Hydrogen Production Infrastructure Options Analysis

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Agenda

1. Project Description and Objective
2. Team Members
3. Approach
4. Model Theory, Structure and Assumptions
5. Model Description
    1. Logic
    2. Features
    3. Cost Components (Production, Delivery & Dispensing)
6. Los Angeles Transitional Example
7. Model Flexibility

Team Members & Interactions

Start: May 2005 (effective)
End: Summer 2007

- **Directed Technologies, Inc**.- Prime
- **Sentech, Inc.**, Research Partner
- **Air Products**, Industrial Gas Supplier
- **Advisory Board**
  - Graham Moore, Chevron Technology Ventures
  - Mike Miller, Teledyne Energy Systems
  - Sandy Thomas, H_2Gen Innovations, Inc.
  - Rajat Sen, Sentech, Inc.
  - Ira Kuhn Jr., Directed Technologies Inc.
  - Ed Kiczek, APCI
- **H2A Interaction**
- **H_2 Production parameters from Industry**
- **Coordination with other DOE Transition Analyses**
- **Coordination with DOE Macro-System Model development**

Approach

- Development of a **time-based, computational dynamic model of H_2 production** in the continental US.
- **Use model** and other methods **to understand** how a H_2 production infrastructure:
  - will develop over time,
  - the factors that will drive it, and
  - the role of externalities, such as policy and technology.
- This model will use consistent financial & technological assumptions to evaluate H_2 production & delivery costs dynamically (as opposed to statically) **with changing demand and utilization**.

Approach, continued

- Economics modelled from **H_2 supplier/investor point of view**.
- Annual demand will be postulated and some foresight provided for planning infrastructure.
- Develop a dynamic H_2 production infrastructure economics model.
- Allow dynamic calculation of hydrogen costs, including the effects of changing **infrastructure utilization**.
- Assess H_2 production facility displacement due to technological and demand changes in time (**stranded assets**).

- **Overall Goal** is that the resulting infrastructure and transition will be modelled from the **business perspective**.

Basic Premises of Model

Simulate decision making process of Hydrogen supplier/investor.

- Business wants to maximize profit.
- Profit is hard to quantify, requires knowledge of H_2 price.
- Will use H_2 cost as surrogate for Price.
- Minimize Cost => Maximizing Profit.
- Cost vs. Price.
  - Price: Dictated by Market.
  - "Profited Cost": Price to yield a specified real, after-tax IRR.
  - Cost: Total cost to produce with zero profit.

Basic Premise of Model, cont.

- Model is **a tool** to allow infrastructure analysis.
- Model applies to **regions of homogeneous H_2 demand** (constant kg H_2/day/km^2).
  - Regions are nominally Urban, Rural, or Interstate but can represent any region of uniform demand.
- Regional results may be combined to portray expected production infrastructure development for entire US (2nd iteration of model).
- Model can simulate existing facilities.
- Model is **written in MATLAB**.
- Model will allow interaction with other models.

Model Inputs and Outputs

- **Inputs:**
  - Production & Delivery Method Data.
    - Capital Cost, Efficiency, Fixed Expenses, etc.
    - For all prod. methods, multiple sizes, for each year.
  - Geographic H_2 Demand (kg/day/km^2).
  - Feedstock cost by year.
  - Maximum Distance between service stations.
  - Externalities (Carbon Taxes, tax treatment, existing surplus H_2, etc.).

- **Outputs:**
  - Determination of each year's lowest cost H_2 production method (minimize objective function).
  - Expected H_2 profited cost by year.
  - Identification/Quantification of stranded production assets.
  - Sensitivity to H_2 production parameters, feedstock cost, changes in H_2 demand, etc.

Infrastructure Options

- Infrastructure Option defined as:

Infrastructure Option = Production Method + Delivery Means + Dispensing

- H_2 will remain in constant state from production through delivery.
- Options where production is in the forecourt have no delivery costs associated with them.

Choices in each segment:			
	Production	Delivery[1]	Dispensing
Gaseous	18	4	6
Liquid	14	2	2[2]

[1] **No delivery is also an option for forecourt production cases.**
[2] **Liquid H2 arrives at dispensing station and is convert to gaseous prior to dispensing.**

Model Inclusive Costs

- Hydrogen costs are based on;

Cost of Hydrogen [$/kg] at Pump =
Production cost + Delivery cost + Dispensing cost + Other Costs

- ***Production costs*** determined by NPV calculations performed dynamically and include effects from;
  - State of technology development,
  - Infrastructure capacity, and
  - Varying plant utilization
- ***Delivery costs*** are determined offline & averaged over analysis period.
- ***Dispensing costs*** are determined offline & averaged over analysis period.
- ***Other costs*** are credits and taxes which can be quantified in $/kg but not directly attributed to a specific segment of the infrastructure.

Decision Logic

- An infrastructure development decision will be made once per year.
- In any given year, no more than one type of new infrastructure can be developed.
- Decision criterion: Infrastructures must satisfy demand requirement for the decision year (May exceed current demand, up to future demand as determined by investor knowledge limitations).

Supply Capacity [YR 20##] >= Demand [YR 20##]

- Decision is purely economic. Infrastructure option that minimizes objective function is implemented.

Infrastructure Choice [YR 20##] = MINIMUM OBJ. FUNCTION (All options)

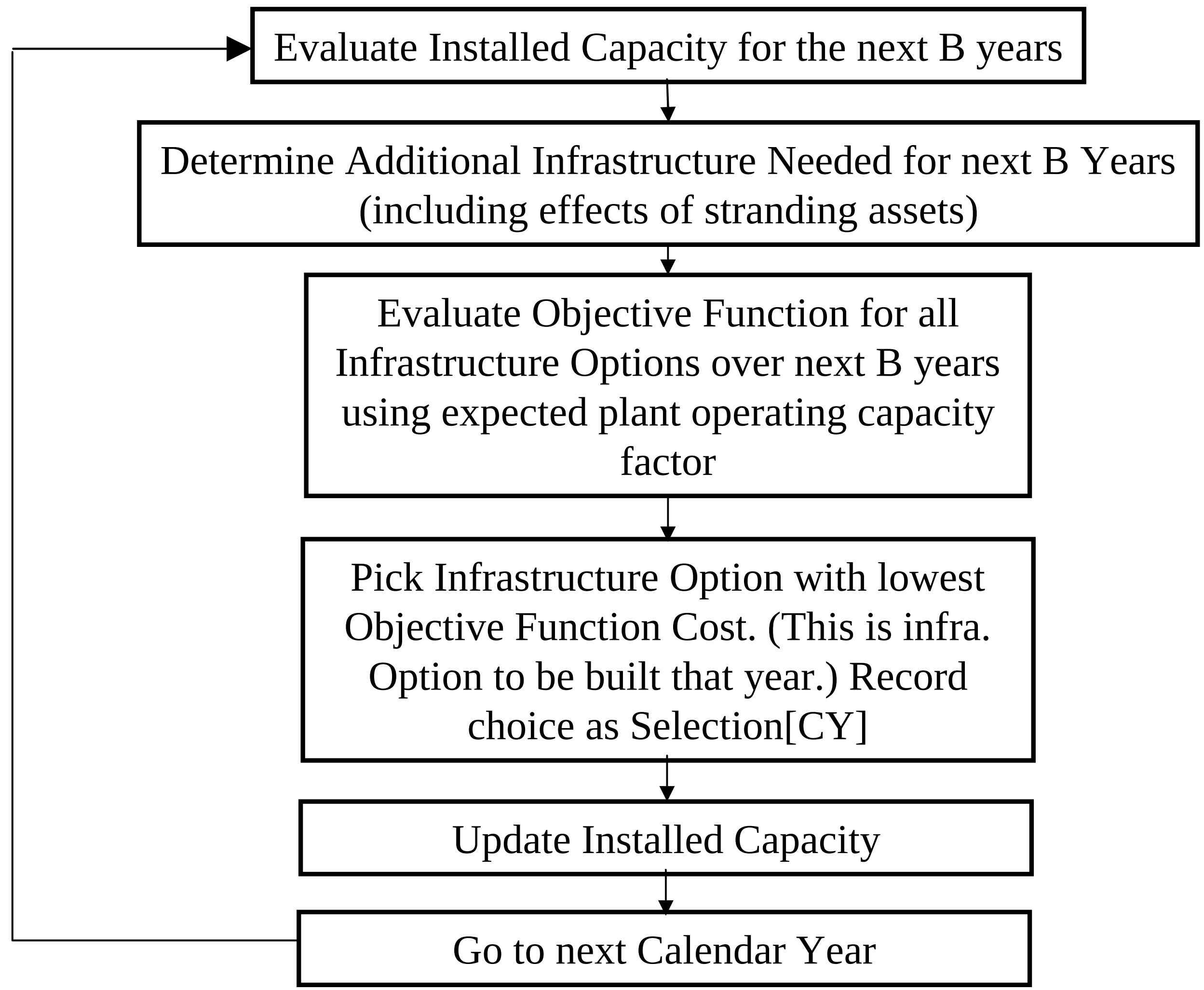
- Objective Function is effectively **average cost of H_2 over X year period**.

Objective Function [YR 20##] =

Aver. Prod. Cost($/kg) + Aver. Del. Cost($/kg) + Aver. Disp. Cost($/kg) + Aver. Other Costs($/kg)

- Rule: Infrastructure can be developed to meet demand up to X years in the future (where X is a model input).
- Logic applies to both Forecourt & Central production options.

Model Logic Diagram



Description of Specific Approach to:

- **Cost Database**
- **Production Cost Computation**
- **Delivery Cost Computation**
- **Dispensing Cost Computation**
- **“Other Cost” Computation**

Cost Assumptions & H2A

- H2A provides **primary/initial source** for cost, performance and model assumptions.
- However, we are free to deviated from H2A assumptions and do so in many areas.
- Database is collection of production costs & performance metrics; other portions of infrastructure costs will be embedded in model.
- Model leverages H2A calculated values for delivery and dispensing portions of model.
- Model also adopts H2A fuel feedstock values for years 2005 to 2070.

32 Production Options

Gaseous Output

1.0 Fossil Fuel Based Hydrogen Production

1.1 Coal

1.1.1.1 Gasification (283 tons/day, 316 tons/day, 247 tons/day)

1.1.1.2 Gasification (15 tons/day)

1.1.2.1 Gasification with CO2 Sequestration (308 tons/day , 316 tons/day, 247 tons/day)

1.2 Natural Gas / Hydrocarbon

1.2.1.1 Steam Reforming (379 tons/day)

1.2.1.2 Steam Reforming (15 tons/day)

1.2.1.5 Steam Reforming (100 kg/day)

1.2.1.6 Steam Reforming (1500 kg/day)

1.2.2.1 Steam Reforming with CO2 Sequestration (379 tons/day)

2.0 Water Based Hydrogen Production

2.1 Water

2.1.1.5 Electrolysis – Marginal Mix Electricity (100 kg/day)

2.1.1.6 Electrolysis – Marginal Mix Electricity (1500 kg/day)

2.1.2.1 Electrolysis by Nuclear (673 tons/day)

2.1.3.1 Thermal Disassociation of Water using Nuclear Energy (719 tons/day)

2.1.4.1 Sulfur-Iodine Thermochemical Hydrogen Cycle (768 tons/day)

3.0 Renewable Energy

3.1 Biomass

3.1.1.1 Gasification (155 tons/day)

Liquid Output

1.0 Fossil Fuel Based Hydrogen Production

1.1 Coal

1.1.1.3 Gasification (283 tons/day, 316 tons/day, 247 tons/day)

1.1.1.4 Gasification (15 tons/day)

1.1.2.3 Gasification with CO2 Sequestration (308 tons/day , 316 tons/day, 247 tons/day)

1.2 Natural Gas / Hydrocarbon

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3.0 Renewable Energy

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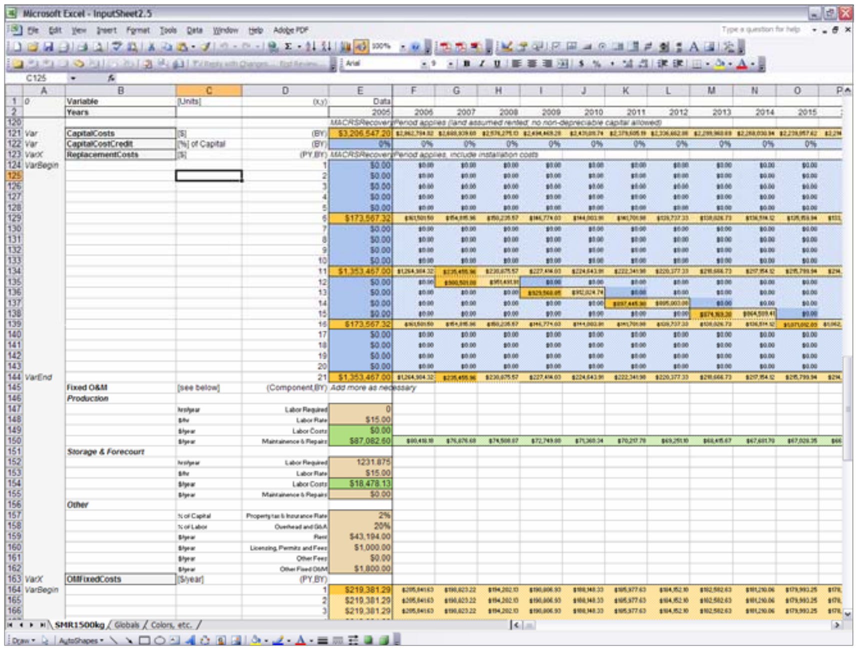
3.1.1.3 Gasification (155 tons/day)

Production Input Sheets

Production cost/performance entered into Excel spreadsheets.

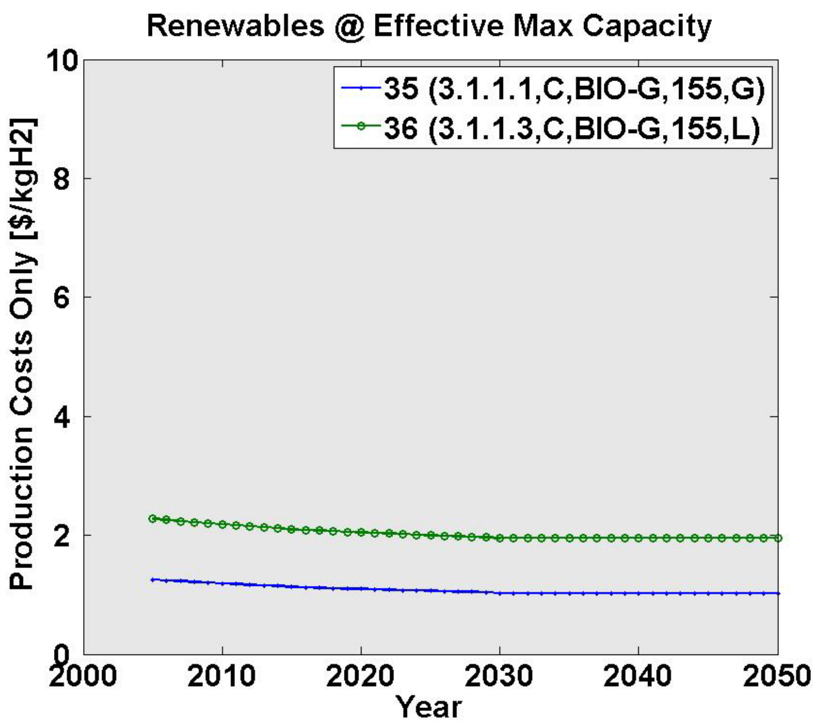


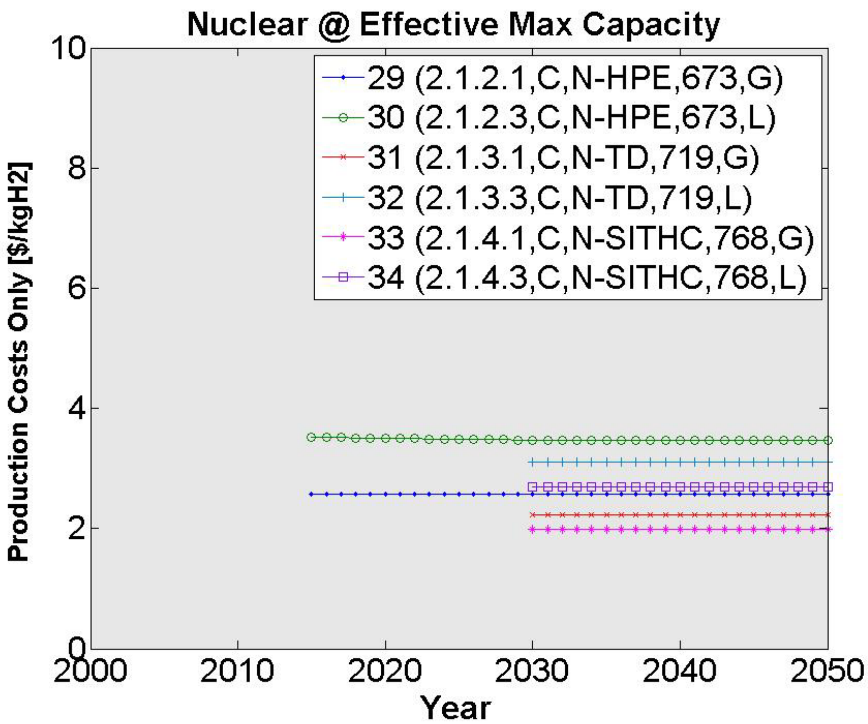
- Each production method is on a separate worksheet tab.
- MATLAB program reads tabs and extracts necessary data.
- Only knowledge of Excel is needed to modify production parameters.

Production Cost Approach

- Based on a **<u>Discounted Cash Flow (DCF) approach</u>**.
- Approach is identical to H2A.
    - Average H_2 "profited cost" is determined to return a given IRR over analysis period.
    - H2A uses 20/40 year analysis, **<u>we nominally use 10/20 years</u>**.
- Unlike H2A, **<u>% utilization of plant can vary</u>** from year to year.
- DCF based on:
    - yearly capital cost expenditures,
    - fixed costs (replacement costs, land, etc.), and
    - variable costs (feedstock, labor, etc.).
- A root-finding approach is used to determine H_2 profited cost that corresponds to the selected IRR (i.e. NPV=0).

Production Only Cost Curves

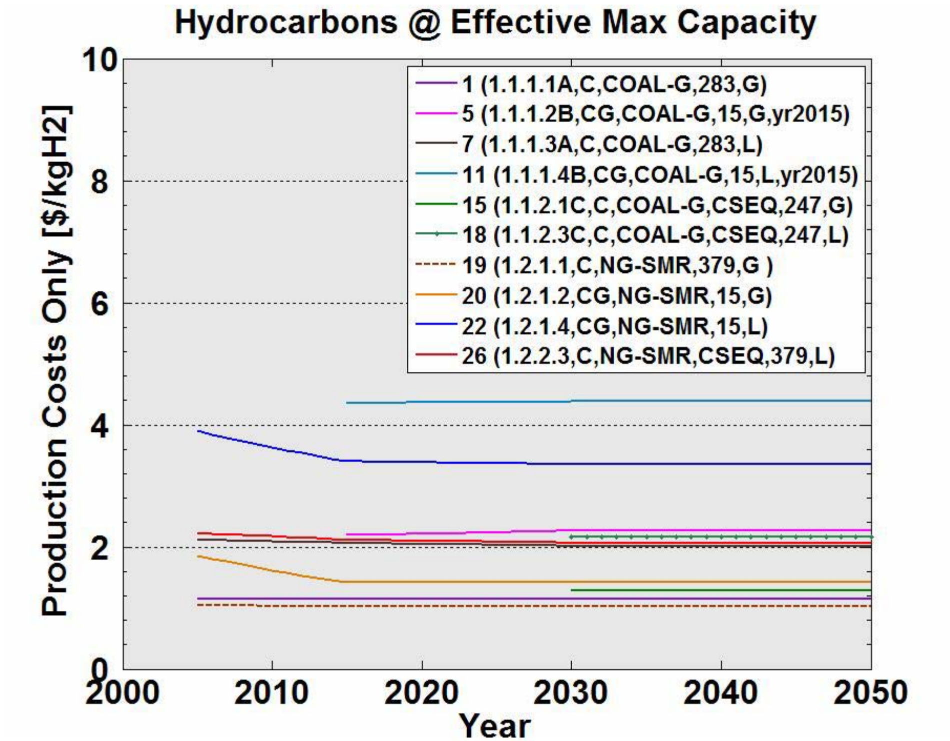


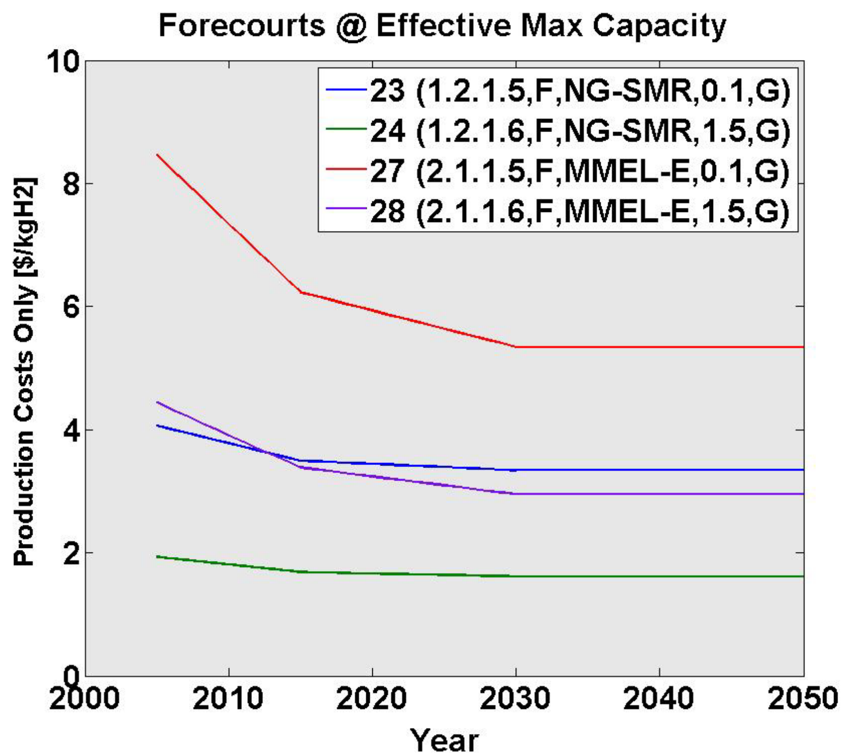


- **Biomass (gaseous) quite cheap (~$1/kg)**
- **Wind electrolysis options pending**

- **Nuclear options more expensive (~$2-$4/kg)**

Production Only Cost Curves





- **Multiple Coal & NG options lead to low cost H_2.**

- **No delivery cost.**
- **Electrolysis options relatively expensive (unless very low electric cost)**
- **Large SMR competitive.**

Delivery Options

Large City Parameters

1. CH2 Truck to 100 kg/day Station
2. CH2 Truck to 1500 kg/day Station
3. LH2 Truck to 100 kg/day Station
4. LH2 Truck to 1500 kg/day Station
5. CH2 Pipeline 100 kg/day Station
6. CH2 Pipeline 1500 kg/day Station
7. No Delivery (used with Forecourt production)

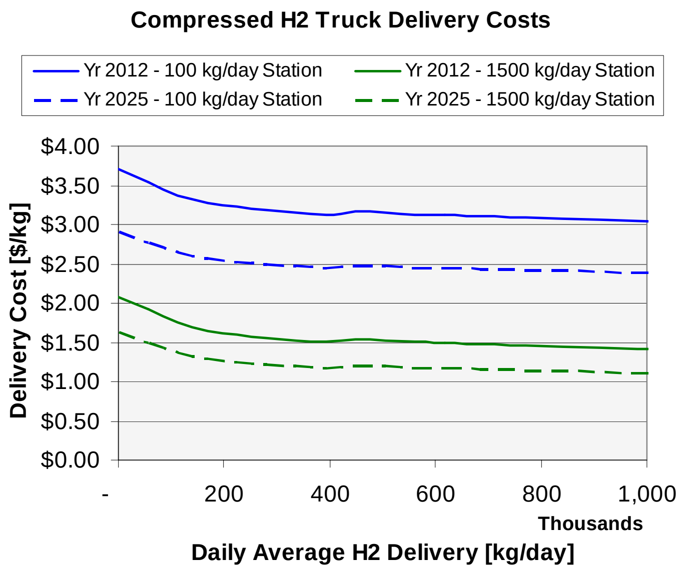
Options 8-14:
Same as above but with Small City parameters

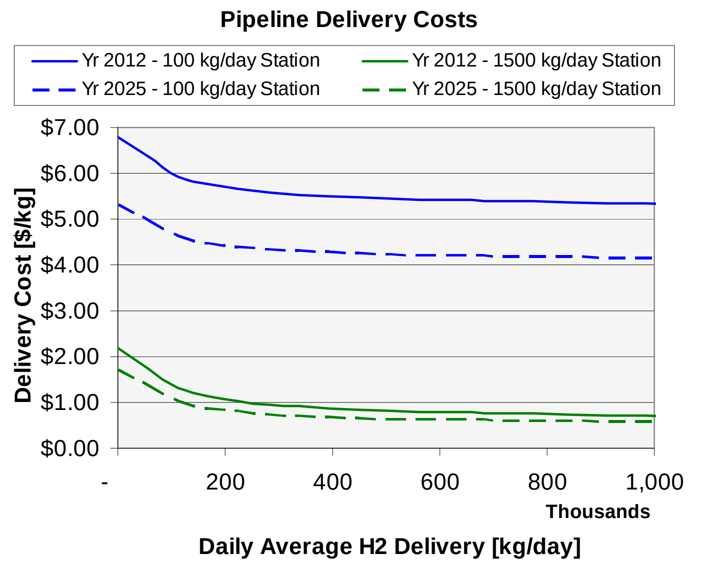
Options 15-21:
Same as above but with Interstate Highway parameters

Delivery Cost Approach & Assumptions

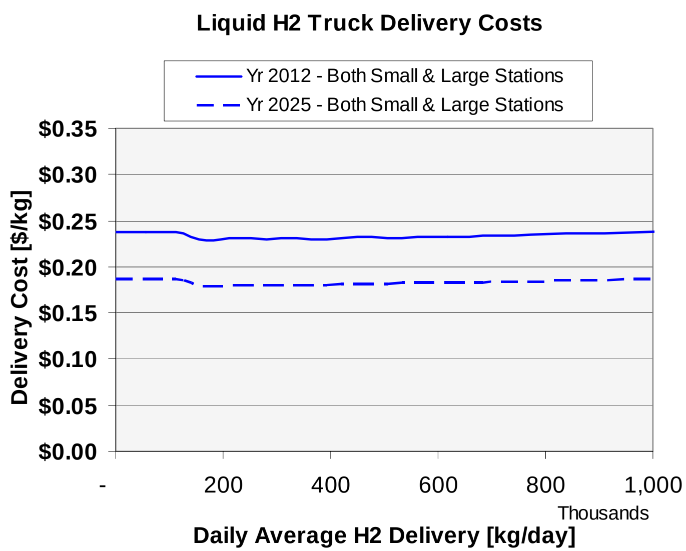
- Based on H2A Scenario Model results (but with heavy manipulation)
- Differs from production costs approach wherein a DCF analysis is conducted within the model.
- Delivery costs are only calculated for infrastructure that include central H_2 production (Delivery costs are set to zero for forecourt cases).
- Truck delivery assumes 100% utilized at all times.
  - Limitation imposed by being based on H2A calculations.
  - Delivery cost is function of demand density.
- Pipeline delivery based on H2A but modified
  - Pipeline built for 10-year expected pipeline demand but capped at 5x first year demand
  - Cost reflects underutilization of pipeline

LA Delivery Costs





Amortization of Service Lines from Trunk Line to Station results in major cost difference between Small and Large Stations.



LH2 Delivery Cost essentially constant with delivery amount.

- **Graphs show costs at constant full utilization.**
- **But model will calculate 10-year average cost based on actual utilization for pipelines.**

Dispensing Options

1. 100 kg/day Station from CH2 Truck Delivery
2. 1500 kg/day Station from CH2 Truck Delivery

3. 100 kg/day Station from LH2 Truck Delivery
4. 1500 kg/day Station from LH2 Truck Delivery

5. 100 kg/day Station from CH2 Pipeline Delivery
6. 1500 kg/day Station from CH2 Pipeline Delivery

7. 100 kg/day Station from Forecourt Production
8. 1500 kg/day Station from Forecourt Production

Dispensing Cost Approach & Assumptions

- Simplified calcs based on H2A DCF results.
- Dispensing cost is a function of station utilization.
- Dispensing costs as function of time.
  - Equipment costs will decrease in the future with increased H_2 demand and technology improvements.
- Process:
  1. H2A results are entered as tables
  2. Linear interpolation conducted between over utilization & time
  3. Dispensing cost is H_2 weighted average over future 10 year period.

Dispensing Algorithm

Use the infrastructure option matrix to determine which dispensing method to use.

↓

Given the production year and % utilization for the infrastructure, select the 4 data points which bound the space.

↓

Perform 3 linear interpolations to achieve the appropriate dispensing cost for that year & % utilization. Repeat for all production years.

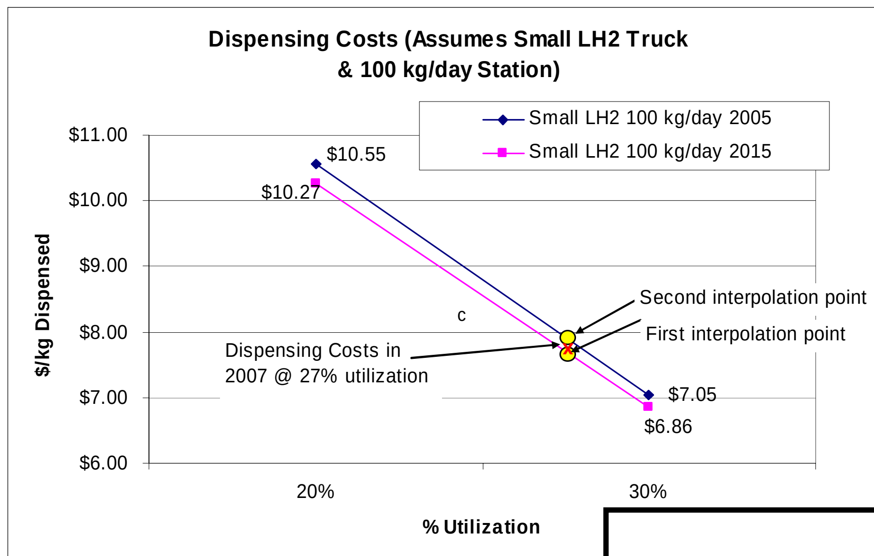
↓

Calculate a weighted average cost of dispensing for the option.

↓

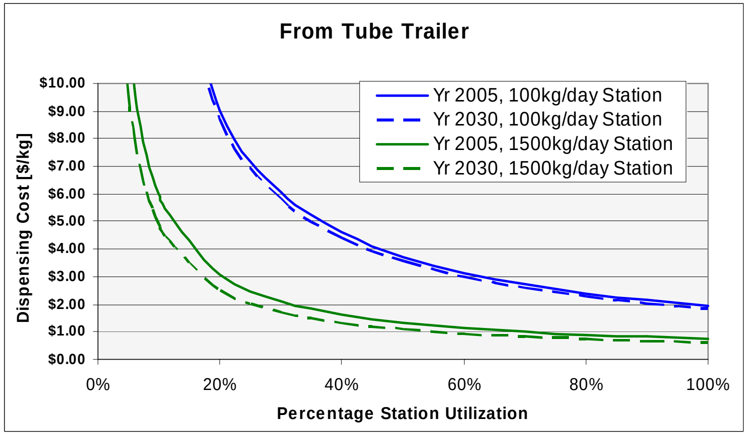
Incorporate this value into the objective function for the infrastructure option.

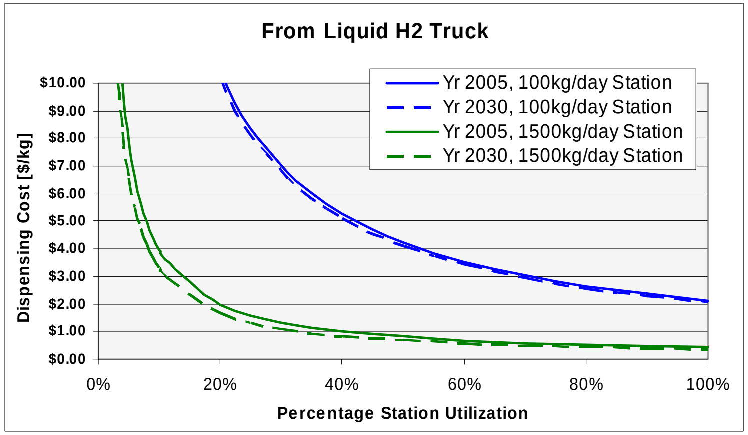
% Util	100 kg/day [Small Truck LH2]			100 kg/day [Tube Trailer CH2]		
	2005	2015	2030	2005	2015	2030
1%	$ 210.59	$204.87	$ 203.51	$177.51	$171.78	$170.40
10%	$21.08	$ 20.51	$ 20.38	$ 17.91	$ 17.32	$ 17.18
20%	$ 10.55	$10.27	$ 10.20	$ 9.04	$ 8.74	$ 8.66
30%	$ 7.05	$6.86	$ 6.81	$ 6.09	$ 5.88	$ 5.82
40%	$ 5.29	$5.15	$ 5.12	$ 4.61	$ 4.45	$ 4.41
50%	$ 4.24	$4.13	$ 4.10	$ 3.72	$ 3.59	$ 3.55
60%	$ 3.54	$3.44	$ 3.42	$ 3.13	$ 3.02	$ 2.99
70%	$ 3.04	$2.95	$ 2.94	$ 2.71	$ 2.61	$ 2.58
80%	$ 2.66	$2.59	$ 2.57	$ 2.39	$ 2.30	$ 2.28
90%	$ 2.37	$2.30	$ 2.29	$ 2.15	$ 2.07	$ 2.04
100%	$ 2.13	$2.08	$ 2.07	$ 1.95	$ 1.88	$ 1.85

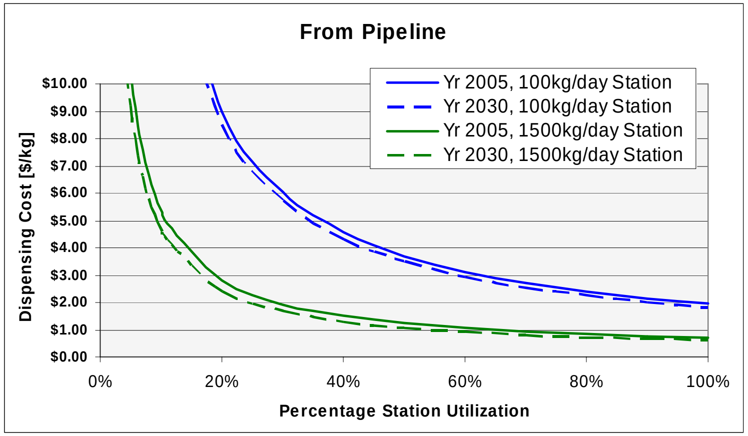


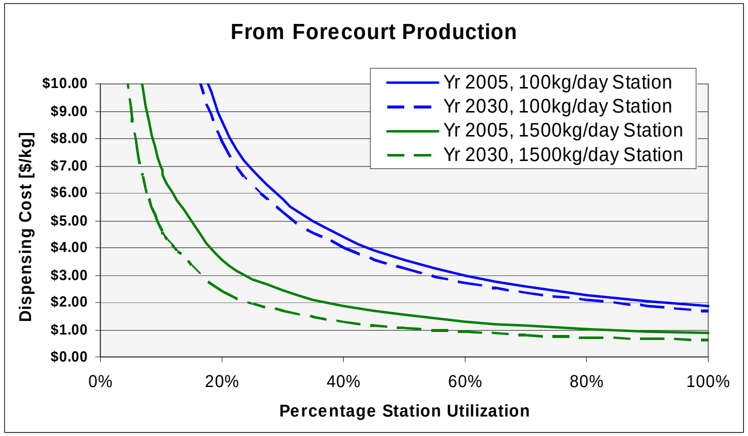
$$\$/kg(dispensng)_n = \frac{\sum_{i=1stprodyr}^{m} (\$/kg(disp)_n * \%util * capacity)_i}{\sum_{i=1stprodyr}^{m} (\%util * capacity)_i}$$

Los Angeles Dispensing Costs









Station Size and % Utilization are main drivers of H_2 Dispensing Cost.

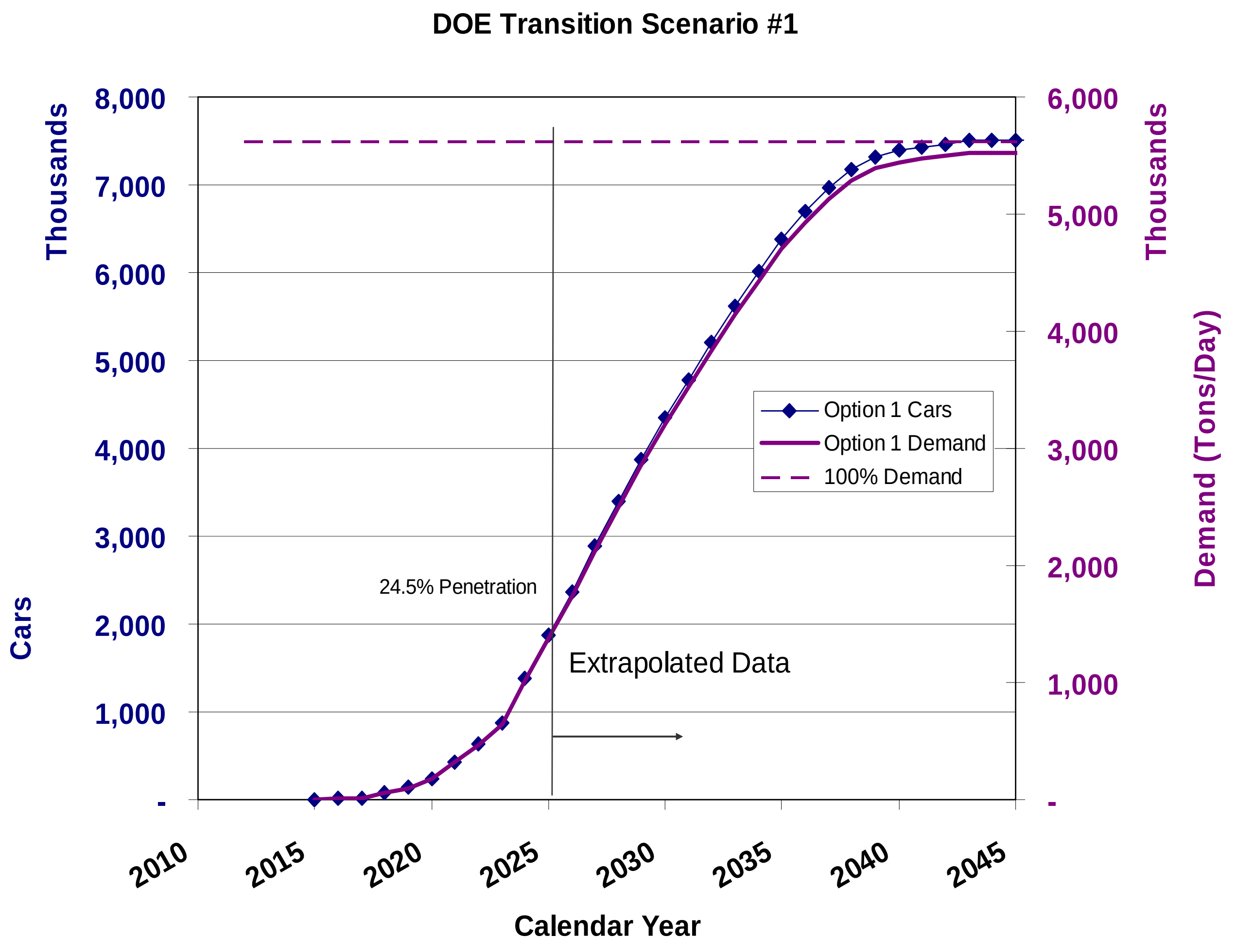
What constitutes "other costs"?

- Externalities to include/consider:
  - GHG emission penalties.
  - Subsidies for renewable resource usage.
  - Infrastructure permits.
  - Hydrogen fuel taxes/rebates/subsidies.
  - Tax credits.
- The effects of any externality can be assessed if they can be quantified on a $/kg basis.

Preliminary Results of Los Angeles Hydrogen Transition

Years 2012-2025

DOE Postulated H_2 Demand Curve



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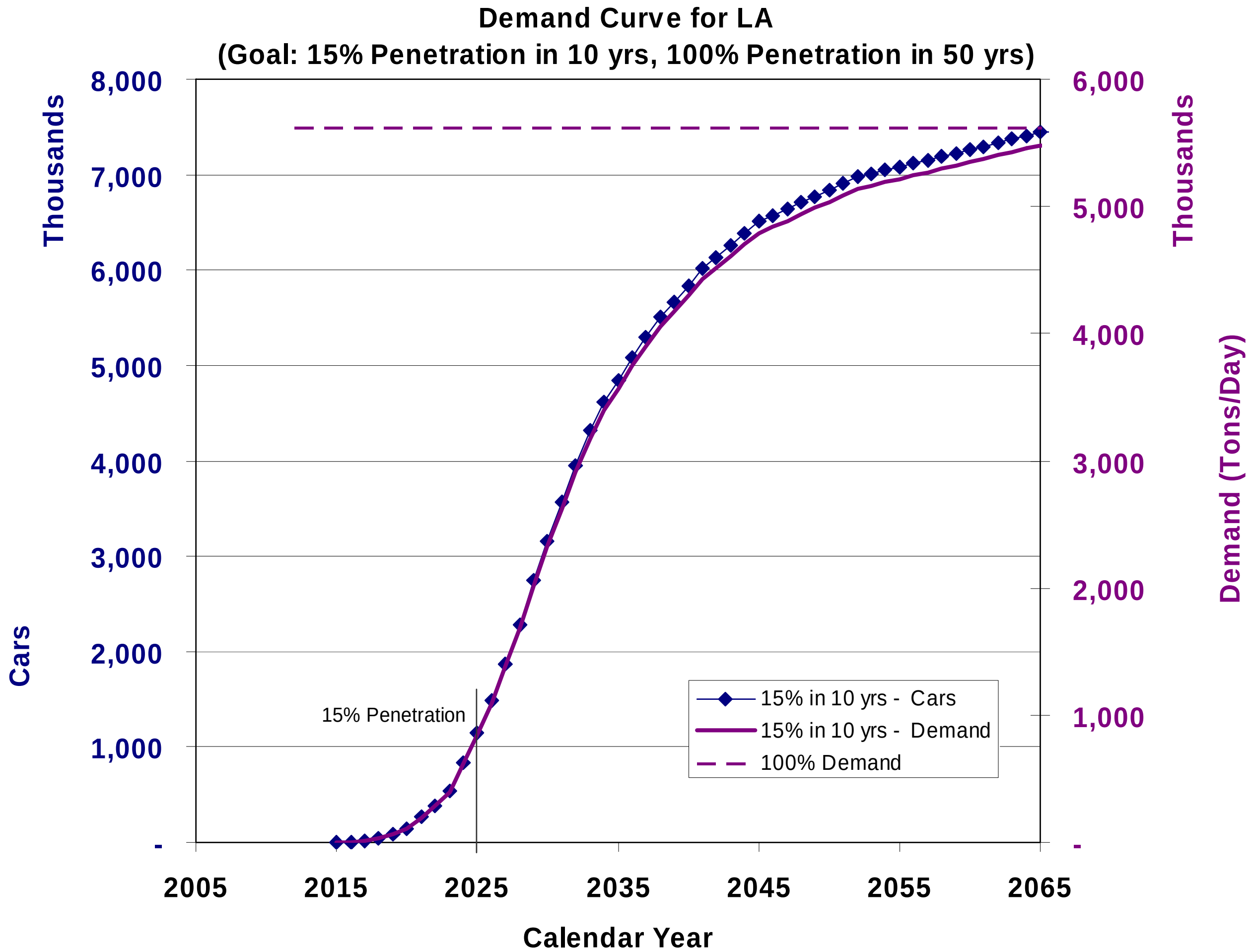
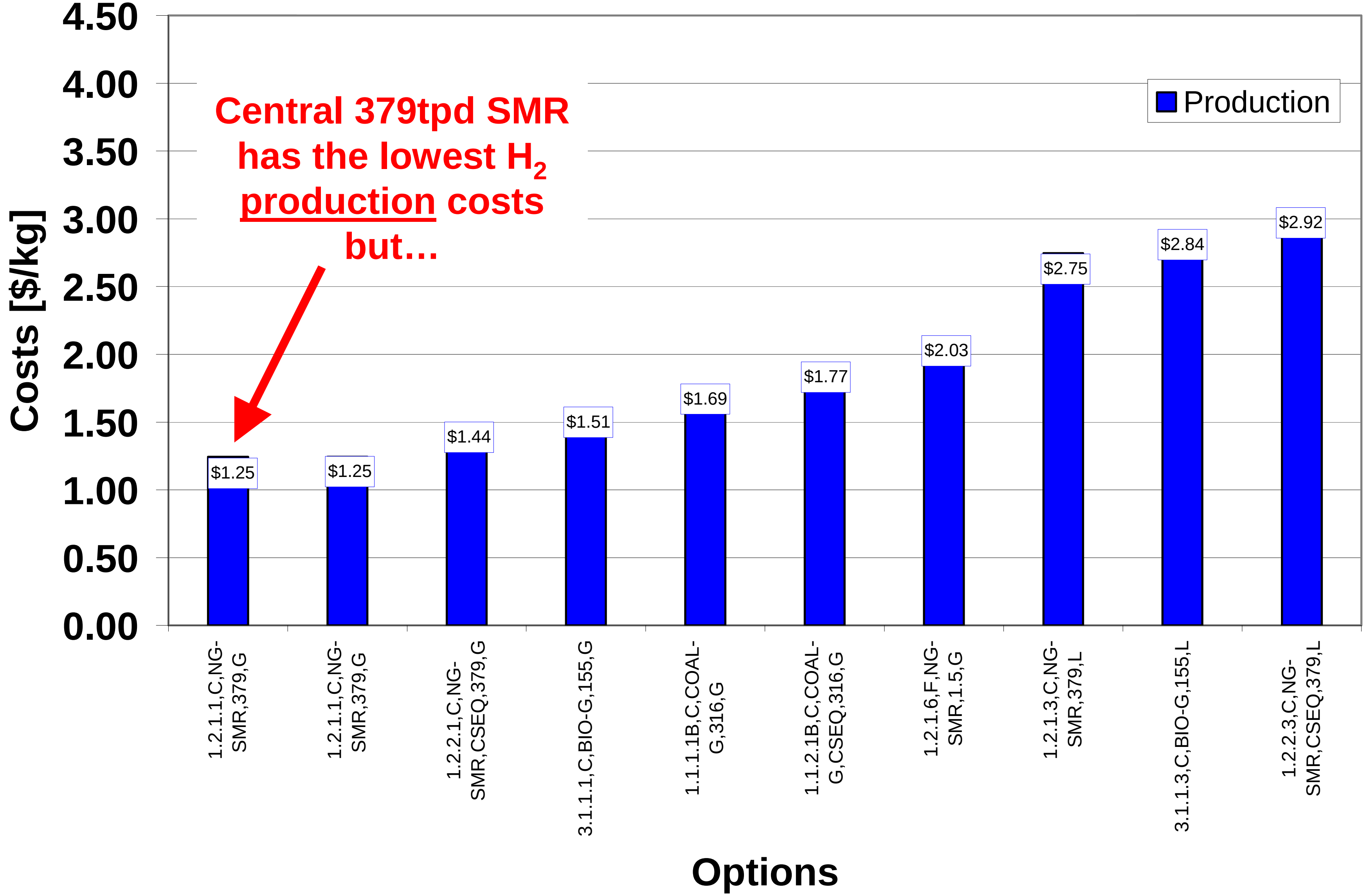
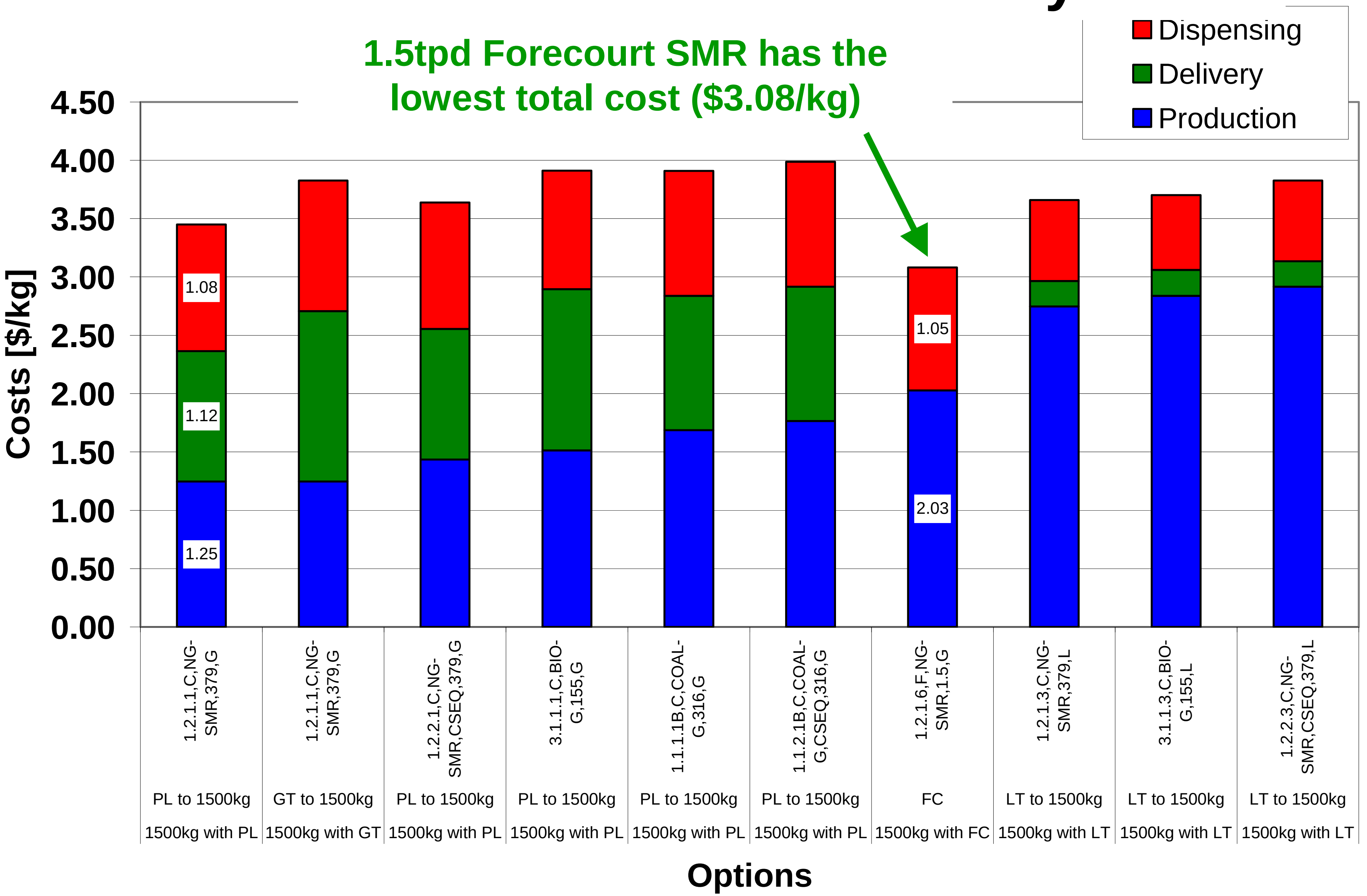
H_2 Demand Curve – Los Angeles

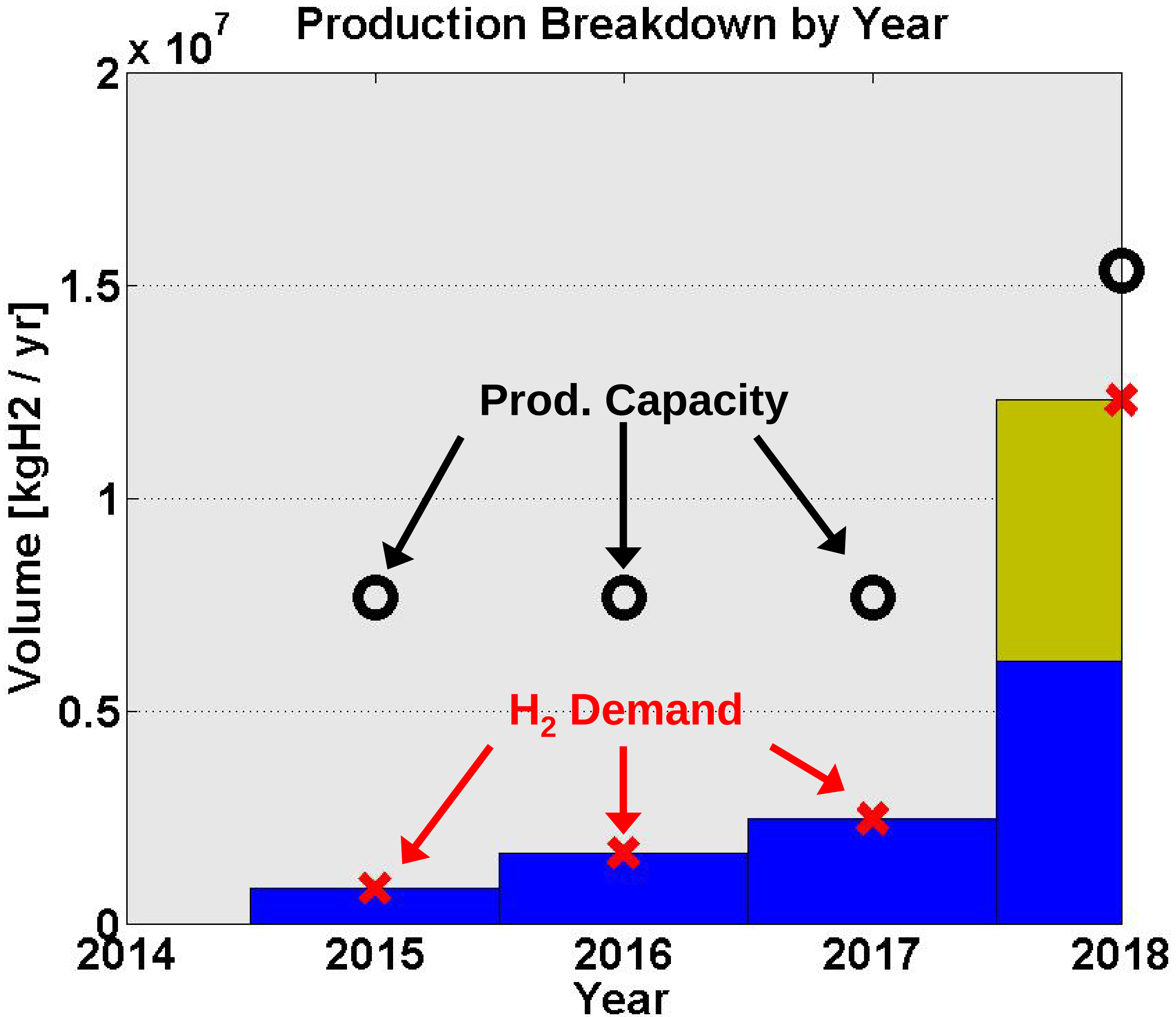


2015 Production Costs



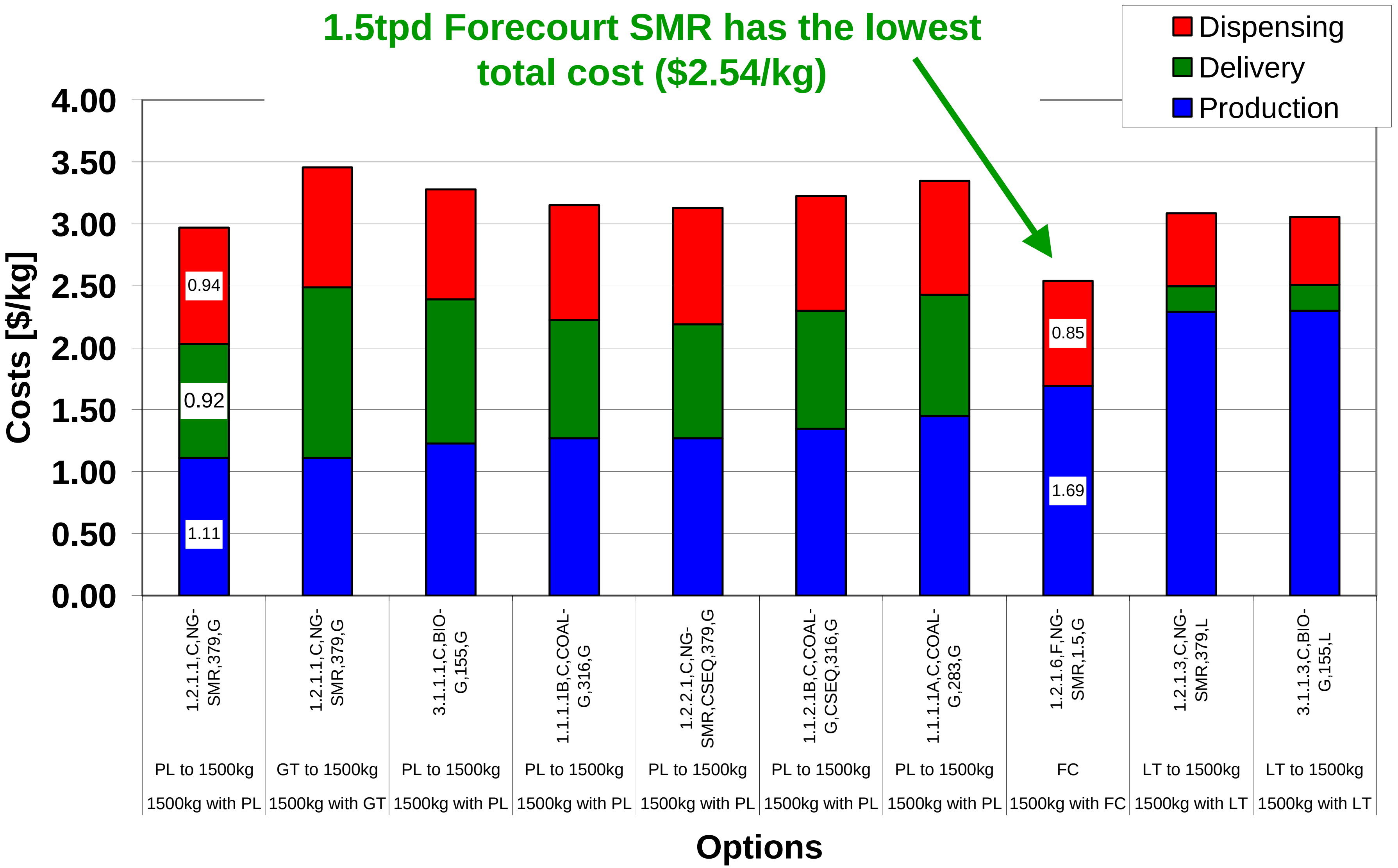
2015 Total Infrastructure Pathway Cost

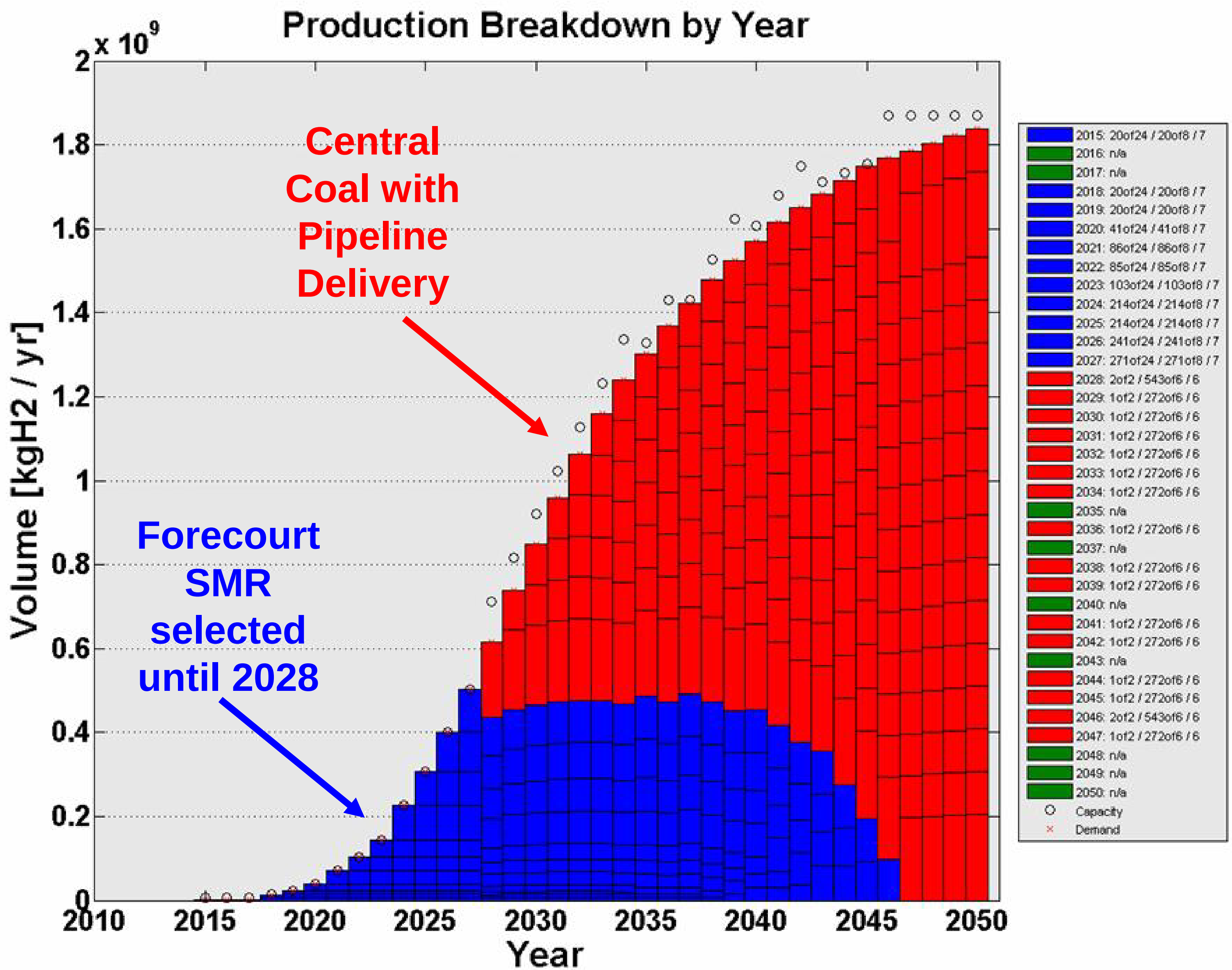




- **2015 Capacity determined by station spacing.**
- **No infra. build required in 2016 or 2017**

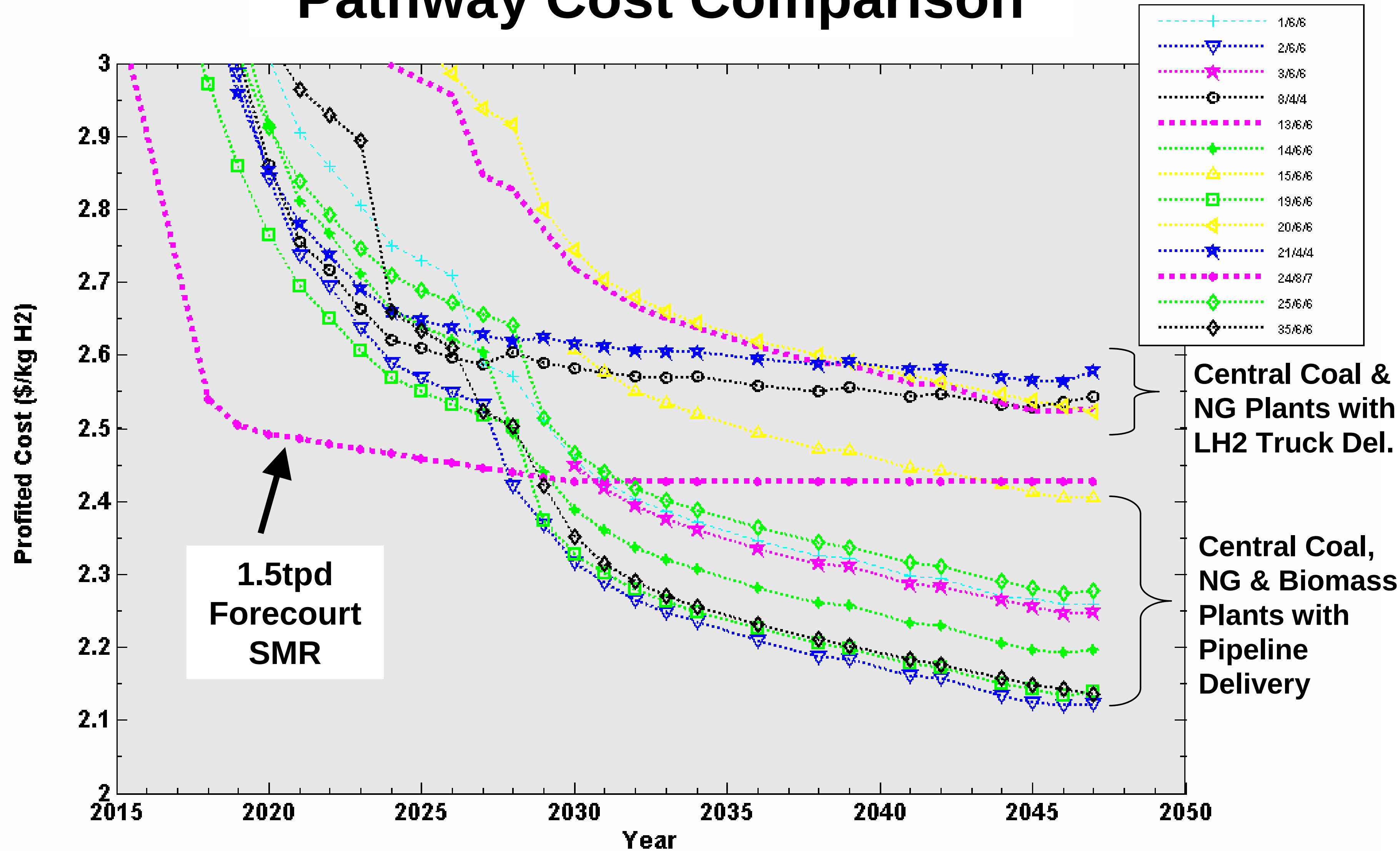
2018 Total Infrastructure Pathway Cost





Feedstock Prices fixed over analysis period.

Pathway Cost Comparison



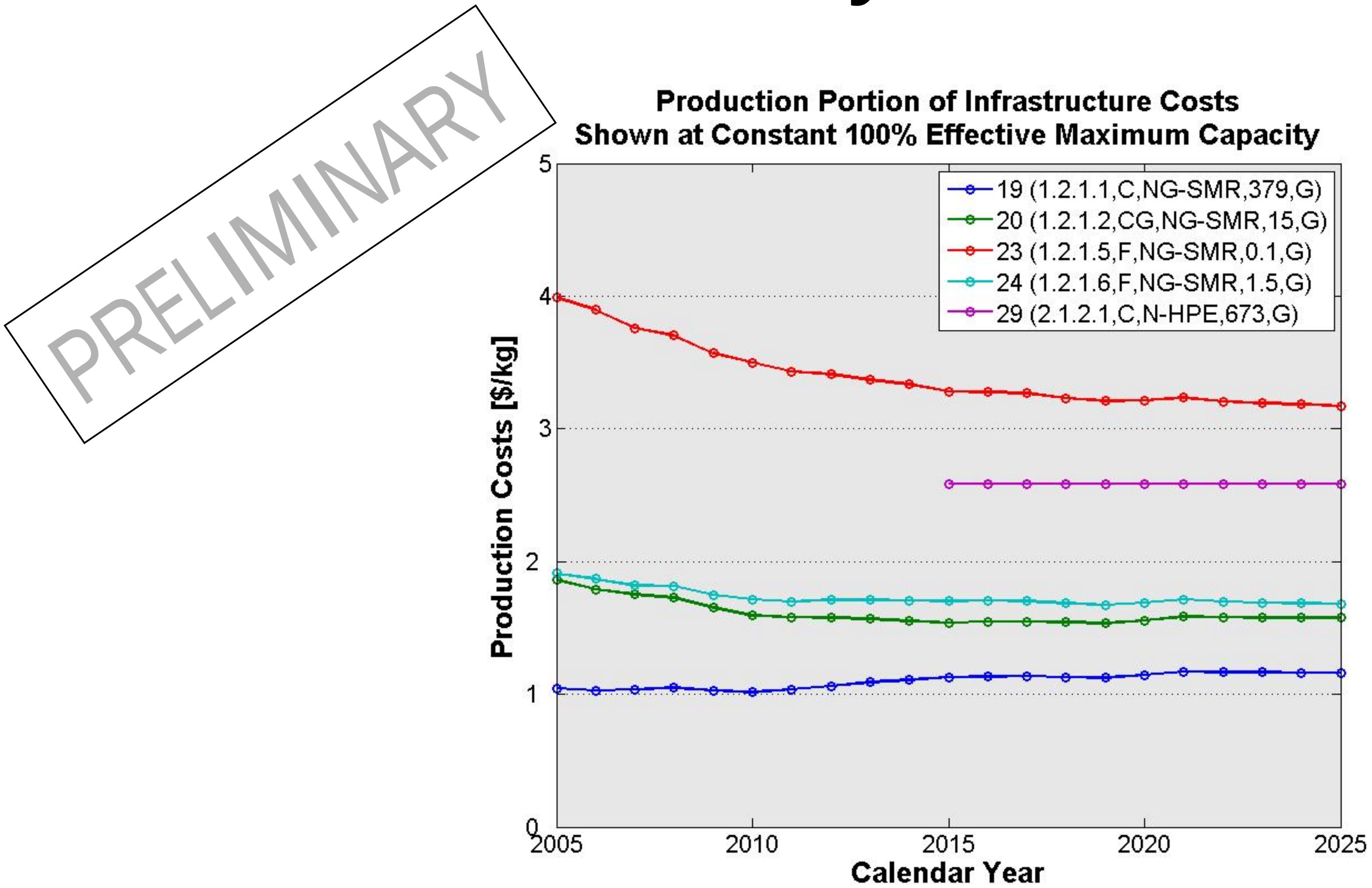
Preliminary Results

Next Steps

1. Improve pipeline modeling
2. Increase years of study (out to 2050+)
3. Add new infrastructure pathways
4. Add externality costs
5. Explore stranded assets
6. Change IRR value
7. Change analysis period
8. Explore DOE goal effects
9. Add variable feedstock prices

Questions?

Production Only Cost Curves



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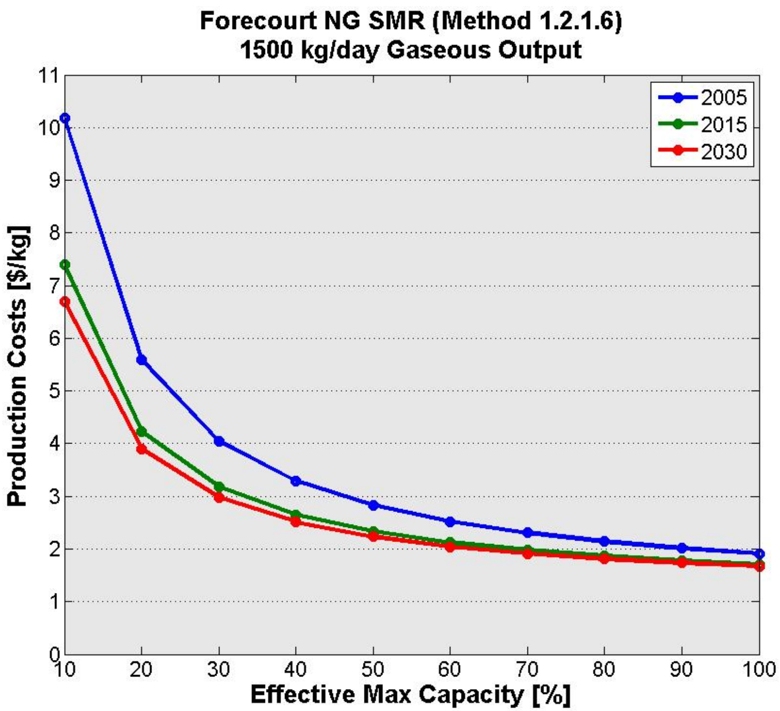

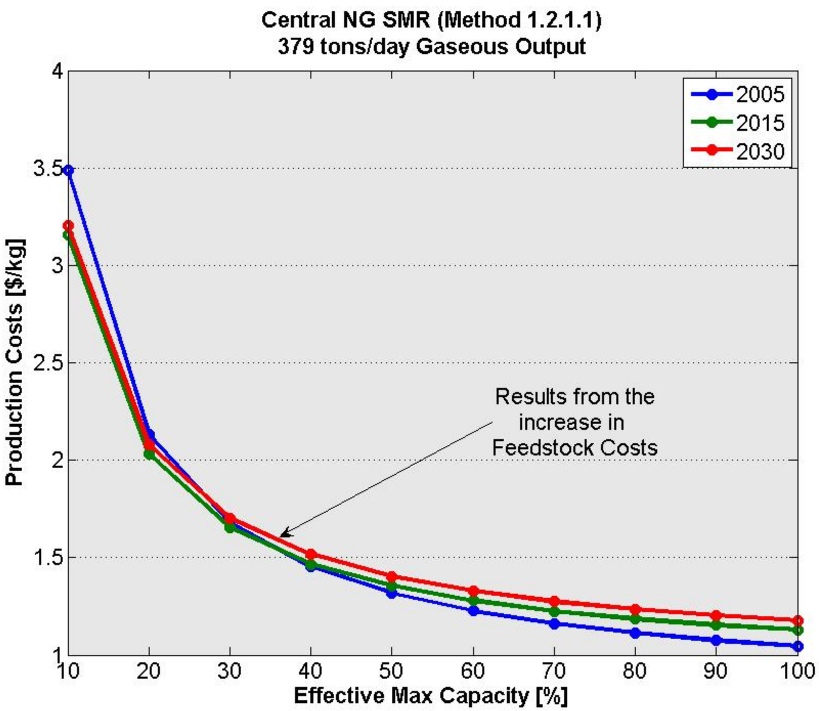

PRELIMINARY