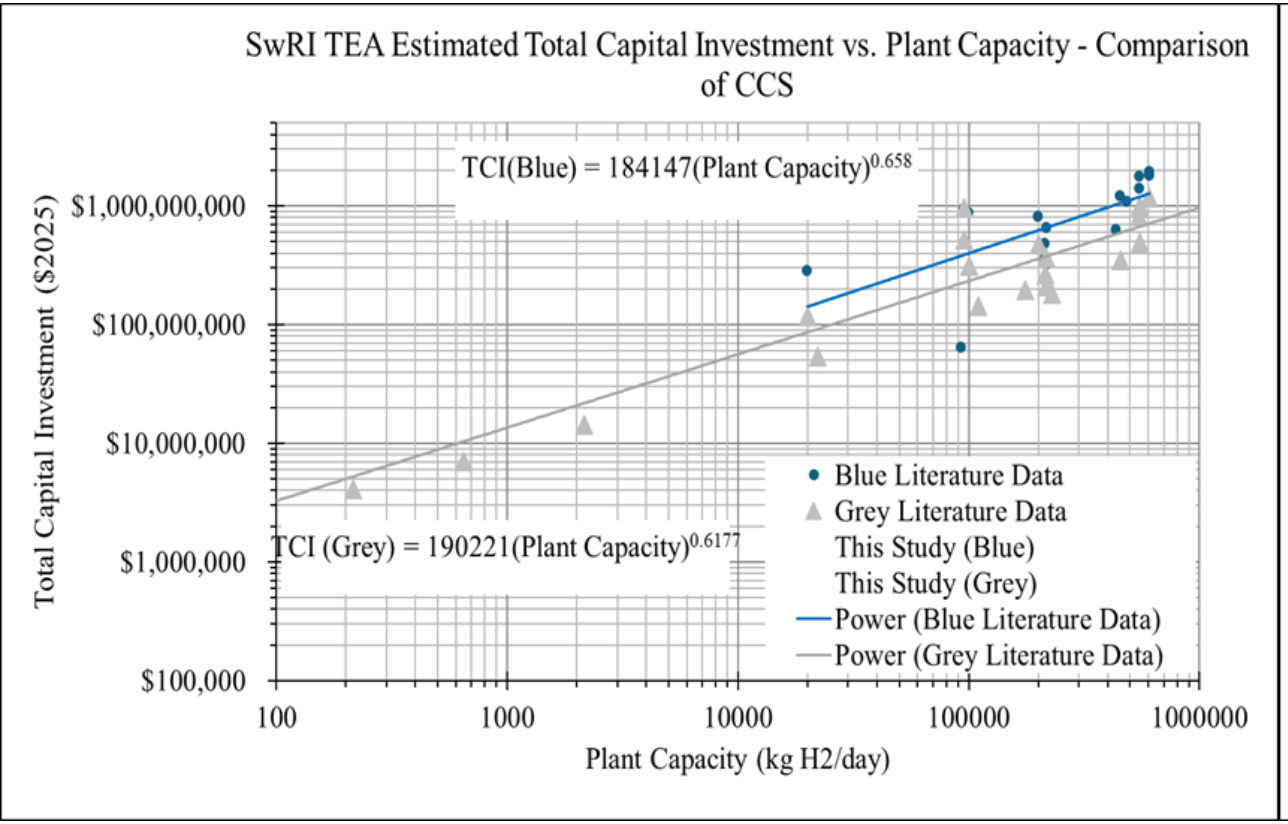


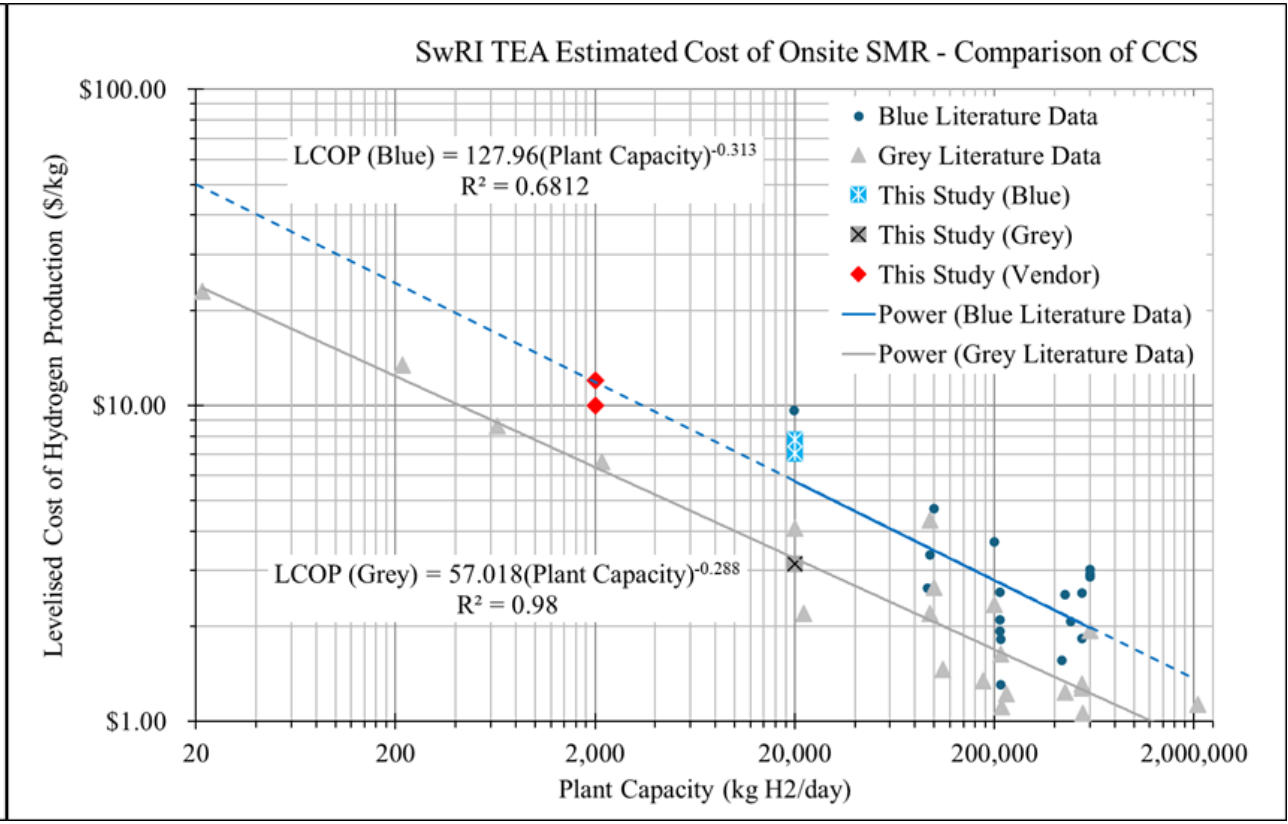




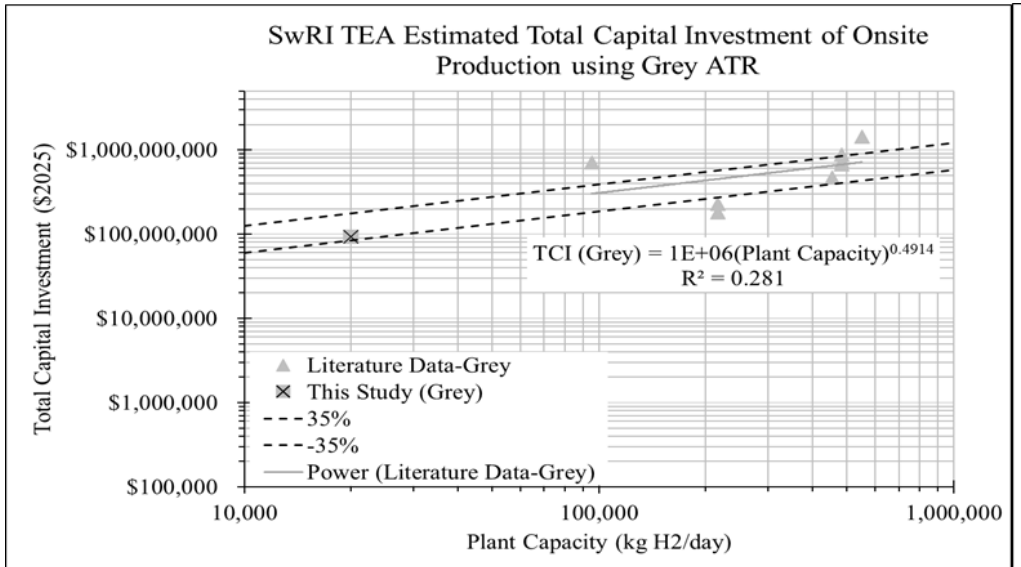


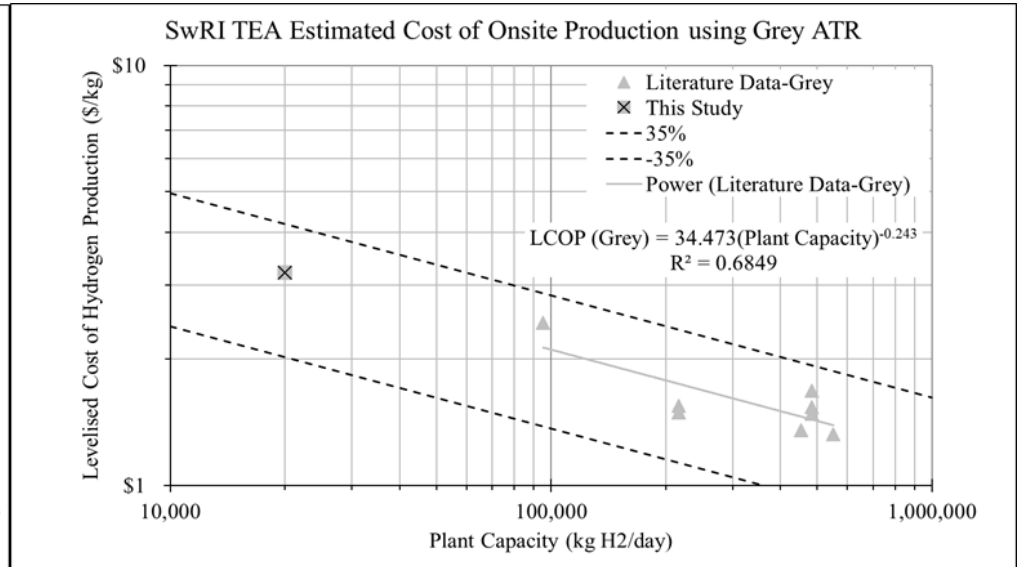
Steam Methane Reforming (SMR), cont.

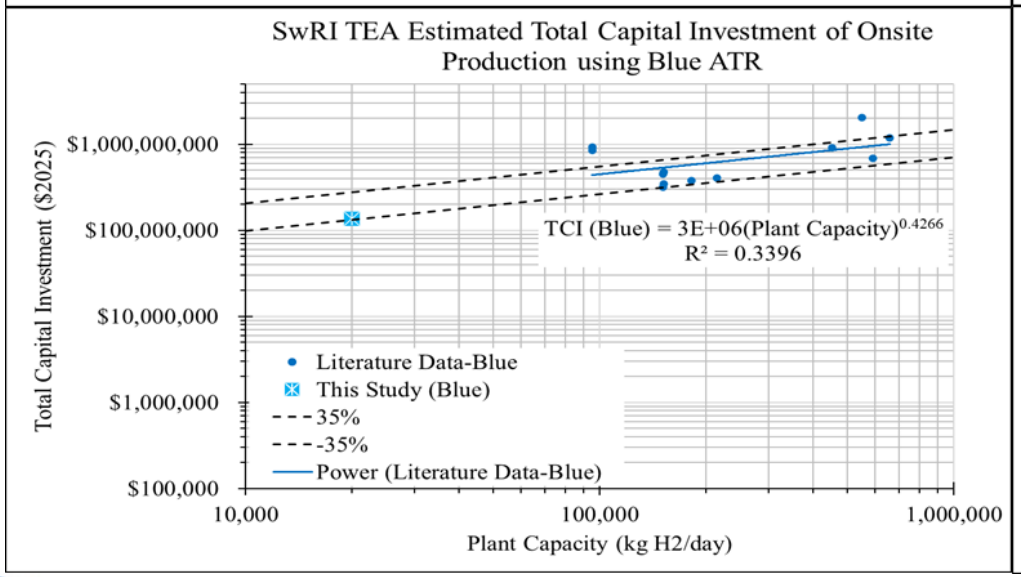


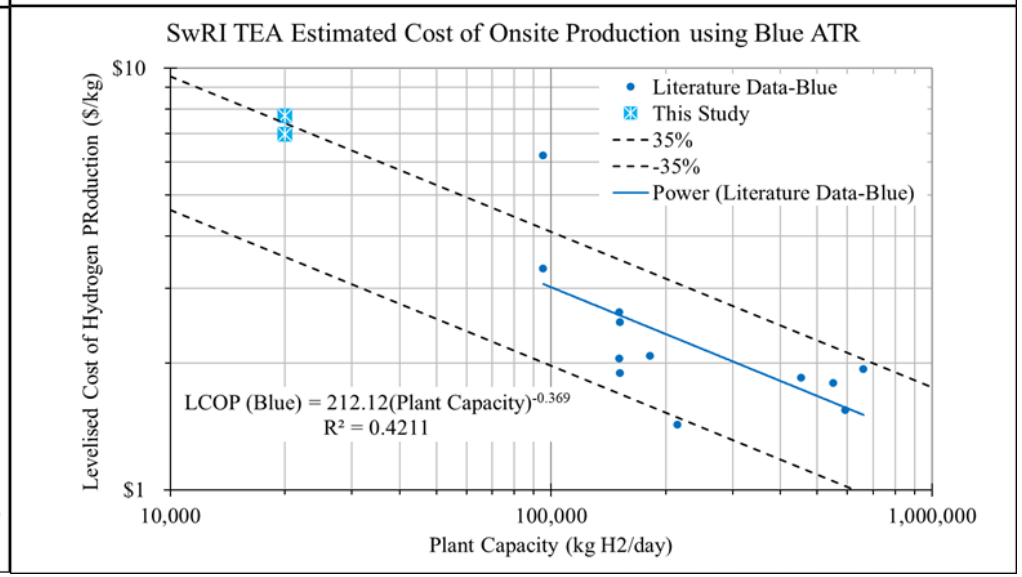


Autothermal Reforming (ATR)

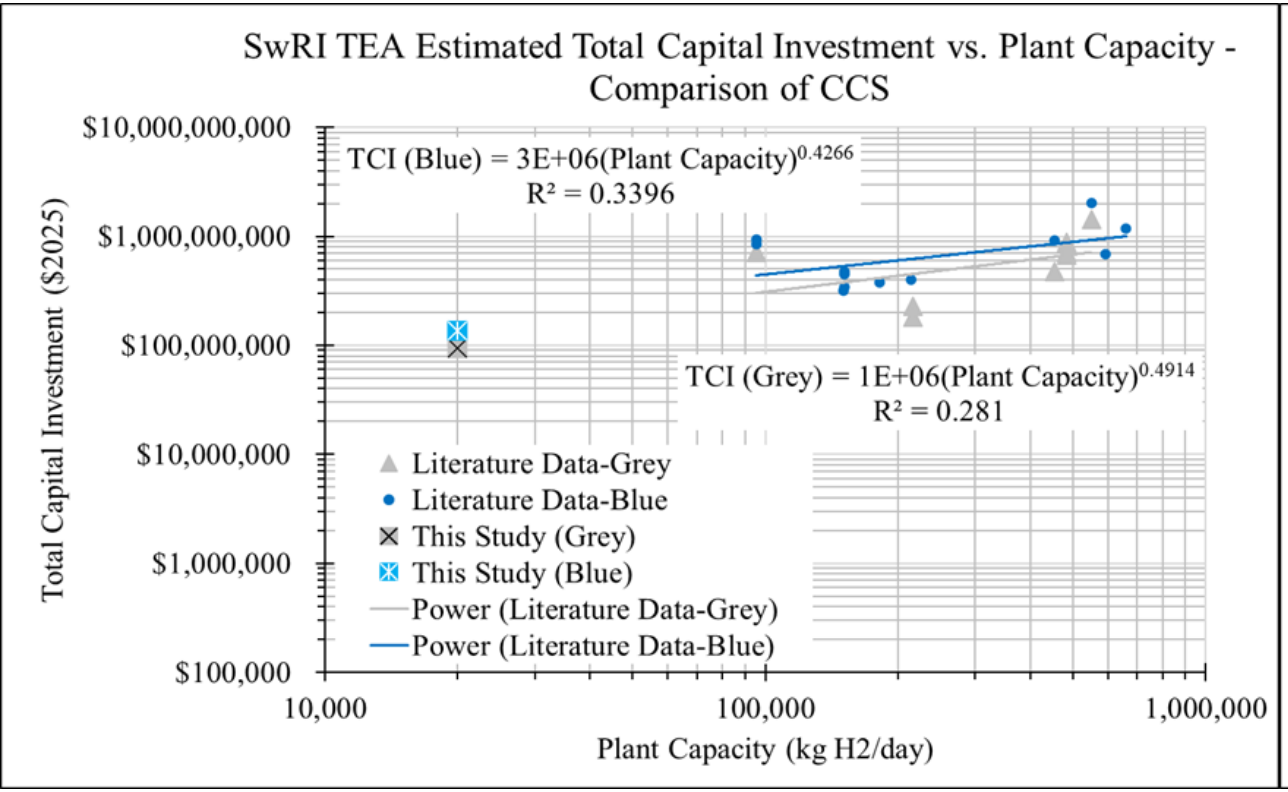


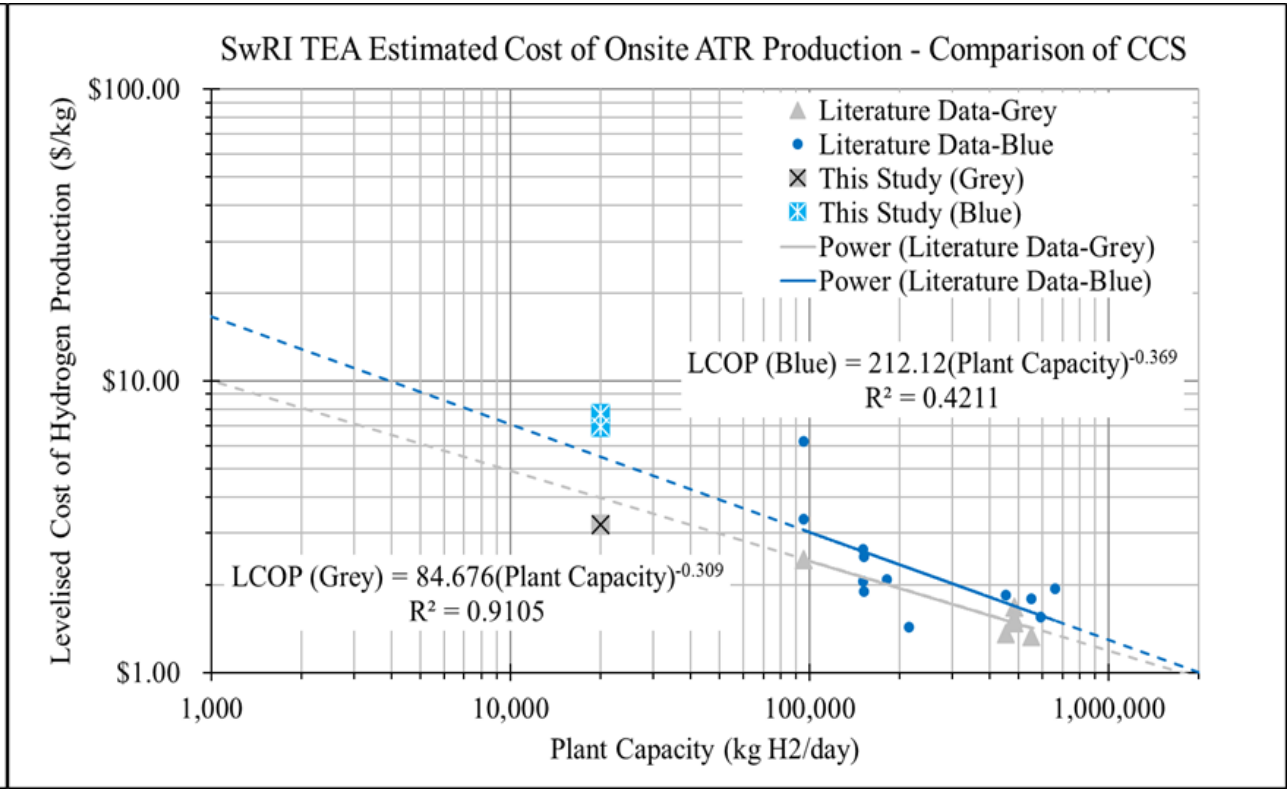




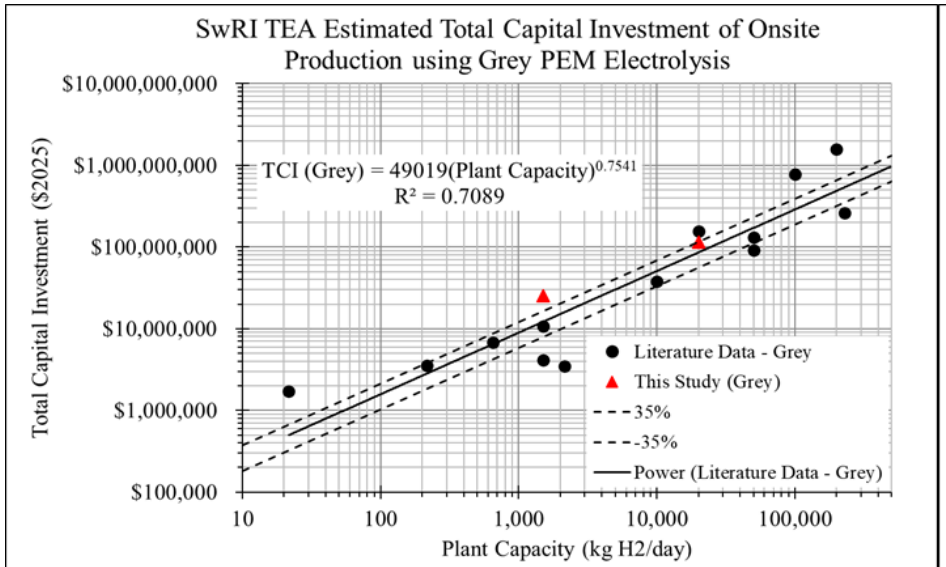


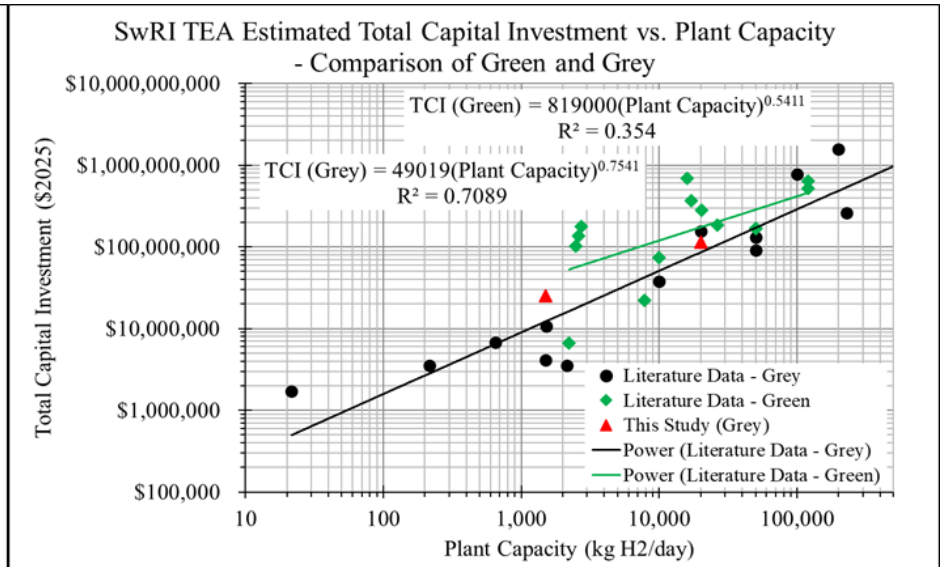
Autothermal Reforming (ATR), cont.

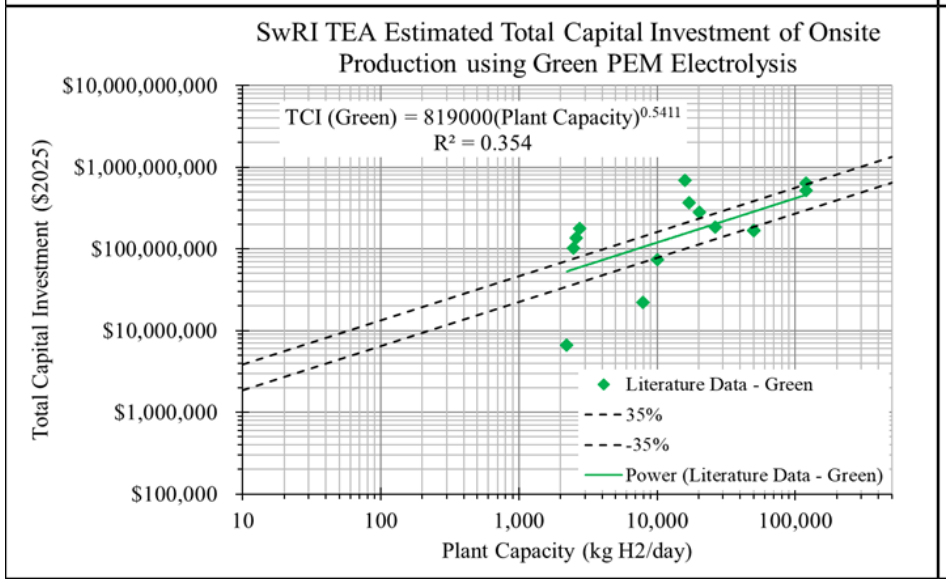


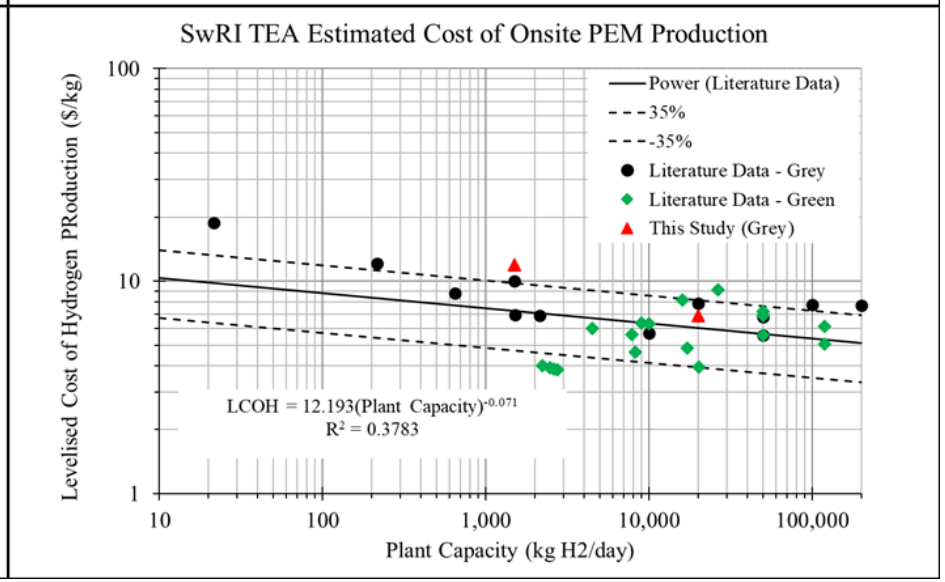


PEM Electrolysis

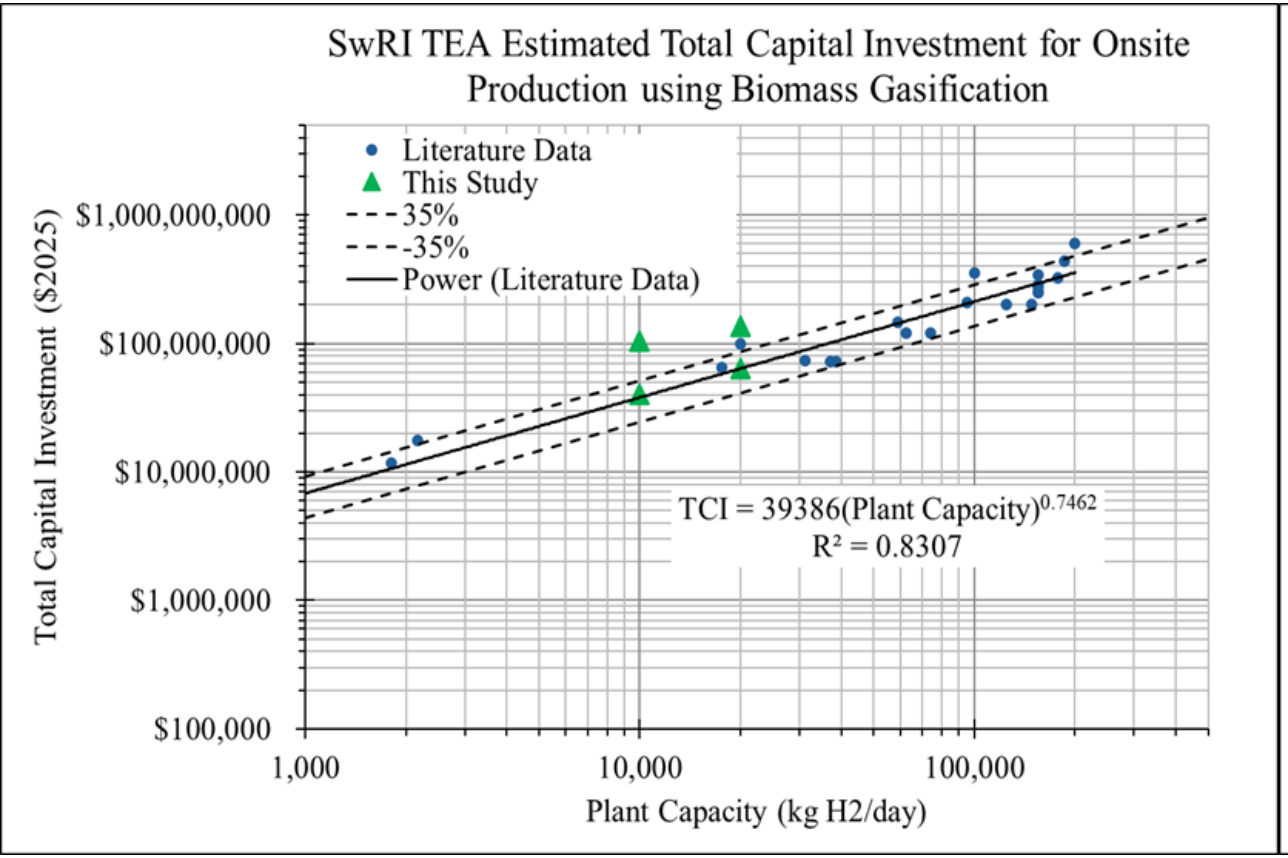


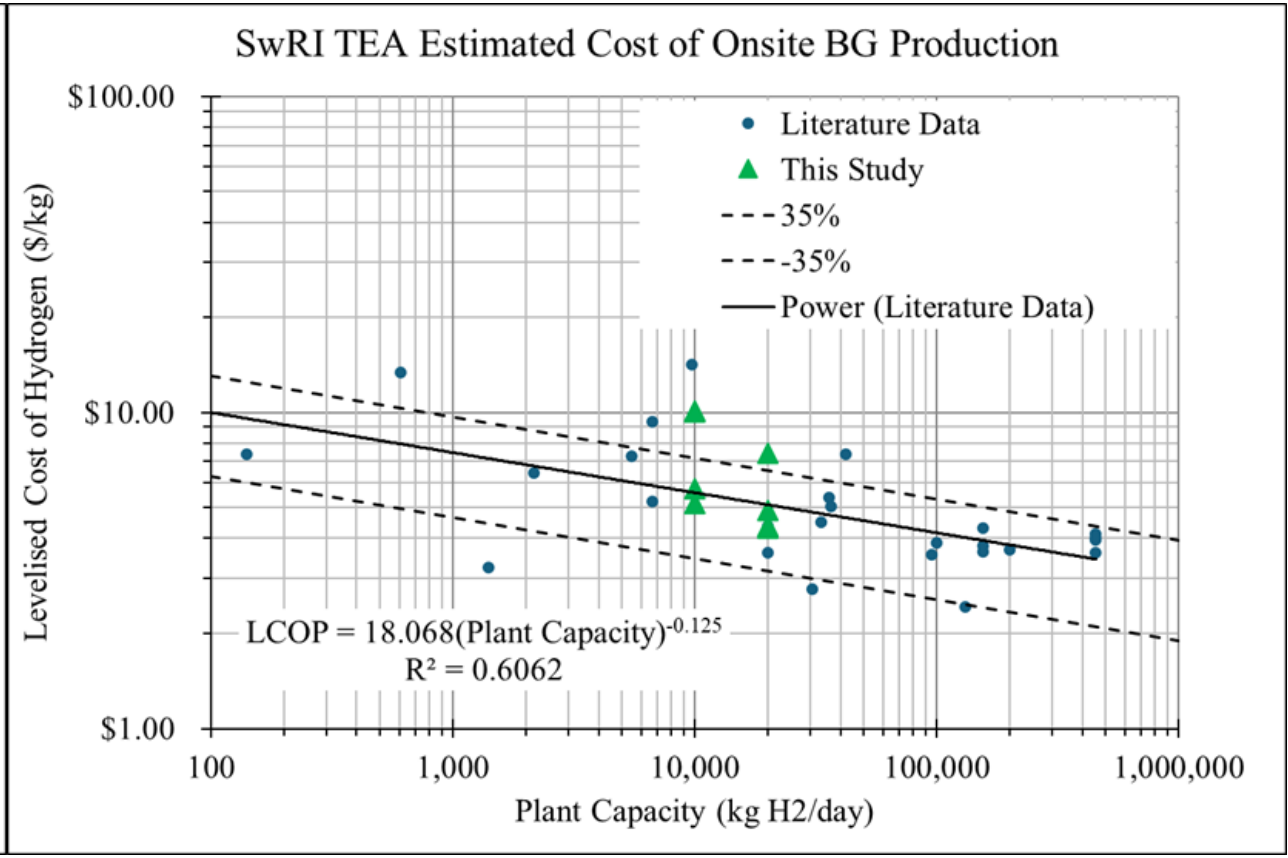




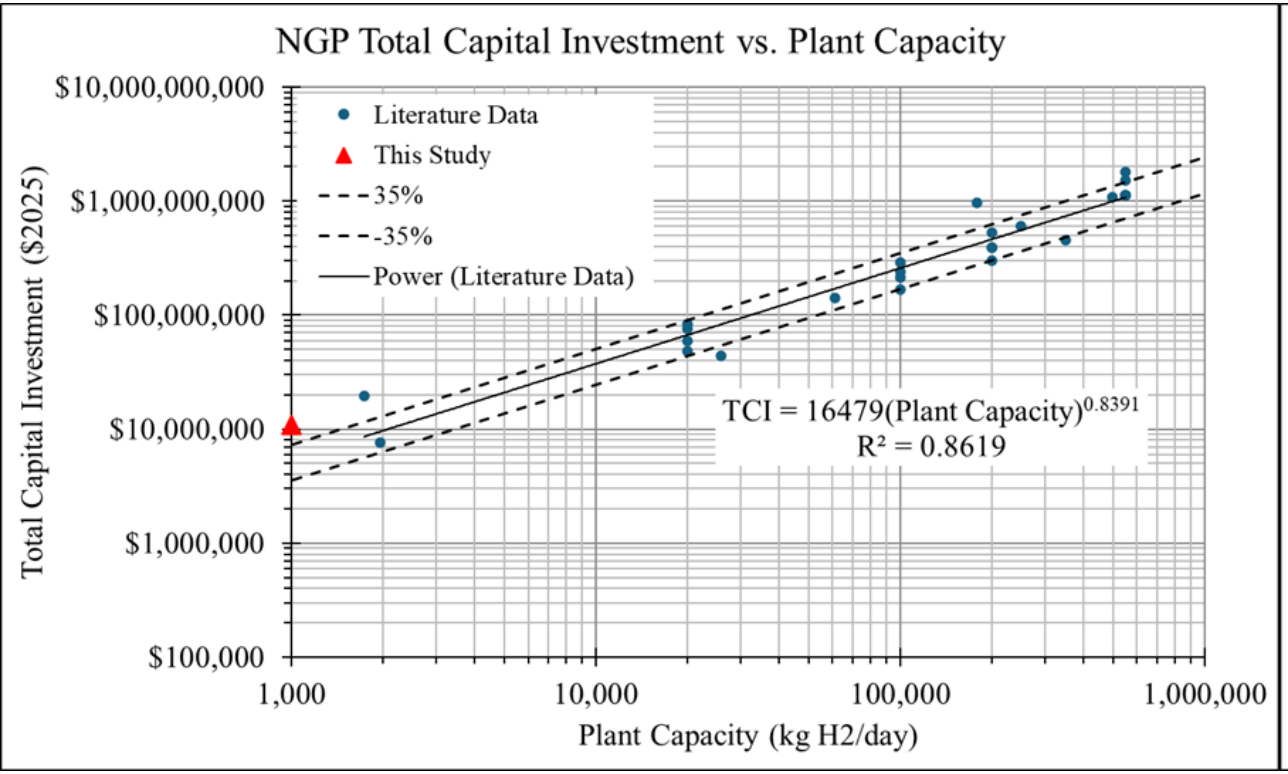


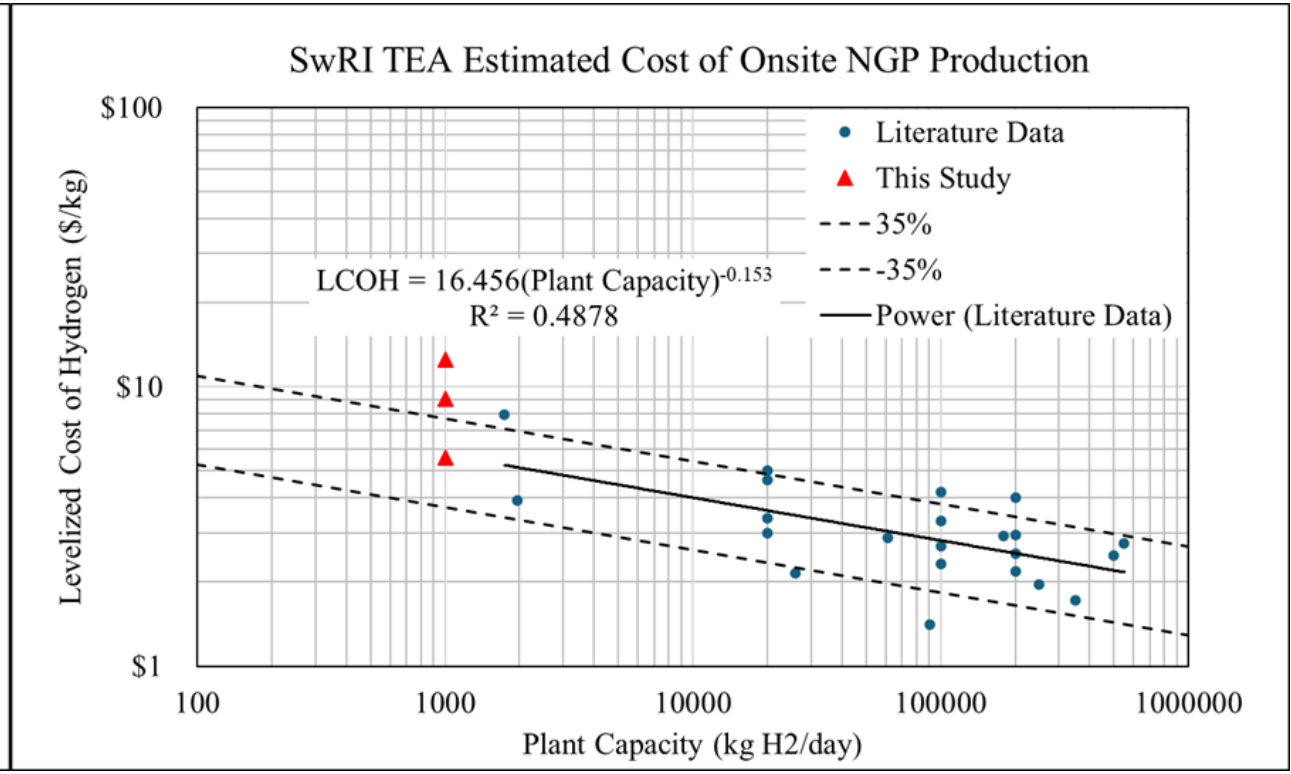
Biomass Gasification (BG)



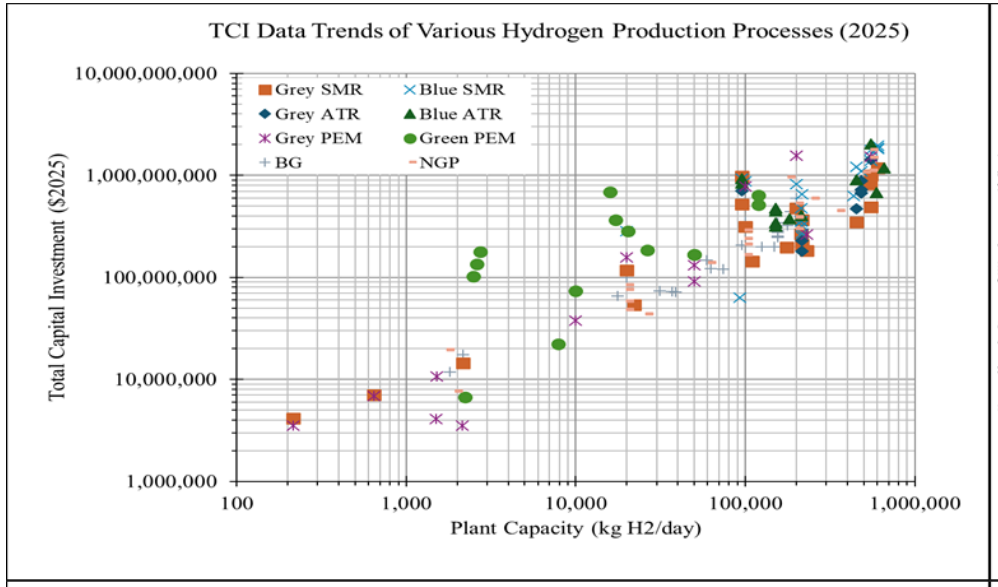


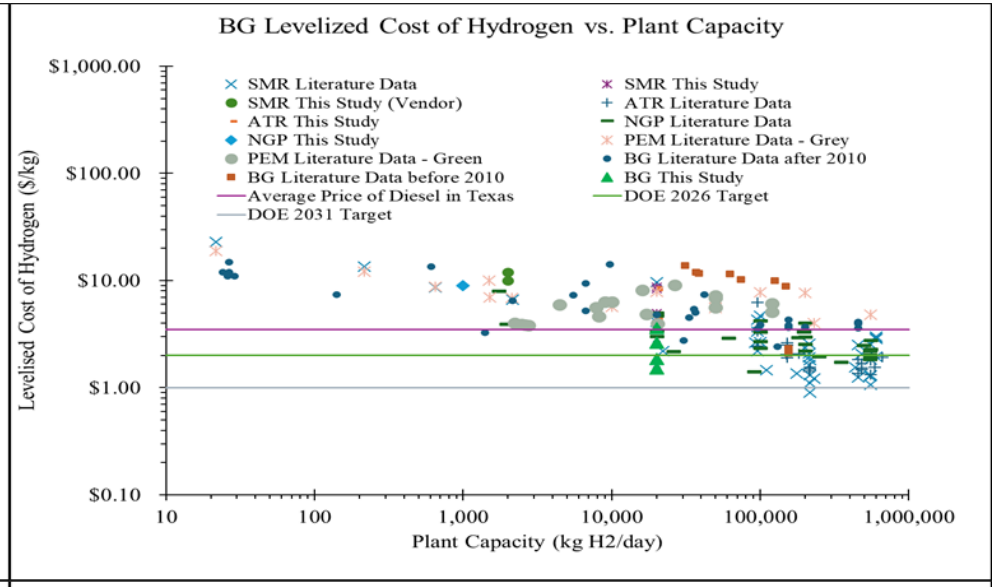
Natural Gas Pyrolysis (NGP)

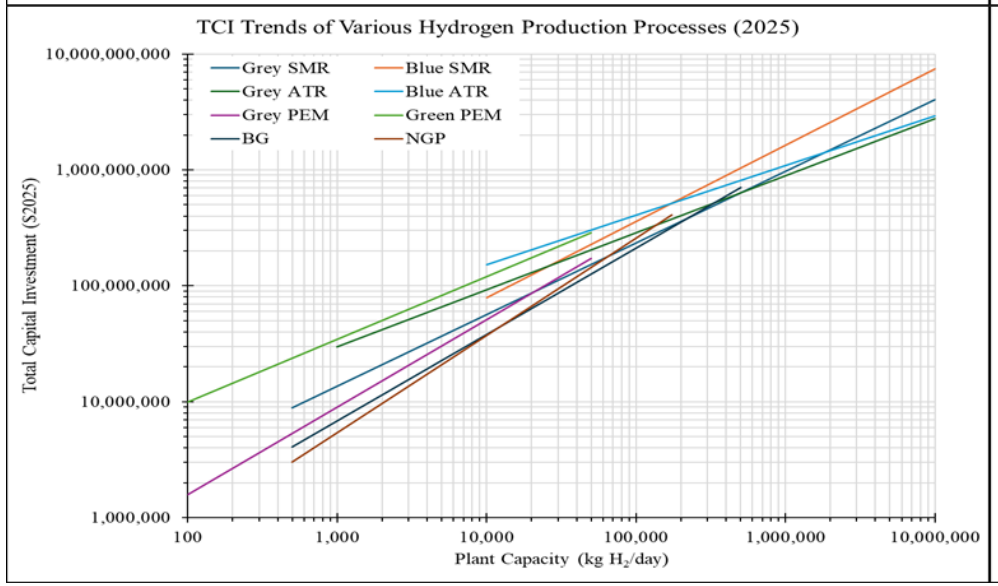


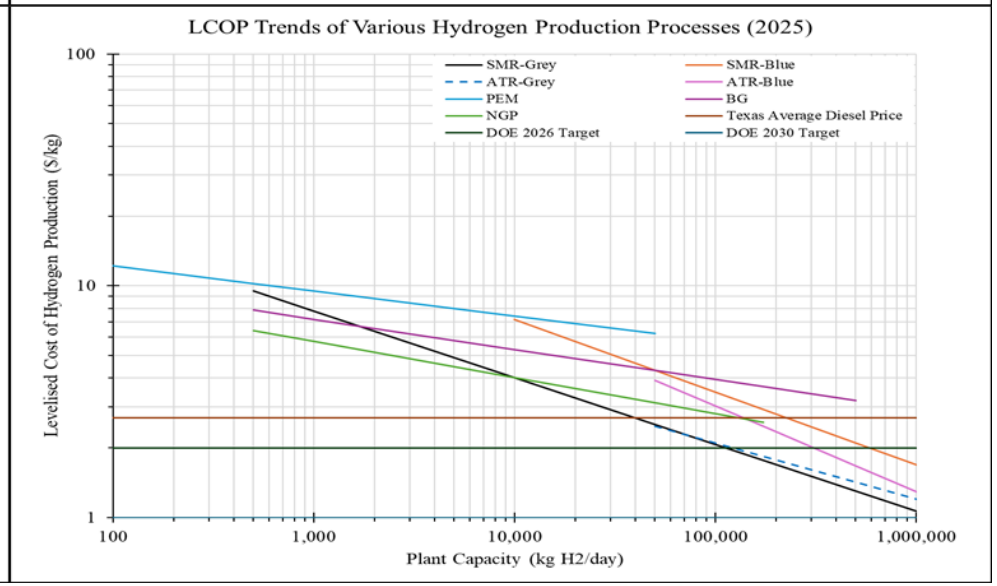


General Process Trends



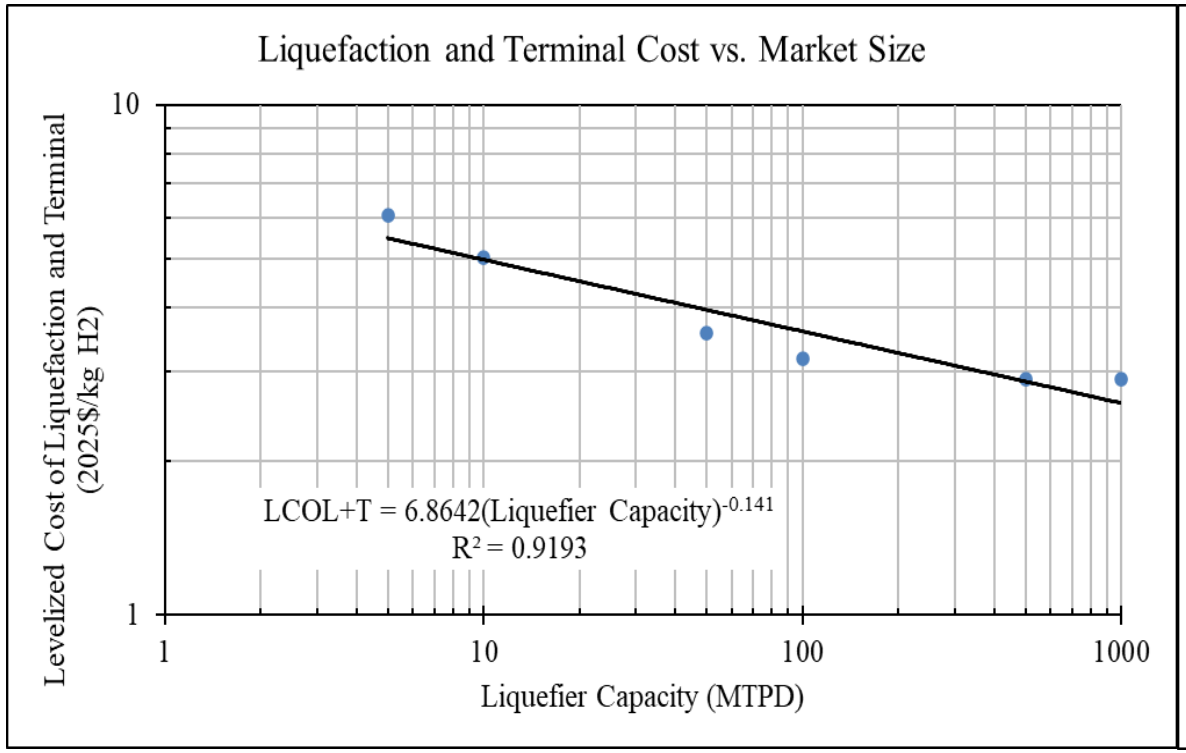


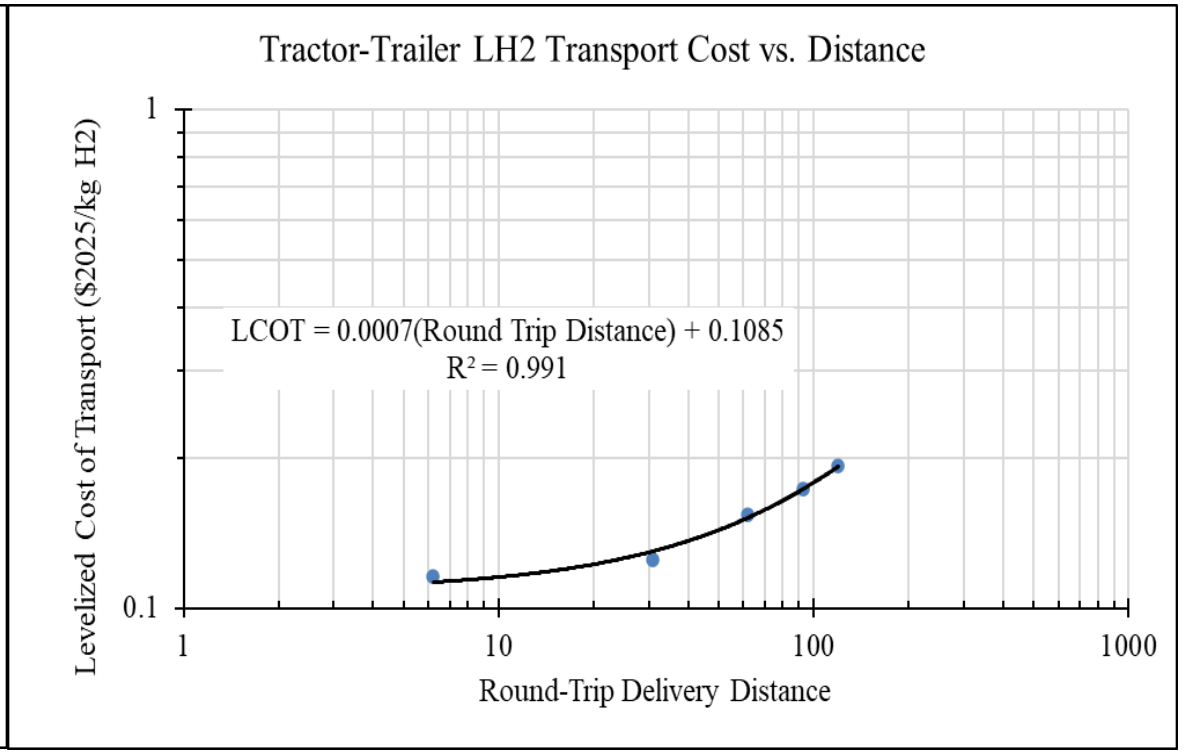




Levelized Cost of Liquefaction, Terminal, and Delivery

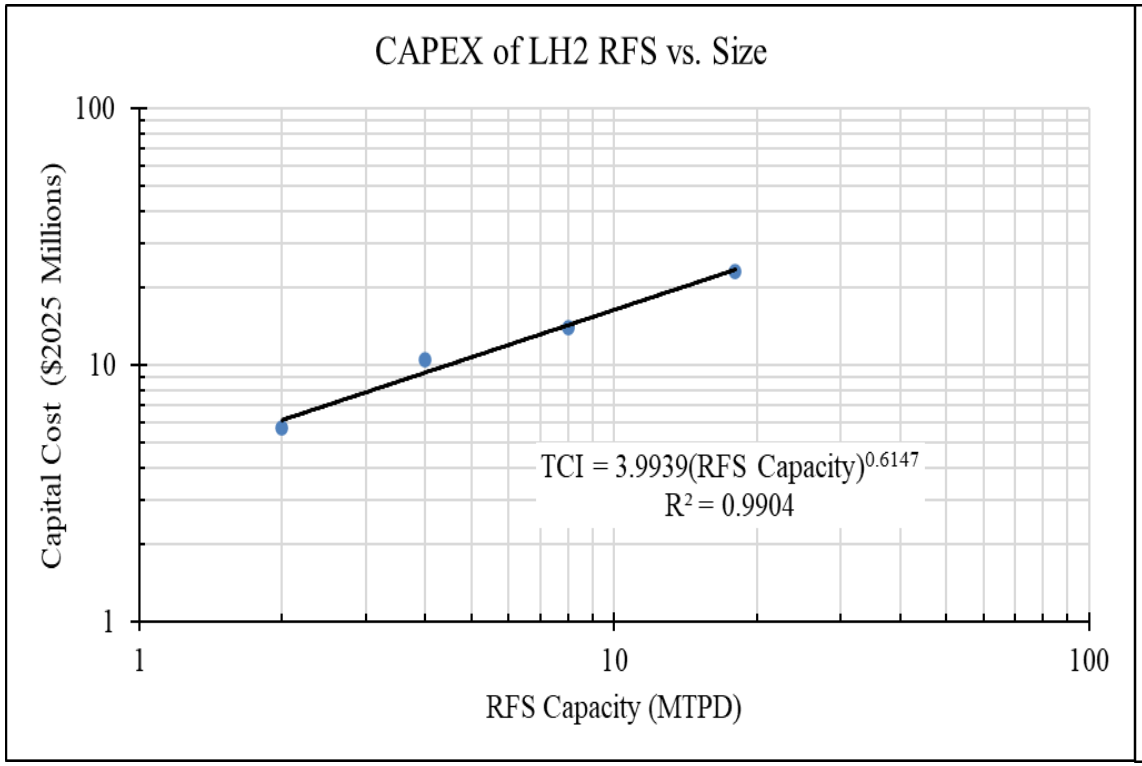
- Data from Bracci et al., *Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles*. NREL Technical Report TP-5400-88818. March 2024.

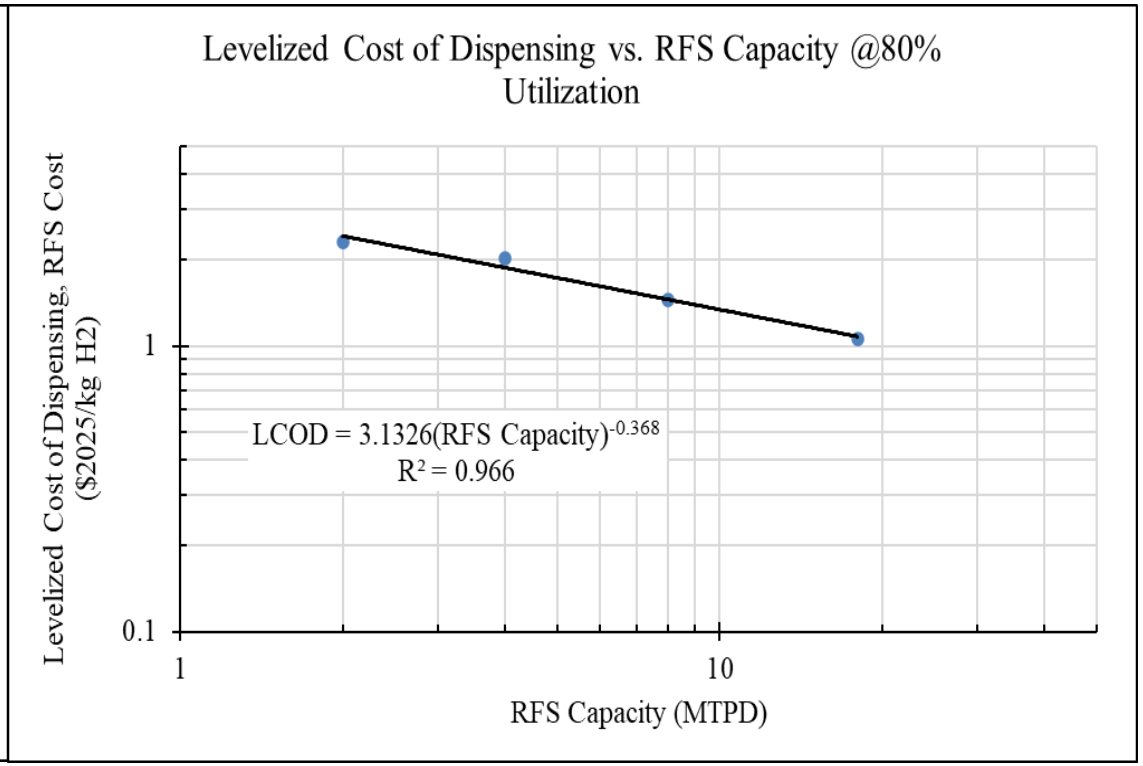




Levelized Cost of Dispensing

- Data from Bracci et al., *Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles*. NREL Technical Report TP-5400-88818. March 2024.





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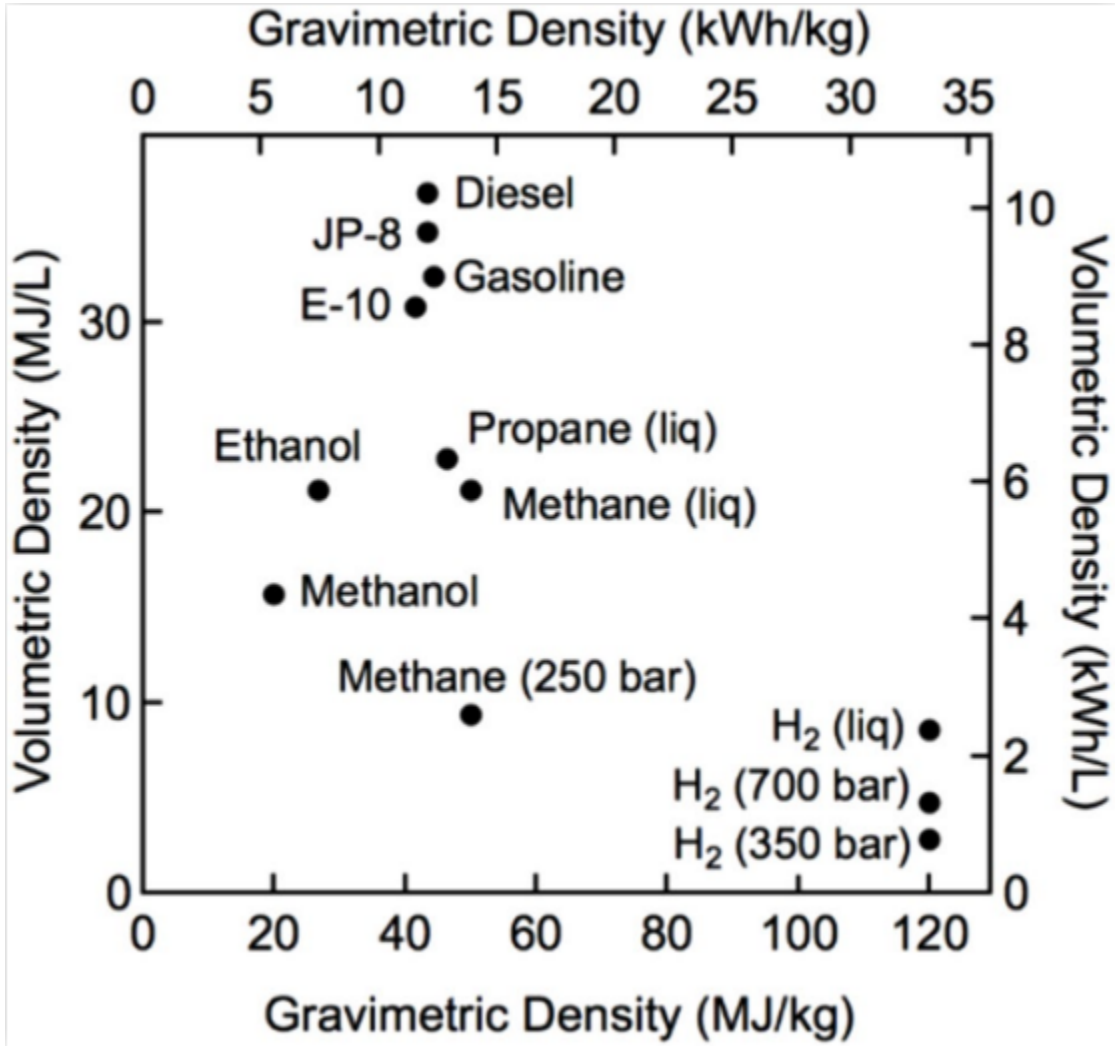
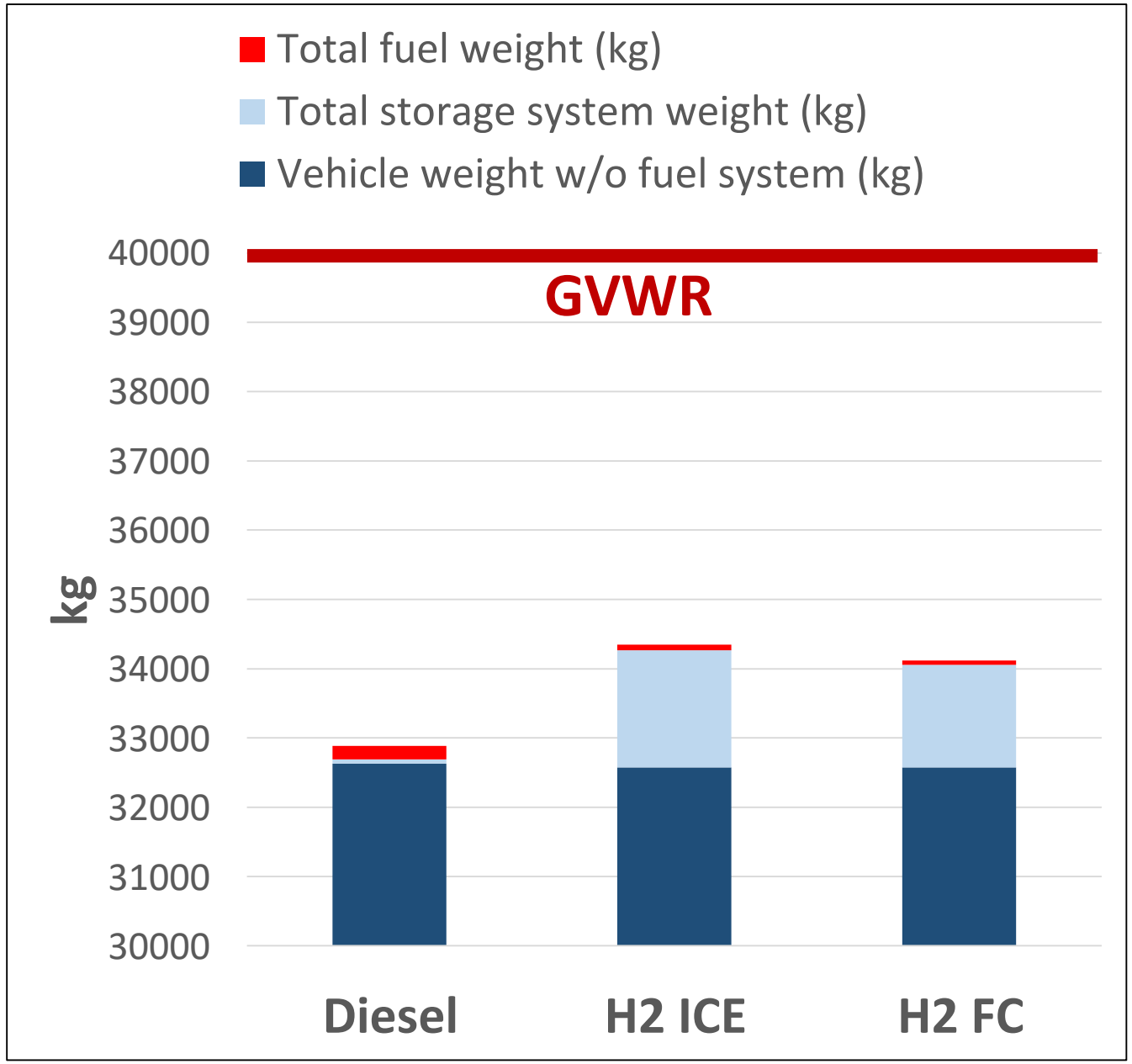
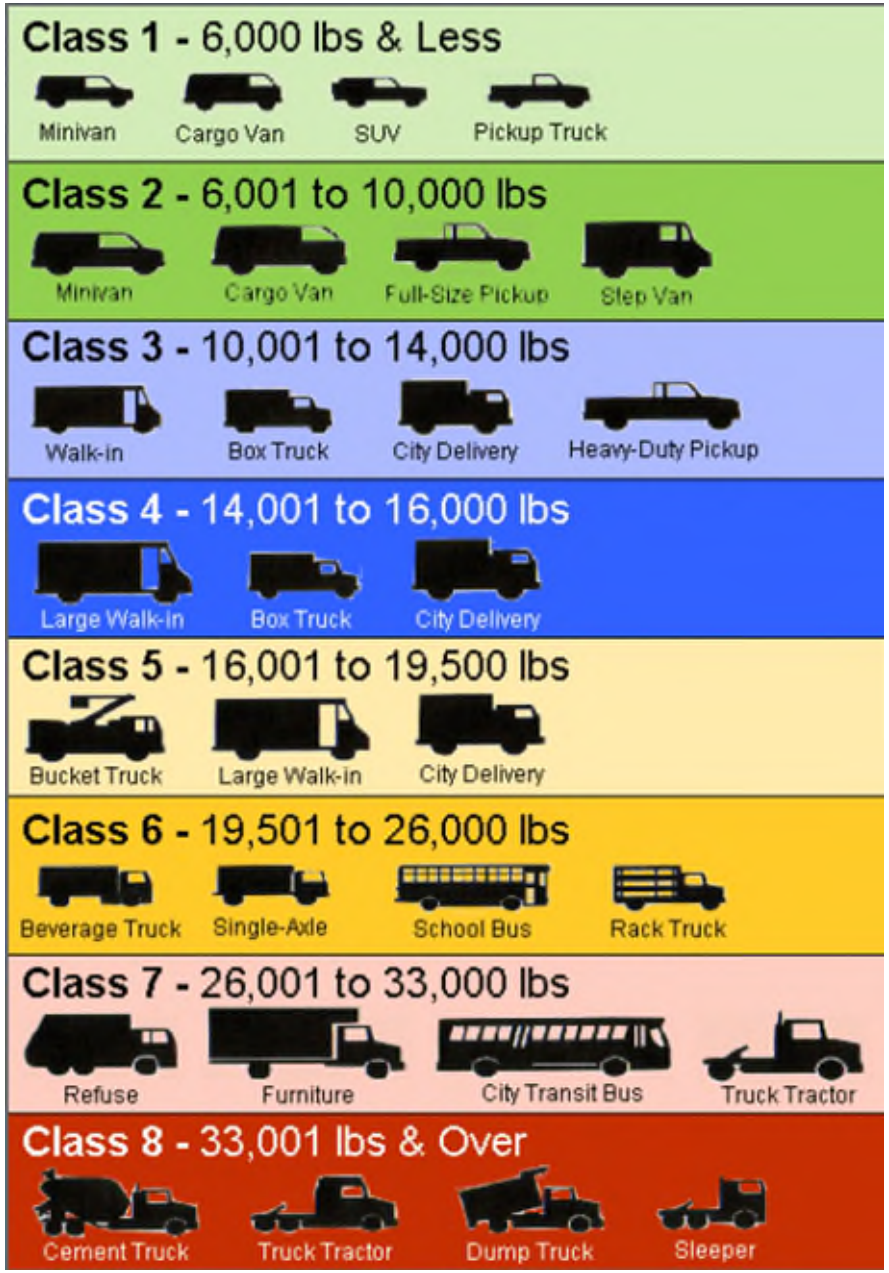


Vehicle Weight Results

- Around 1500 kg increase in weight because of H2 cylinders
  - 8 for H2 ICE
  - 7 for H2 FC

- Assuming half-loaded truck as (GVWR + Curb Weight)/2, the final weight is less than the GVWR, which is 40,000 kg but for full loading applications, there will be around a 2000 kg payload penalty





Insurance Cost

- $Annual\ Insurance\ Cost = [Comprehensive\ \ Collision] + [\text{Liability}]$
- $Annual\ Insurance\ Cost = [3\%\ of\ MSRP] + [0.065 * \frac{VMT}{Year}]$
- Assumed same for all powertrains

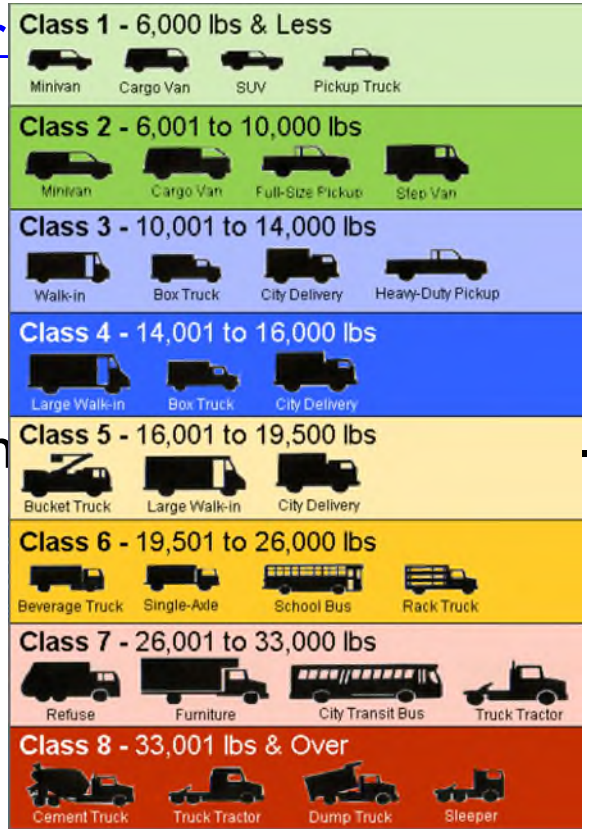
Insurance

Insurance costs for tractor-trailers can be a significant TCO component. This study considers comprehensive and collision insurance in addition to liability insurance. The former is an annual cost estimated to be around 3% of the truck purchase price, and

the latter is calculated as a fixed per-mile cost at $0.065/mi, similar to Burnham et al. (2021). This approach distinguishes between different powertrain technologies with different retail prices, and also distinguishes between different truck annual VMT.

Prep Notes AB

- FC background / powertrain: energy conversions, PEM design
- H2 FC case studies
  - https://www.mv-voice.com/environment/2024/09/13/north-amer powered-garbage-truck-debuts-in-redwood-shores-cleaner-but-costly/?utm_source=chatgpt.com
- North Central Texas Council of Governments program
- CoSA notes and data
- https://www.epa.gov/system/files/documents/2024-06/chdv-gran webinar-2024-06-17.pdf



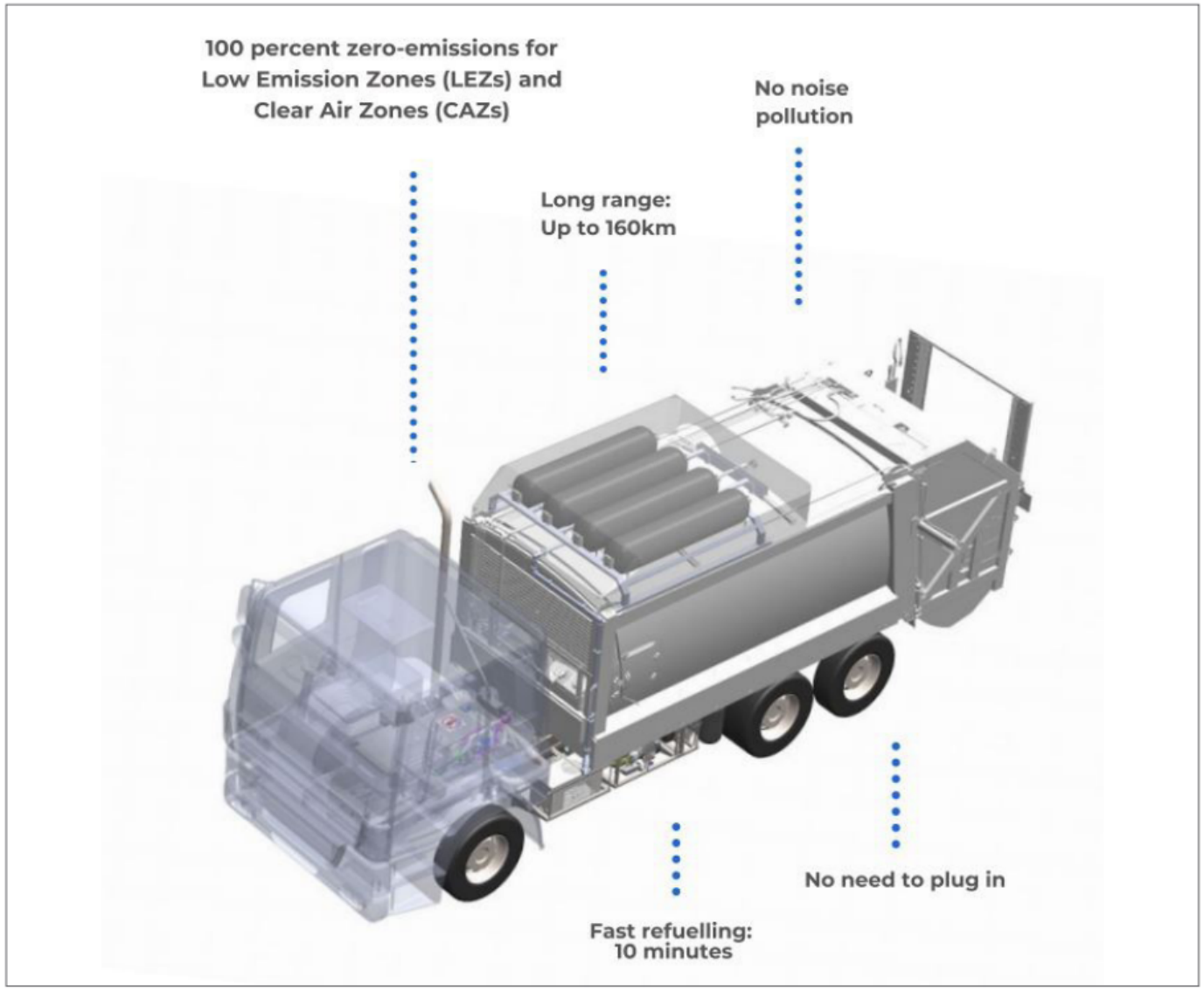
BALLARD

arcola energy

Zero Emission

Fuel Cell Electric Refuse Collection Vehicles

March 2021



- Almost half the range and half of H2 consumption

b. Range

Hydrogen fuel provides all the energy needed by the zero emission fuel cell refuse truck to meet the range requirements without encumbering the RCV with heavy batteries (which can reduce payload).

For refuse collection, with high energy requirements despite typically very low speed and distance, we found that required duration (hours) of operation is a better metric than range (km) of operation. This is reflected in the TCO work presented later in this paper.

For this study, we modeled fuel cell RCVs with 30kg of hydrogen to provide more than 16 hours of refuse collection for both the arc and node duty cycles, Table 3.

Based on typical energy requirements of the arc duty cycle, Arcola estimates the fuel cell RCV with 30kg of hydrogen can complete a duty cycle of more than 125km containing more than 3,000 bin lifts before reaching 90% depletion of the hydrogen tanks. Just 30kg of hydrogen opens the possibility of zero emission operation over multiple shifts without unproductive stops for opportunity charging of batteries. And 30kg of hydrogen requires less than 10 minutes to refuel. This high-utilisation capability of the RCV asset is an important differentiating characteristic of fuel cell solutions.

The flexibility of the fuel cell RCV to complete short and long duration arc and node duty cycles coupled with the capability to operate multiple consecutive shifts per day presents opportunities for waste management companies to complete the workload with fewer vehicles and a consistent mix of trucks, thereby reducing the total cost of operations. This is an important point that we recommend operators and local authorities study for potential cost savings.

- FC_$=1.65xDiesel_$
- But, FC is 1.5x more efficient, hence larger engine assumed than needed
- If FC is 1.2x more efficient, and cost of engine decreases proportionally with size, FC_$=2xDiesel_$

Table 5: TCO Inputs

Diesel RCV Costs	**low**	**high**
Duty Cycle Duration, h	8	12
RCV Cost, £/RCV	179,360	179,360
Energy/Fuel Cost, £/kWh	0.099	0.111
Maintenance Cost, £/h	3.80	3.80
Payload Capability, kg	10,000	10,000
Required number of RCV	30	30
Energy consumption rate, kWh/h	68.72	79.68
Battery RCV Costs	**low**	**high**
Duty Cycle Duration, h	8	12
RCV Cost, £/RCV	192,041	237,641
Energy/Fuel Cost, £/kWh	0.114	0.114
Maintenance Cost, £/h	2.85	3.80
Battery Lifetime, years	4	8
Payload Capability, kg	9211	9211
Required number of RCV	33	33
Energy consumption rate, kWh/h	20.1	23.1
Fuel Cell RCV Costs	**low**	**high**
Duty Cycle Duration, h	8	12
RCV Cost, £/RCV	177,518	295,678
Energy/Fuel Cost, £/kWh	0.091	0.183
Maintenance Cost, £/h	3.42	5.70
Payload Capability, kg	9570	9823
Required number of RCV	30	31
Energy consumption rate, kWh/h	46.5	53.6