HyPro: Modeling the H_2 Transition

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Outline

- **Model Overview**
- **Results Summary**
- **Cost & Methodology Assumptions**

Project Objectives

Overall	• Create a tool robust enough to test the impact of different assumptions on the development of hydrogen infrastructure and exercise it to determine the key drivers of the hydrogen transition.
2005	• Develop a production database from H2A and an economic cost model to determine and compare discounted cash flows.
2006	• Enhance model's capabilities by adding DCF of delivery and dispensing and costs tables for results • Increase database options and sources of data • Exercise the tool under different assumptions to understand the infrastructure's sensitivity to different parameters.
2007	• Model upgrades • Further sensitivity analyses • Analyze different scenarios • Document results

Overall Approach

Research

Assumptions
Costs
Technologies

UC Davis
H2A Production
HDSAM
FPITT
Transition Team
HYTRANS

Cost Database

Capital Cost
Efficiency
Feedstock prices
Plant Location

DTI Model (Tool)

Determine net Demand

Calculate Cost Function for all available options at this Demand

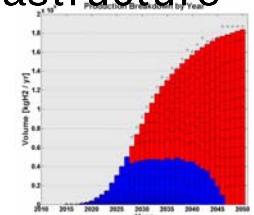
Select & Build Lowest Cost Option

Update Installed Capacity

Iterate next Year

Results & Sensitivity

Cheapest Build
H_2 Profited Cost
Stranded Assets
Capital Costs,
Infrastructure

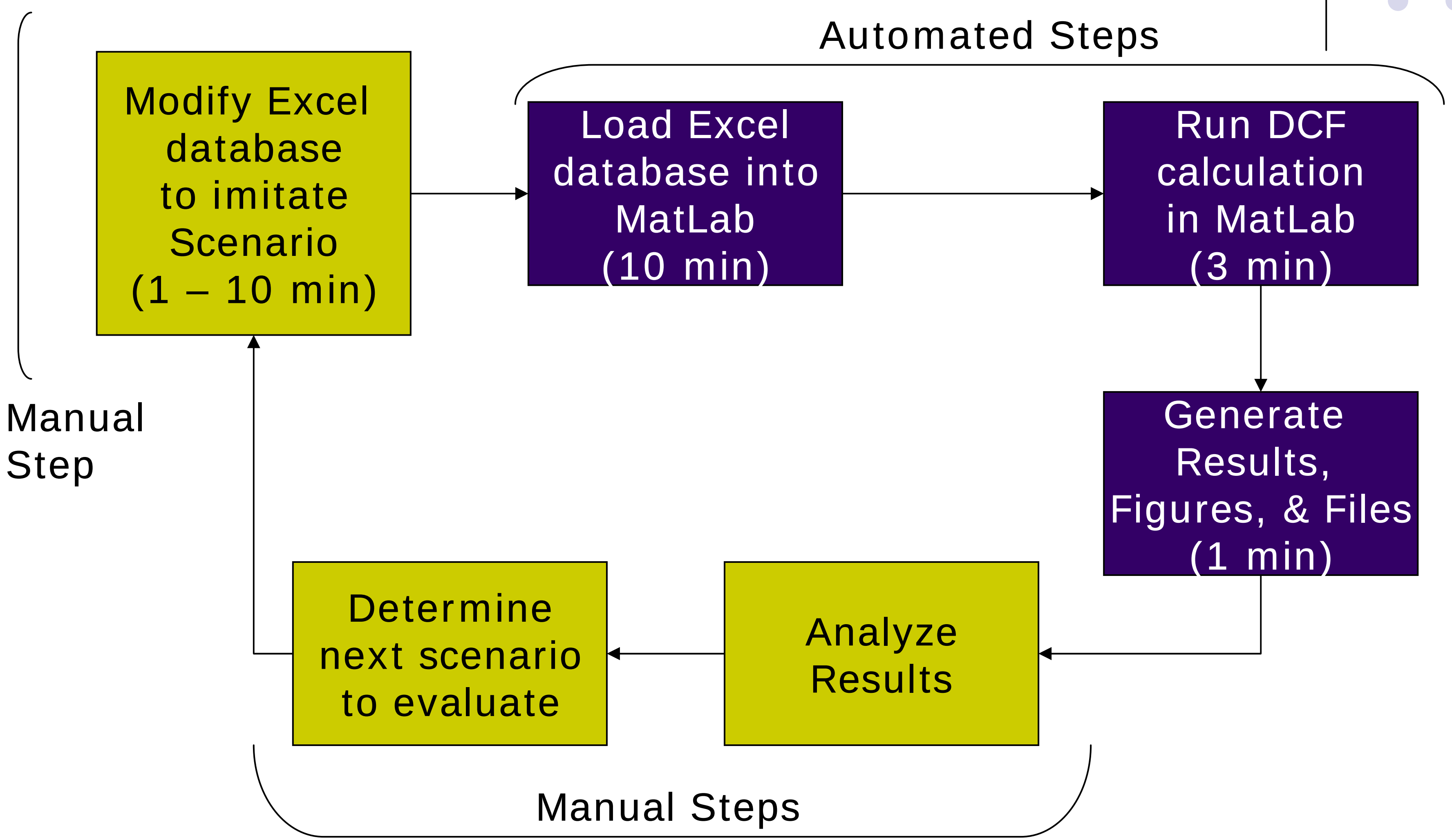


Modify parameters

Cost Database

Re-run model to assess impact

Analysis Methodology



Key Analysis Assumptions

- **Demand is user entered**
  - Demand is an input of the model and is assumed to be increasing every year.
- **Regional Model without Inter-regional feedback**
  - Influence of manufacturing learning factor from national build out is not currently modeled.
- **Perfect foresight**
  - All investors have perfect foresight. Uncertainty is currently not modeled.
- **Analysis Period**
  - 10 years for distributed production
  - 20 years for central production
- **Remote infrastructure pathways include production, terminal, delivery and dispensing**
- **Distributed infrastructure pathways include production and dispensing**
- **Capital Cost of 1.5 TPD Forecourt SMR Pathway**
  - Range of costs projected by industry for this option is large and brackets cost of several other options.

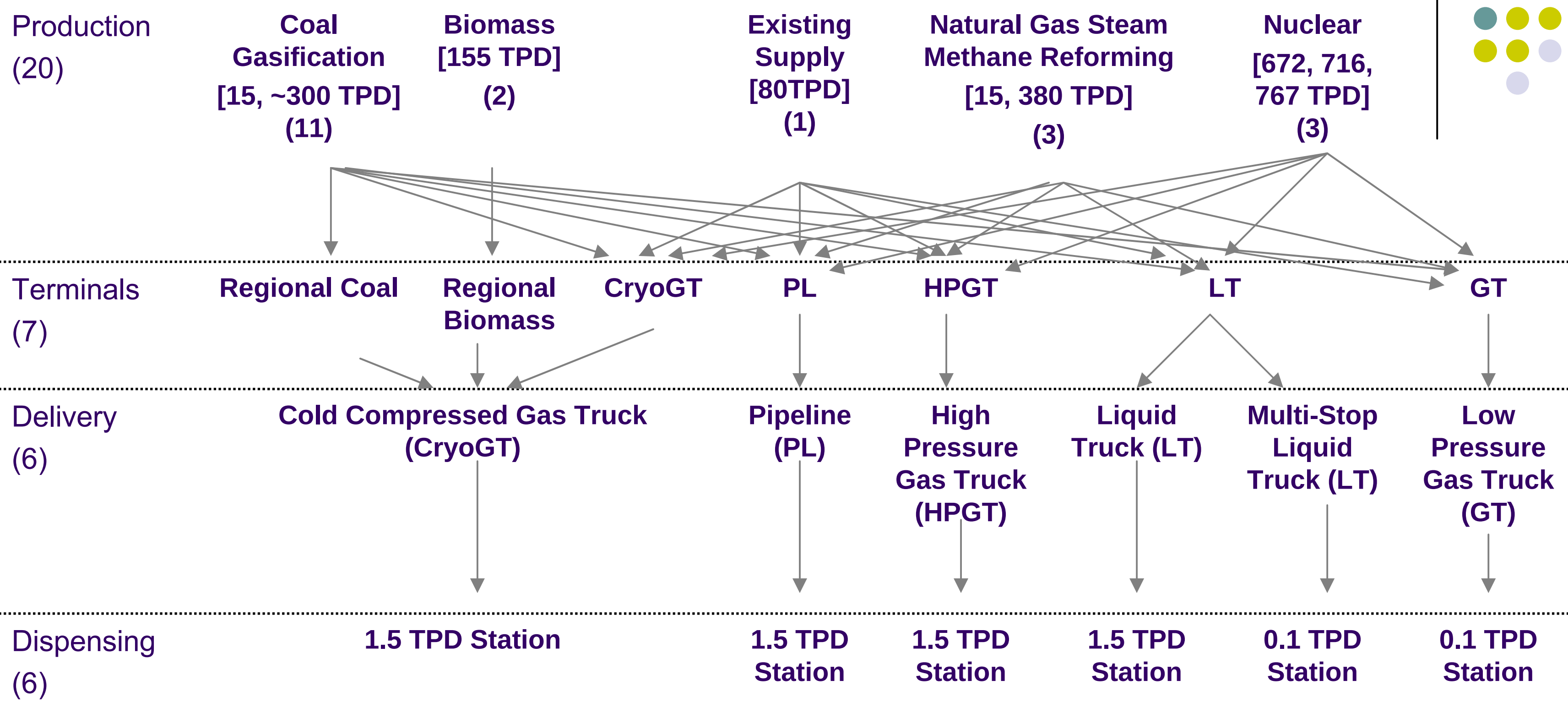
Objective Cost Function

Cost of Hydrogen [$/kg] at Pump =

Production cost + Terminal cost + Delivery cost + Dispensing cost + Other Costs

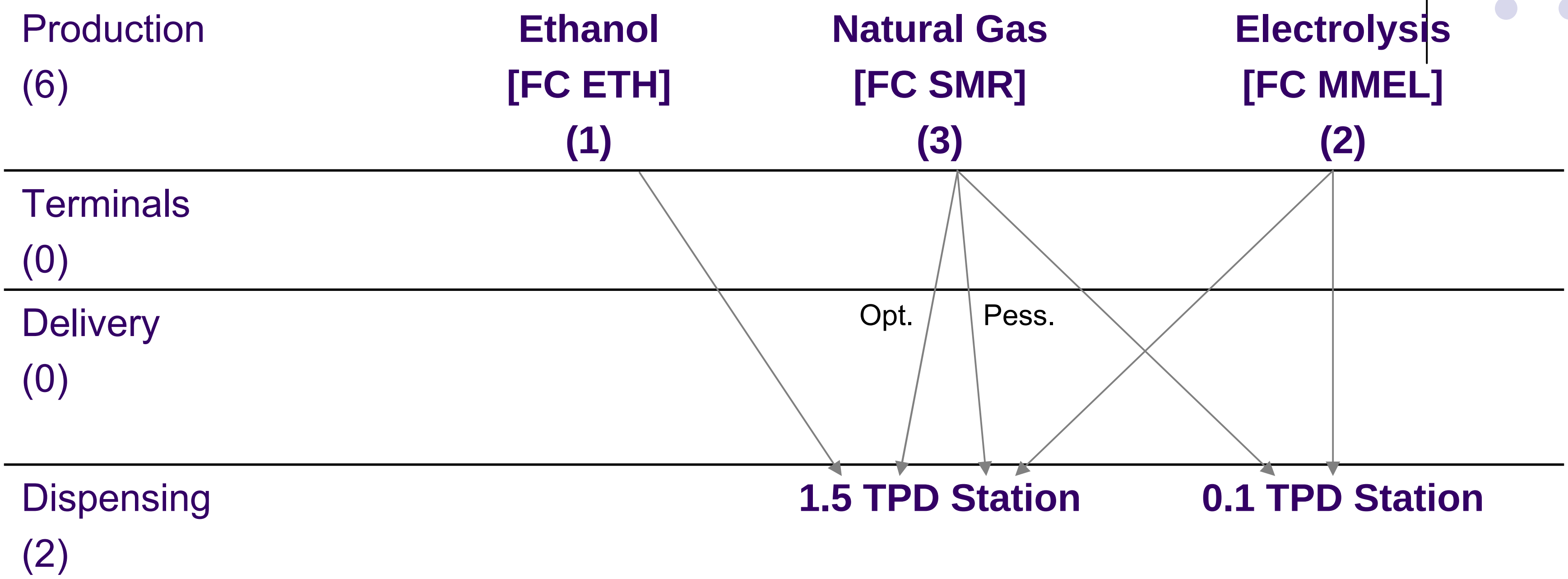
- **All component costs are determined by NPV calculations performed dynamically.**
- **Component costs include effects from;**
  - State of technology development,
  - Infrastructure capacity, and
  - Varying plant utilization
- ***Production*** **includes feedstock, capital, and O&M. Plants are point designs.**
- ***Terminals*** **are the transport staging area converting 300 psi H_2 to the appropriate pressure and state for transport.**
- ***Delivery*** **encompasses the various types of trucks and pipeline transport.**
- ***Dispensing*** **includes all the equipment needs at the station to convert delivered H_2 into the form accepted by vehicles.**
- ***Other costs*** **are credits and taxes which can be quantified in $/kg can applied to a specific segment or the complete infrastructure.**

Remote Production Pathways



- **Remote production refers to large production plants that require delivery to dispensing stations.**
- **Feedstock costs vary with plant location.**
- **Natural Gas and Coal plants are evaluated with and without Carbon Capture, Sequestration and Disposal (CCS&D).**

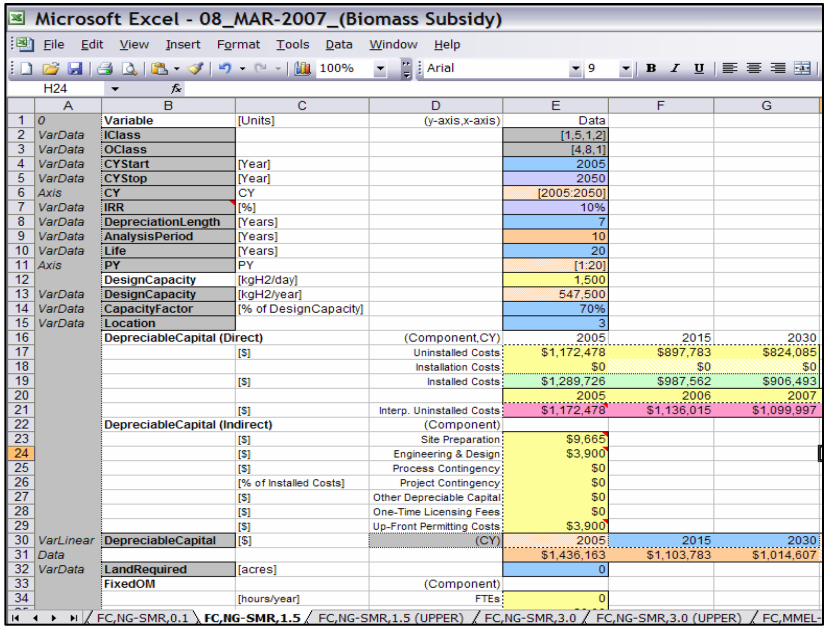
Distributed Production Pathways



- Distributed production refers to small production plants that include dispensing stations at the same location.
- Plants are located within the city, like gas stations.

Input Database

Design Philosophy: User modifies production/terminal/delivery/dispensing parameters in *Excel*, and *MatLab* code reads and extracts necessary data for calculations.



Microsoft Excel - 08_MAR-2007_(Biomass Subsidy)

	A	B	C	D	E	F	G
1	0	Variable	[Units]	(y-axis,x-axis)	Data		
2	VarData	IClass			[1,5,1,2]		
3	VarData	OClass			[4,8,1]		
4	VarData	CYStart	[Year]		2005		
5	VarData	CYStop	[Year]		2050		
6	Axis	CY	CY		[2005:2050]		
7	VarData	IRR	[%]		10%		
8	VarData	DepreciationLength	[Years]		7		
9	VarData	AnalysisPeriod	[Years]		10		
10	VarData	Life	[Years]		20		
11	Axis	PY	PY		[1:20]		
12		DesignCapacity	[kgH2/day]		1,500		
13	VarData	DesignCapacity	[kgH2/year]		547,500		
14	VarData	CapacityFactor	[% of DesignCapacity]		70%		
15	VarData	Location			3		
16		DepreciableCapital (Direct)		(Component,CY)	2005	2015	2030
17			[$]	Uninstalled Costs	$1,172,478	$897,783	$824,085
18				Installation Costs	$0	$0	$0
19			[$]	Installed Costs	$1,289,726	$987,562	$906,493
20					2005	2006	2007
21			[$]	Interp. Uninstalled Costs	$1,172,478	$1,136,015	$1,099,997
22		DepreciableCapital (Indirect)		(Component)			
23			[$]	Site Preparation	$9,665		
24			[$]	Engineering & Design	$3,900		
25			[$]	Process Contingency	$0		
26			[% of Installed Costs]	Project Contingency	$0		
27			[$]	Other Depreciable Capital	$0		
28			[$]	One-Time Licensing Fees	$0		
29			[$]	Up-Front Permitting Costs	$3,900		
30	VarLinear	DepreciableCapital	[$]	(CY)	2005	2015	2030
31	Data				$1,436,163	$1,103,783	$1,014,607
32	VarData	LandRequired	[acres]		0		
33		FixedOM		(Component)			
34			[hours/year]	FTEs	0		

FC,NG-SMR,0.1 / FC,NG-SMR,1.5 / FC,NG-SMR,1.5 (UPPER) / FC,NG-SMR,3.0 / FC,NG-SMR,3.0 (UPPER) / FC,MMEL-

Sentech contributed greatly to this research effort.

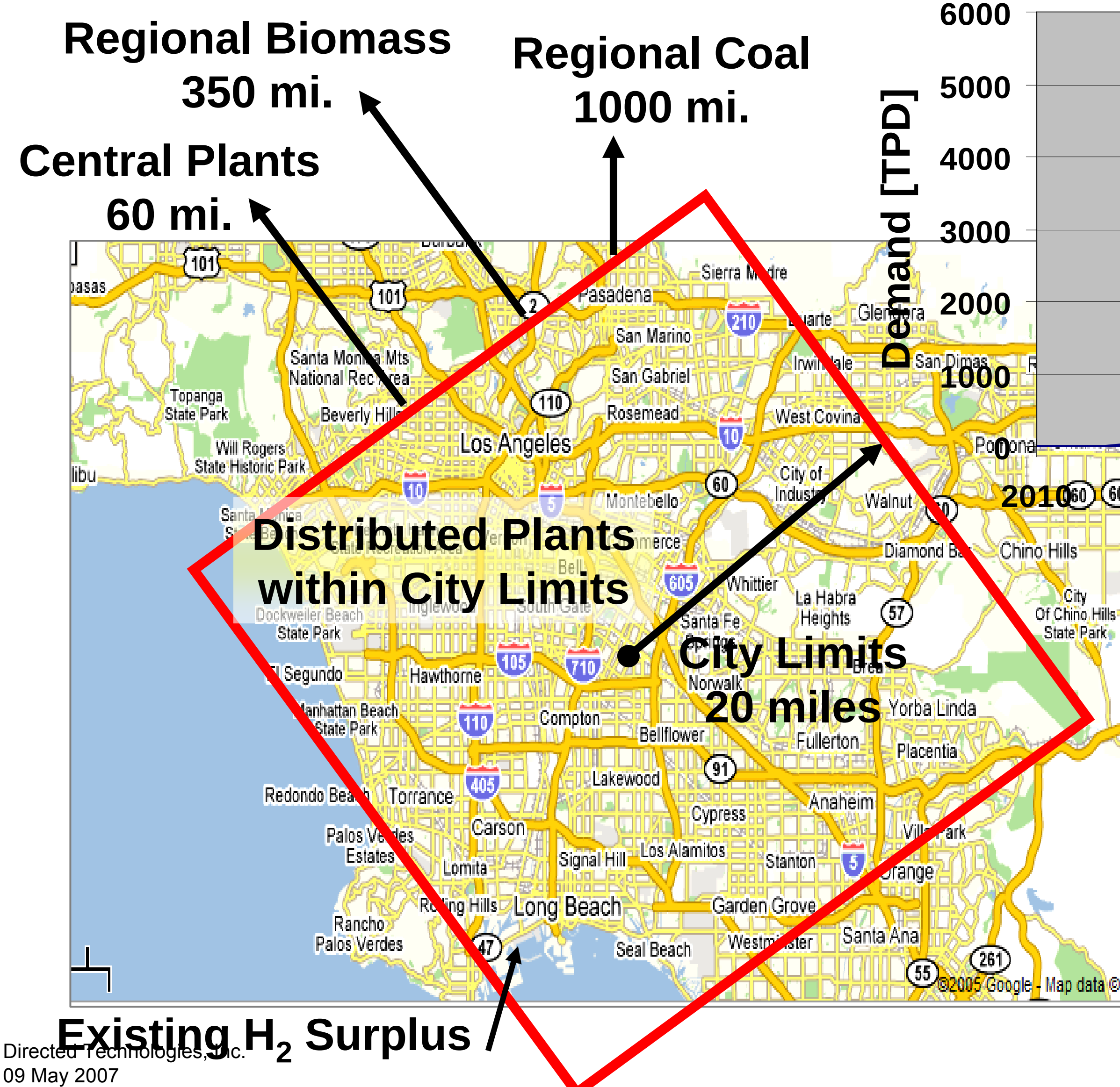
- **Excel database consists of a** Global **worksheet, a** City **worksheet,** Technology **worksheets, and any number of** Supplemental **worksheets (in that order)**
- Global **worksheet contains data relevant to all technologies in a given workbook (e.g. Feedstock Prices)**
- City **worksheets contain data relevant to demand and city geography (e.g. Central Plant Distance)**
- Technology **worksheets contain data relevant to a certain technology of the appropriate type (e.g. FC NG-SMR for the Production option)**
- **Each production, terminal, delivery, and dispensing method is on a separate** Technology **worksheet.**

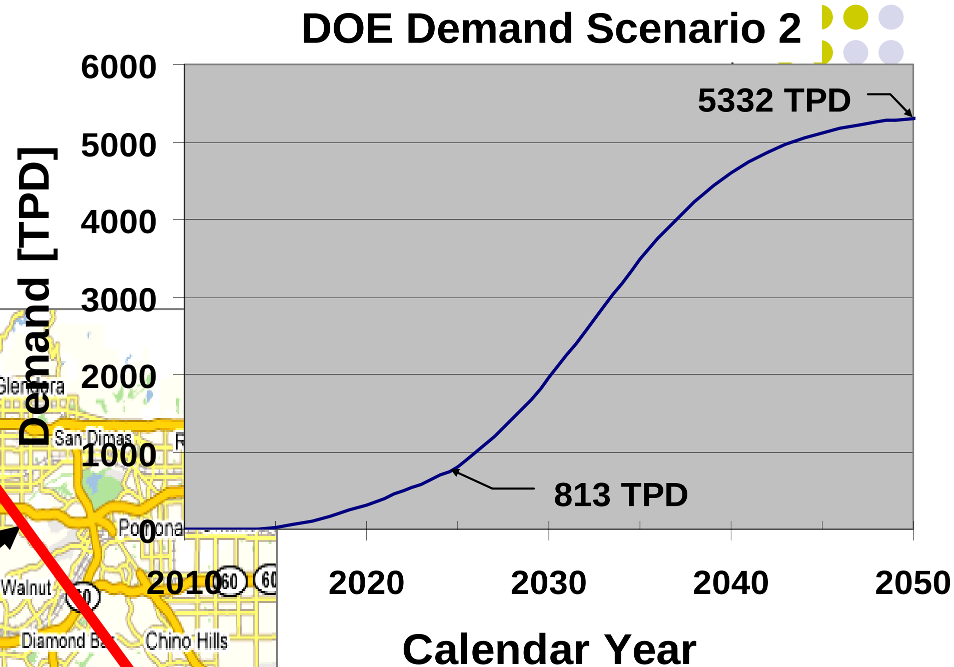
Results Summary

Baseline Scenario Parameters

- **City of Choice: Los Angeles**
- **DOE Demand Scenario 2 for LA**
  - Demand reaches 15% of maximum by 2025, maximum by 2050
- **Initially city must have 40 dispensing stations**
- **Vary utilization of pathways with increasing penetration**
- **Held feedstock prices constant at 2005 values**
- **Coal Production facilities must have CO_2 Sequestration**
- **Evaluate all pathways throughout the analysis period, 2012 - 2050**
- **Technology jumps in compression and storage occur in 2020**
- **Cold Compressed Gas Trucks [CryoGT] are available in 2020**
- **Pipelines [PL] are available in 2025**

Baseline Case





Area: 1668 mi^2
Population: ~12 Million
CA dictates Coal options to be sequestered.
Feedstocks at 2005 EIA prices.

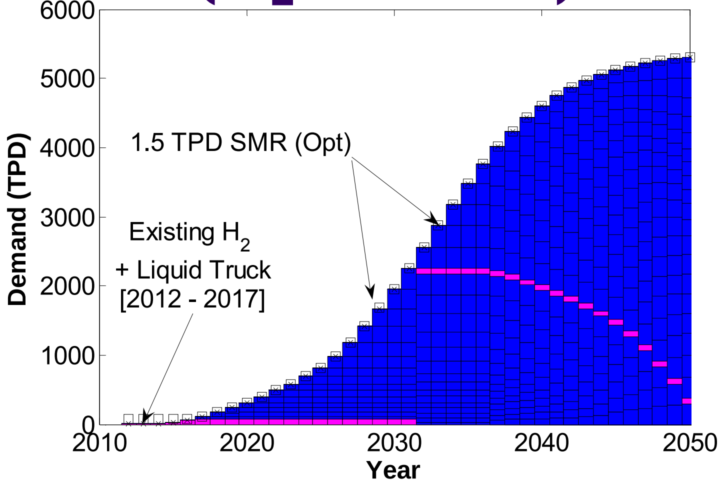
2005 Feedstock Prices

Feedstock	$/GJ	Unit Cost	Sites used
Commercial Natural Gas	**$8.78**	**$9.26/MMBtu**	**Distributed**
Industrial Natural Gas	**$6.27**	**$6.61/MMBtu**	**Remote Central**
Coal (Central)	**$1.22**	**$31.90/ton (metric)**	**Remote Central**
Coal (Regional)	**$0.78**	**$20.50/ton (metric)**	**Remote Regional**
Biomass	**$2.56**	**$40/ton**	**Regional**
Ethanol	**$13.27**	**$1.07/gal**	**Distributed**
Commercial Electricity	**$22.67**	**$0.082/kWh**	**Distributed**
Industrial Electricity	**$15.41**	**$0.056/kWh**	**Central**

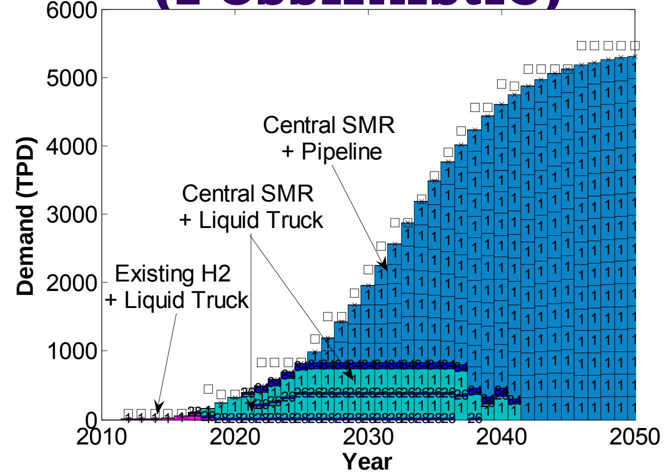
- **Baseline case is evaluated with constant feedstock price to more clearly visualize trends.**
- **Variable feedstock prices considered in a sensitivity analysis.**

Infrastructure Build out

Baseline 1.5 TPD SMR (Optimistic)



Build out assuming 1.5 TPD SMR (Pessimistic)



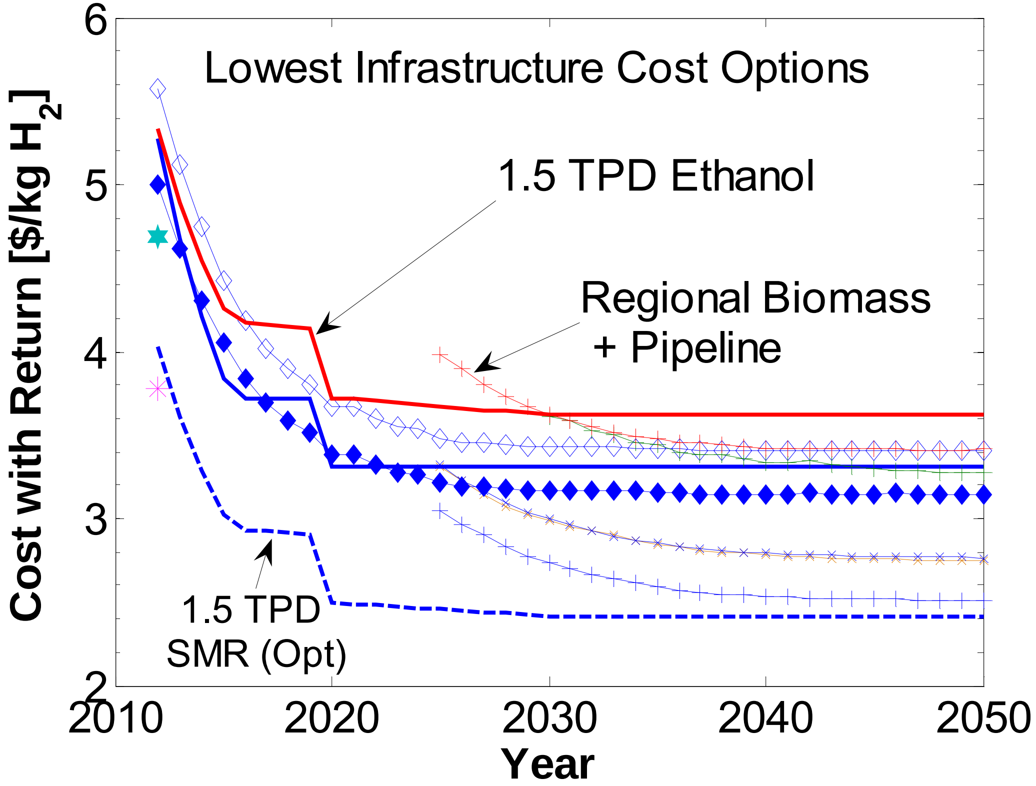
- **If Optimistic 1.5 TPD SMR is available it is the lowest cost option after 2017.**
- **If Pessimistic 1.5 TPD SMR exists the build out is:**

Existing H_2 (2012) → 1.5 TPD SMR (2017) →

Central SMR + Liquid Truck (2022) → Central SMR + Pipeline (2026)

In an unrestricted market, the cost of the 1.5 TPD Natural Gas SMR option will determine which infrastructure is built.

Lowest Cost Pathways



There are several central plant infrastructure alternatives if the 1.5 TPD SMR (Opt) is not feasible.

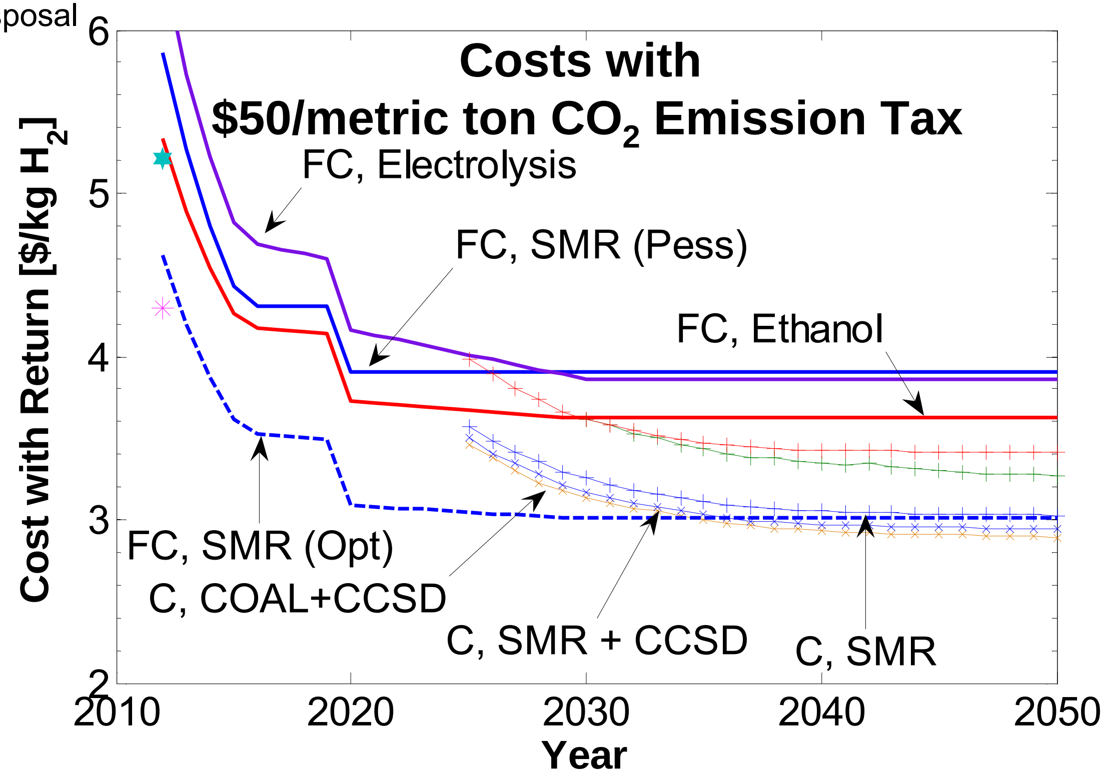
Sensitivities Evaluated

Parameters Explored	Baseline Value	Sensitivity	Comparison to Baseline Results
Distributed SMR Capital Cost	H2A Installation Costs (Opt)	~140% (Referred to as Pessimistic)	Shown on previous slide
Emissions Tax [$/ton CO_2]	$0	$10, $50, $100	See results
Sequestration & Renewable Mandates	None	Beginning in 2020, 2032, 2040	See results
DOE Transition Scenario 1	15% in 13 yrs	5.79% in 10 yrs	Build out unchanged
IRR	10%	20%	Build out unchanged
Variable Feedstock	EIA AEO Table (Constant 2005 Values)	EIA AEO Table	COAL with PL in 2043
Location of Biomass Plant	350 mi. from city limits	60 mi. from city limits	Baseline unchanged, (Cost of Bio+PL < Pessimistic 1.5 TPD SMR)
CA Regional Feedstock Pricing	EIA AEO Table (Constant 2005 Values)	NG: 80% EIA Coal: 86% EIA Elec: 150% EIA	Existing Capacity with LT > SMR (Opt) in 2012

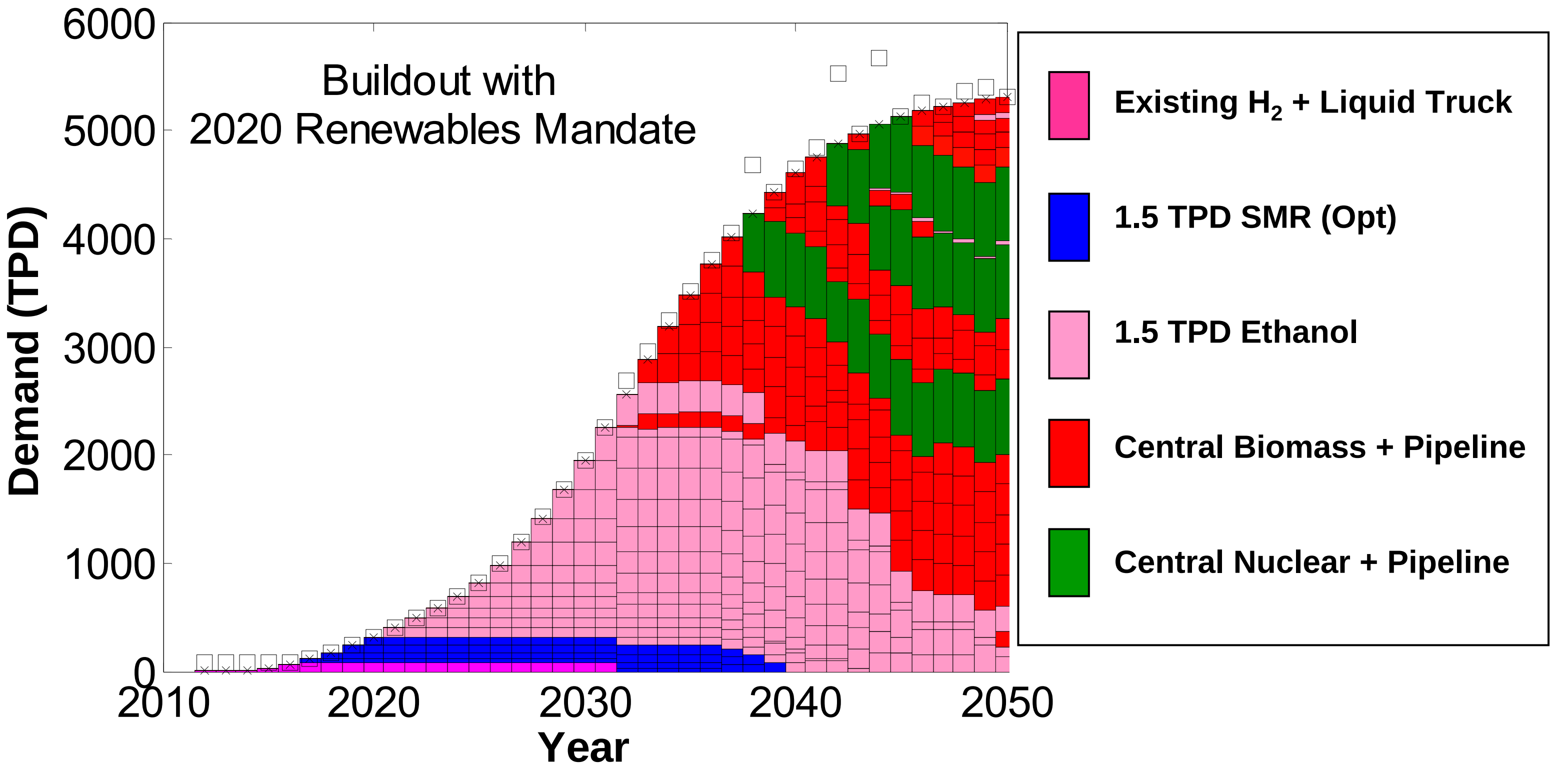
Impact of CCSD and CO_2 Emission Tax ($50/ton)

		w/o CCSD	w/ CCSD
CCSD Cost Adder [$/kg H_2]	Forecourt SMR		NA
	Central SMR		~$0.24
	Central Coal		~$0.43
Carbon Tax Cost Adder at $50/ton CO_2 [$/kg H_2]	Forecourt SMR	~$0.58	NA
	Central SMR	~$0.53	~$0.43
	Central Coal	~$1.38	~$0.60

CCSD = Carbon Capture, Sequestration and Disposal
$50/ton emission tax= $50 per metric ton of CO_2 released into atmosphere



2020 Renewables Mandate

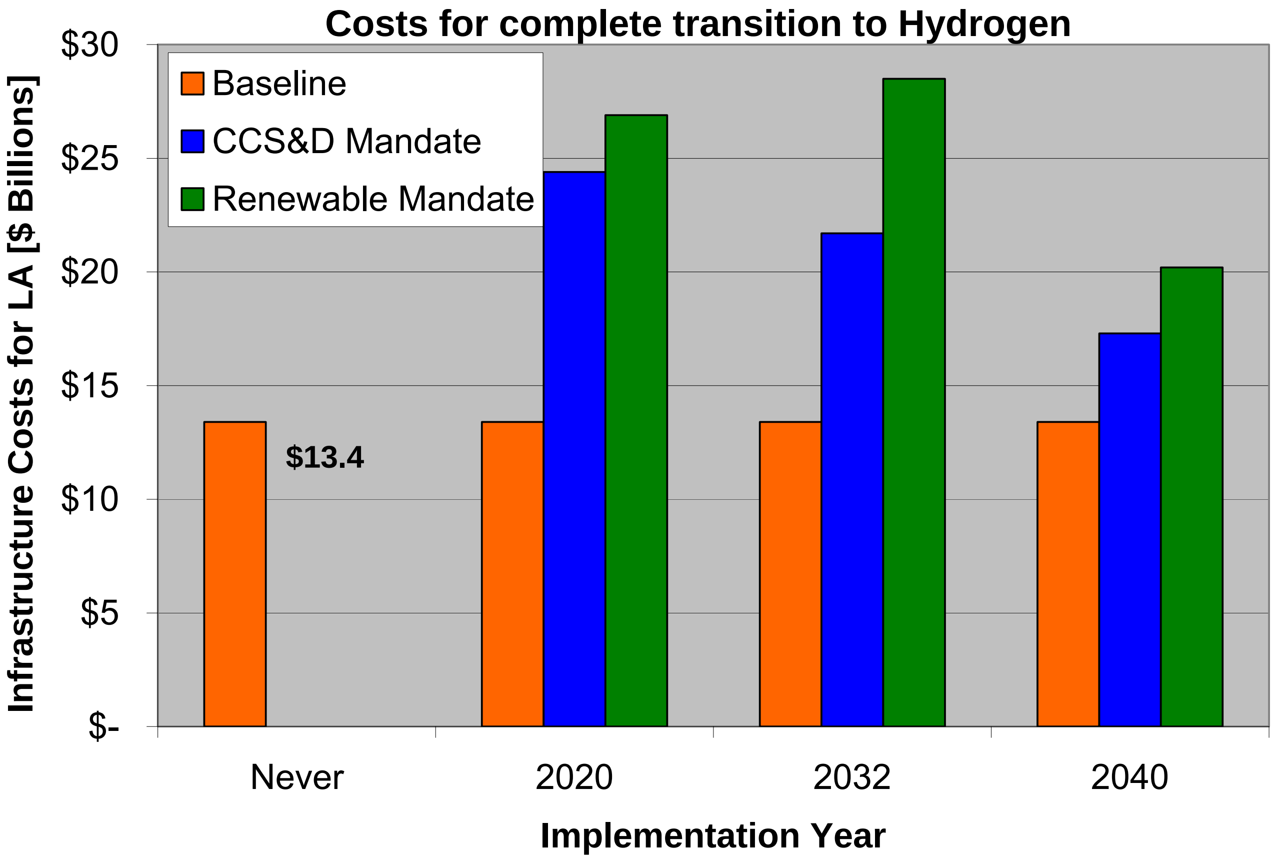


- **2020 Renewables Mandate:**

Existing + Liquid Truck → 1.5 TPD SMR (Opt) → 1.5 TPD Ethanol → Biomass + Pipeline → Nuclear + Pipeline

With a renewable mandate, Distributed Ethanol could play an interim role at low demands.

Los Angeles Infrastructure Costs

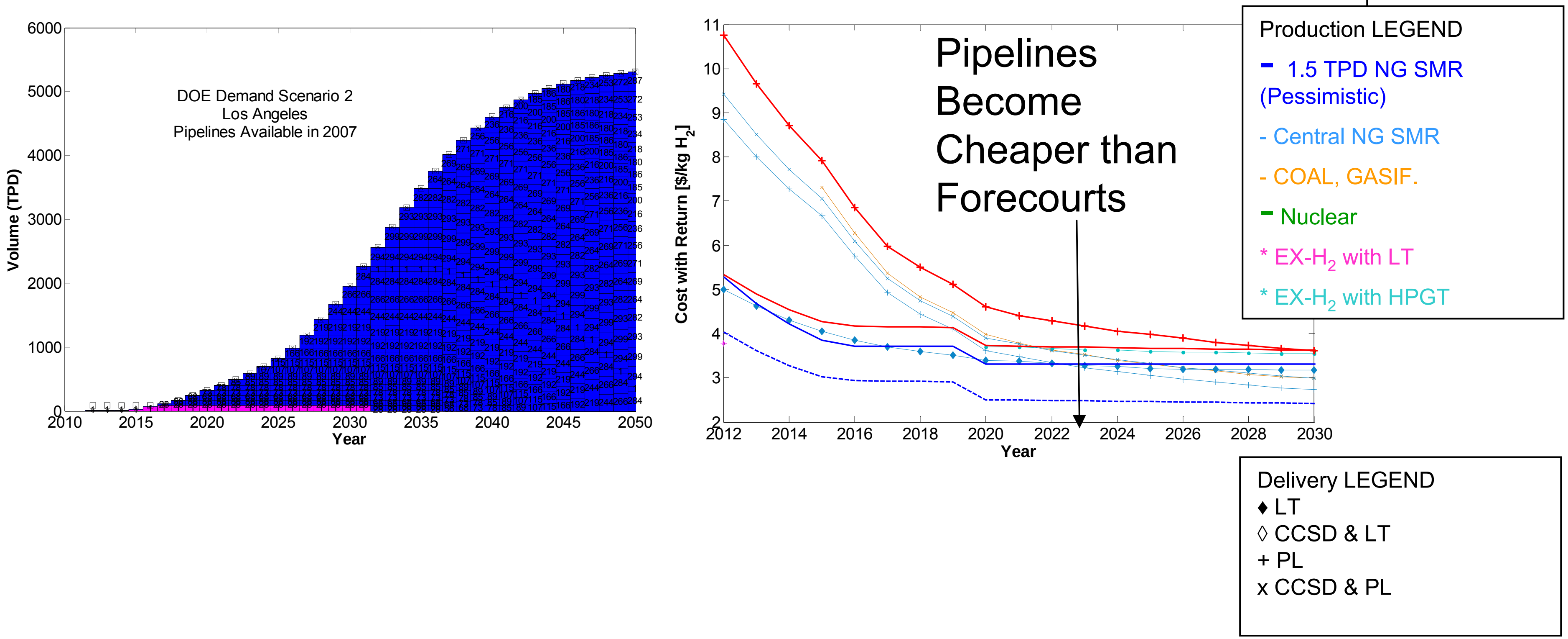


Mandates increase the total infrastructure cost.
Earlier implementation more costly than delayed mandates.

Assumptions Sensitivities

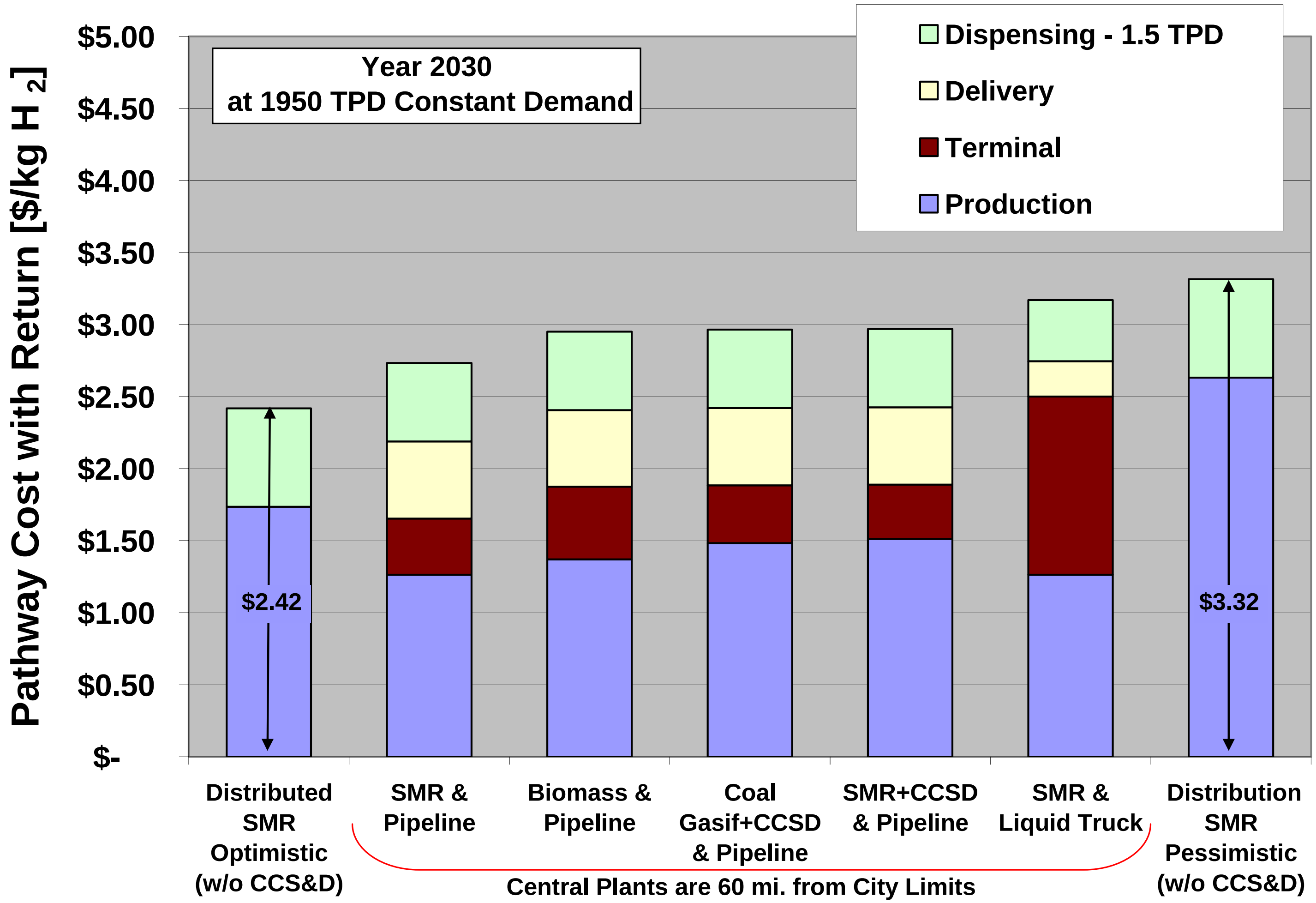
Assumption in Question	Baseline Value	Test Condition	Results
Entry date of Pipeline into market	2025	2005	Yearly demand increase insufficient for PL before 2023
Whether varying utilization affects results	DOE Demand Scenario 2	Constant demand of 1950 TPD	Ranking of options does vary with time
Dispensing Station size	1.5 TPD Max	3.0 TPD Max	Cost difference is negligible

Pipeline Market Entry



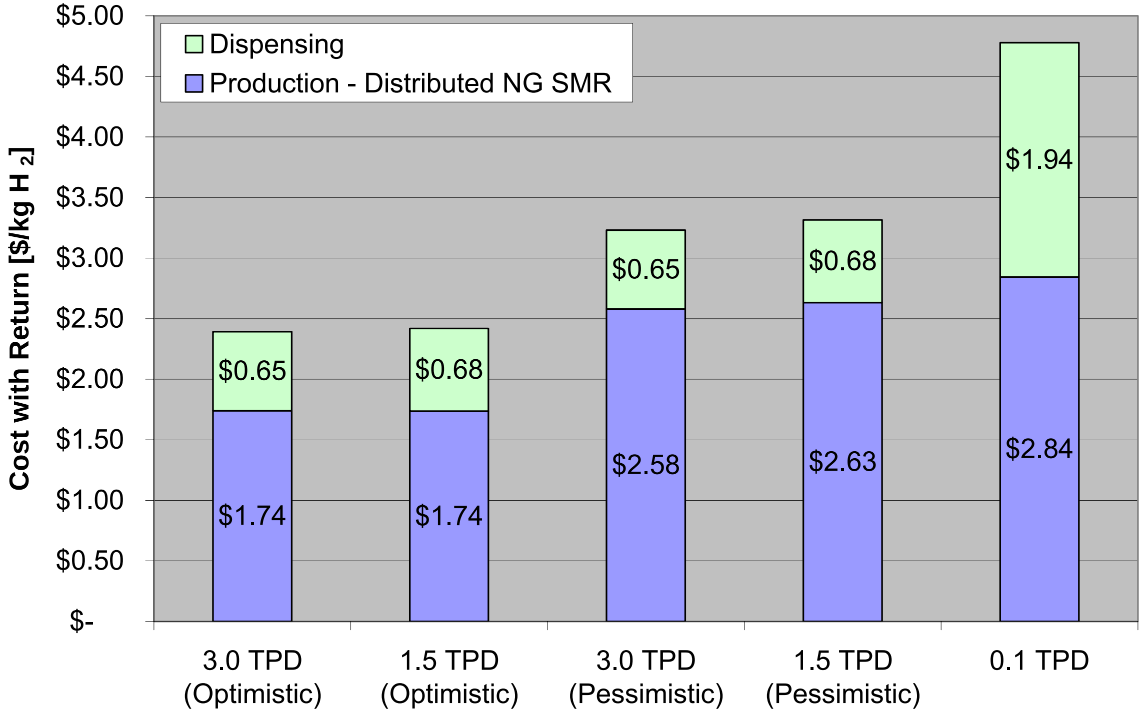
- **If Optimistic 1.5 TPD SMR is achievable it is the lowest cost option after 2017.**
- **The demand is not sufficiently high until 2023 for pipelines to be competitive with next lowest option, Pessimistic 1.5 TPD SMR**

Fully Utilized Remote Pathway Costs



Difference in cost projections for Distributed SMR means several options are competitive.

What about larger stations?

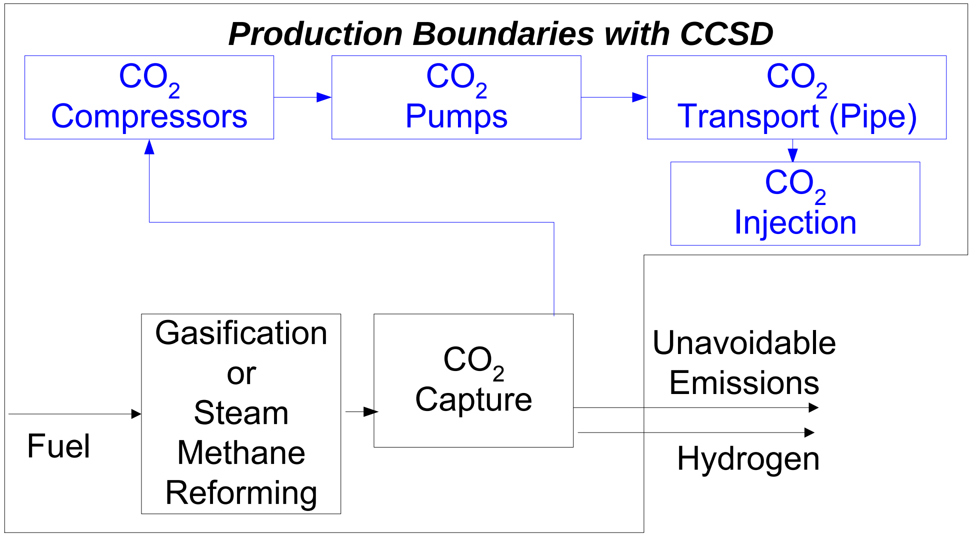


- **Costs of 1.5 TPD and 3.0 TPD are similar but with 1.5 TPD stations you get better coverage.**
- **Note, even fully utilized, 0.1 TPD dispensing and production are more costly alternatives.**

Cost and Methodology Assumptions

Production Database Features

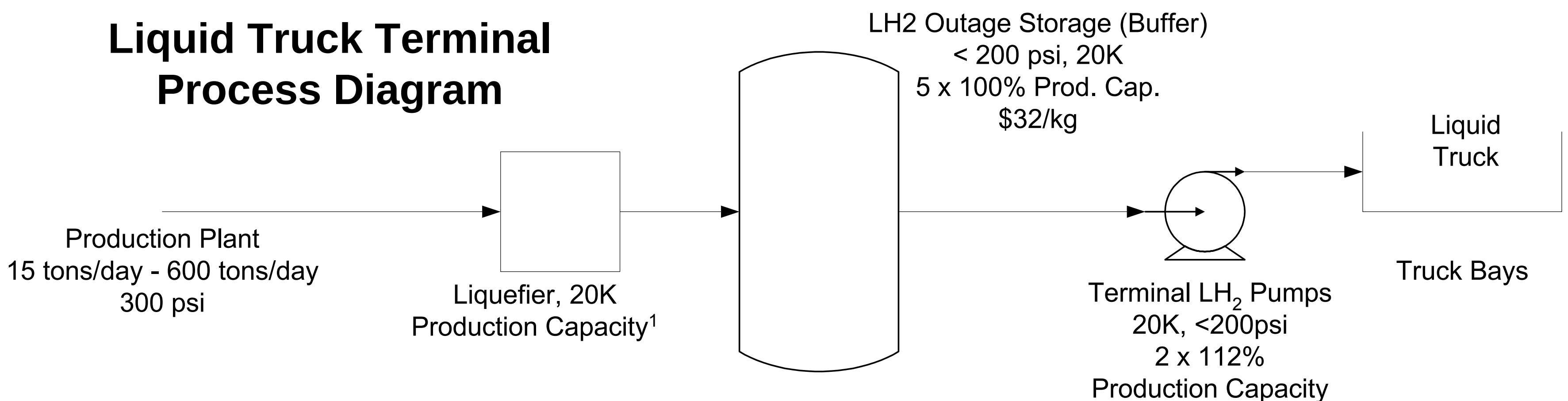
- **Forecourt ethanol option available**
- **Regional 2015 Coal Plant in Wyoming**
- **Located Biomass Plant at Regional rice fields**
- **CO2 system includes cost for Carbon Capture, Sequestration and Disposal**
  - 94 mile distance from remote plant to the sequestration site



Terminal Database & Methodology

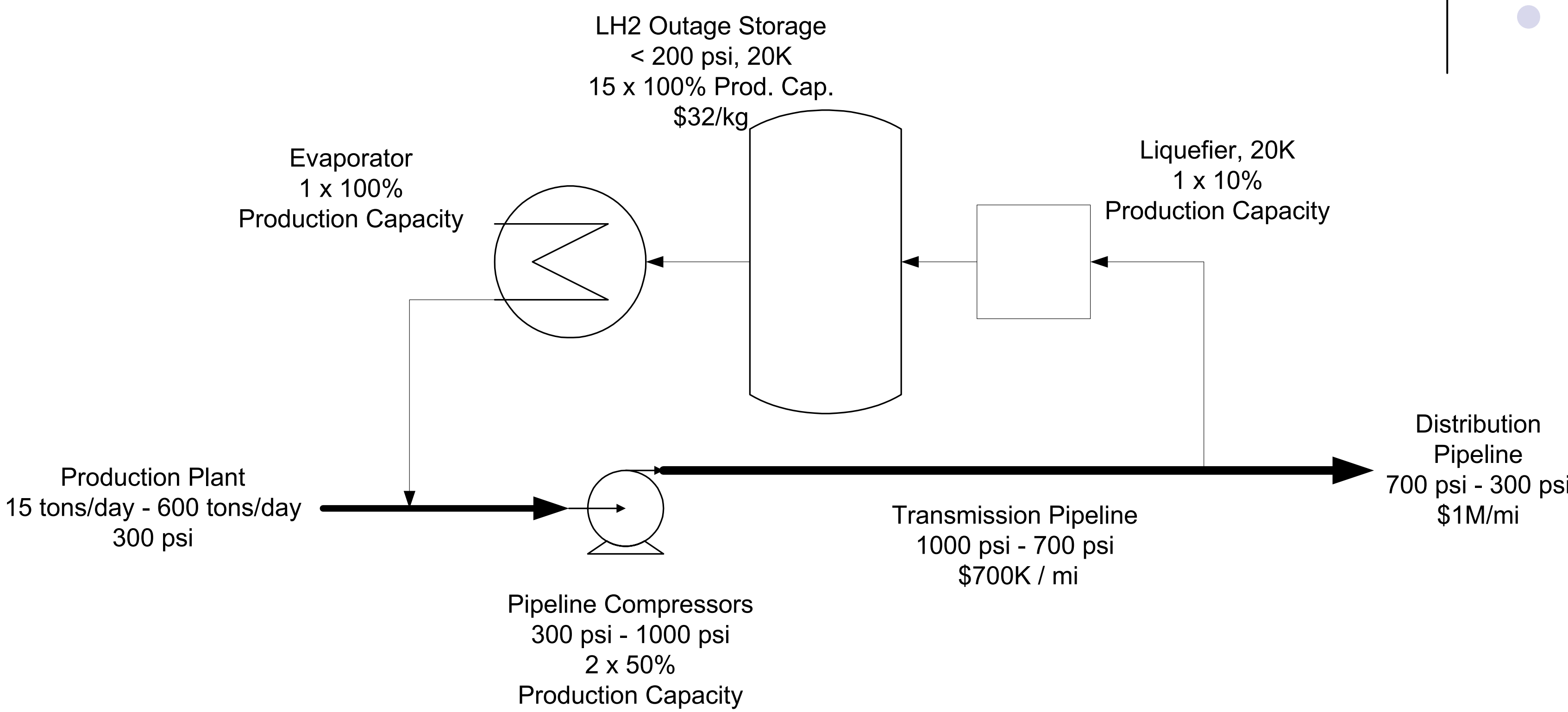
- **Geological storage is NOT modeled**
- **1 -to-1 ratio of terminal to remote plants**
- **Incorporated 5-days of bulk liquid H_2 storage & 10% scale Liquefier for outages**
- **Added terminals for mixed-mode delivery from regional plants**
- **Incorporated technology improvements in 2020**
- **Limited Liquefier size to 100 tpd and included learning effects**

Liquid Truck Terminal Process Diagram



[1] Trains vary by plant size. Liquefiers are limited to 100 TPD. For a 400 TPD Production plant then train is 4 x 25%.

Terminal Components for Pipeline Delivery



Gaseous Terminal for Pipeline

Terminal Parameters

- **Liquefier Power Consumption**
  - All years: varies of liquefier size
    - ~10kWh/kg H2 for 100tpd liquefier (full-scale liquefier for LH2 delivery)
    - ~16kWh/kg H2 for 8tpd liquefier (sub-scale liquefier for bulk storage)
- **Cryo Cooler (ambient temperature to 80K)**
  - Electricity [kWh/kg H2] is 40% of full liquefier
  - Capital cost is 50% of full liquefier
- **Pipeline & Storage Compressor Technology**
  - 2005: cost factor 1.3 (NG), 1 on standby, 80% Efficient (no standby for storage)
  - 2020: cost factor 0.8 (NG), no standby, 80% Efficient
- **Gaseous Storage Costs**
  - 2005: $818/kg (steel tanks)
  - 2020: $355/kg (composite tanks)
- **Pipelines**
  - 2020: Regional transmission lines ~$700K/mi matches DOT report guidelines
  - 2025: Urban distribution lines $1M/mi slightly higher than DOT report guidelines

Delivery Database & Methodology

- **Incorporated H2A component model costs for DCF analysis in HyPro (allows for varying utilization over lifetime)**
- **Similar rules to HDSAM**
  - No Pipeline to small dispensing stations
  - Liquid truck stops at 3 small stations or 1 large station
- **Distance Calculations**
  - Average Manhattan Distance
  - Modified Min Spanning Tree algorithm for Pipeline
- **Added Cryogenic H_2 trucks option for large dispensing station**

Delivery Options

Low Pressure Gas Truck
2,700 psi, 25 ^oC
280 kg H_2

Liquid Gas Truck
<200 psi, 20 Kelvin
4,153 kg H_2, 1 stop
(for 1.5 tpd disp. station)

High Pressure Gas Truck
7,000 psi, 25 ^oC
657 kg H_2

Liquid Gas Truck
<200 psi, 20 Kelvin
4,153 kg H_2, 3 stops
(for 0.1 tpd disp. station)

Cryo Gas Truck
2,000 psi, 80 Kelvin
2,100 kg H_2
Available in 2020

Not Optimized

Pipeline
700 - 300 psi, 25 ^oC
Available in 2025

Delivery Parameters

- **Drivers**
  - Delivery hours decreased to 12 hrs/day
  - Hourly loaded wage raised to $40/hr
- **Trailer Costs**
  - Tractor: $75K, down from $100K
  - LPGT: $225K, up from $165K
  - CryoGT: $745K
  - HPGT: $350K
- **Pipeline**
  - Costs comparable to guidelines
  - Length of pipeline determined by Minimum Spanning Tree method

2002 EEA Report to NETL Morgantown

Cost of Steel Gas Distribution Pipe (8+ Inches)

	$/Foot-Inch	8 Inch ($/Ft)	12 Inch ($/Ft)	16 Inch ($/Ft)	20 Inch ($/Ft)
Rural	$7.40	$59	$89	$118	$148
Suburban	$8.70	$70	$104	$139	$174
Urban	$15.60	$125	$187	$250	$312
Downtown	$50.00	$400	$600	$800	$1,000

Cost of Plastic Gas Distribution Pipe

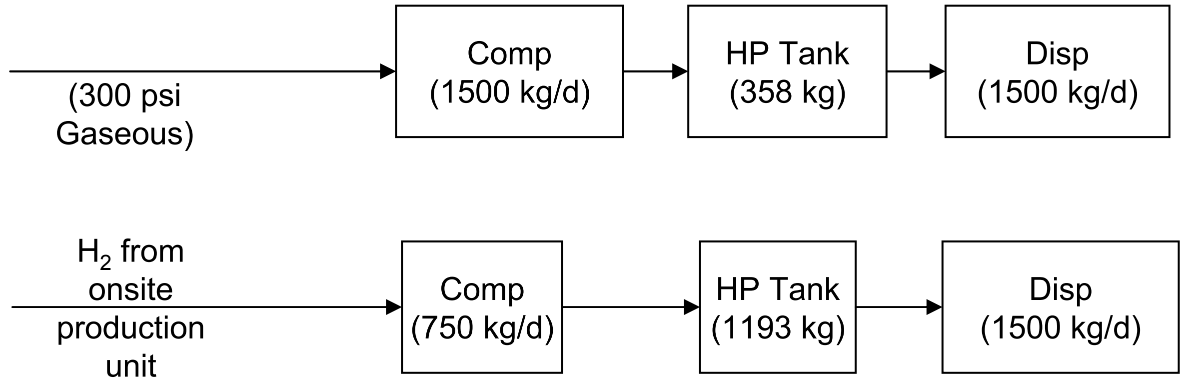
	Fixed $/Foot	$/Foot-Inch	2 Inch ($/Ft)	4 Inch ($/Ft)	6 Inch ($/Ft)	8 Inch ($/Ft)
Rural	$6.80	$1.70	$10	$14	$17	$20
Suburban	$8.00	$2.00	$12	$16	$20	$24
Urban	$14.40	$3.60	$22	$29	$36	$43
Downtown	$85.00	$20.00	$125	$165	$205	$245

Dispensing Database & Methodology

- **Incorporated H2A component model costs for DCF analysis in HyPro (allows for varying utilization over lifetime)**
- **Sized storage & compressors appropriately to interface with the delivery means**
- **Incorporated technology improvements in 2020**

Pipeline Station

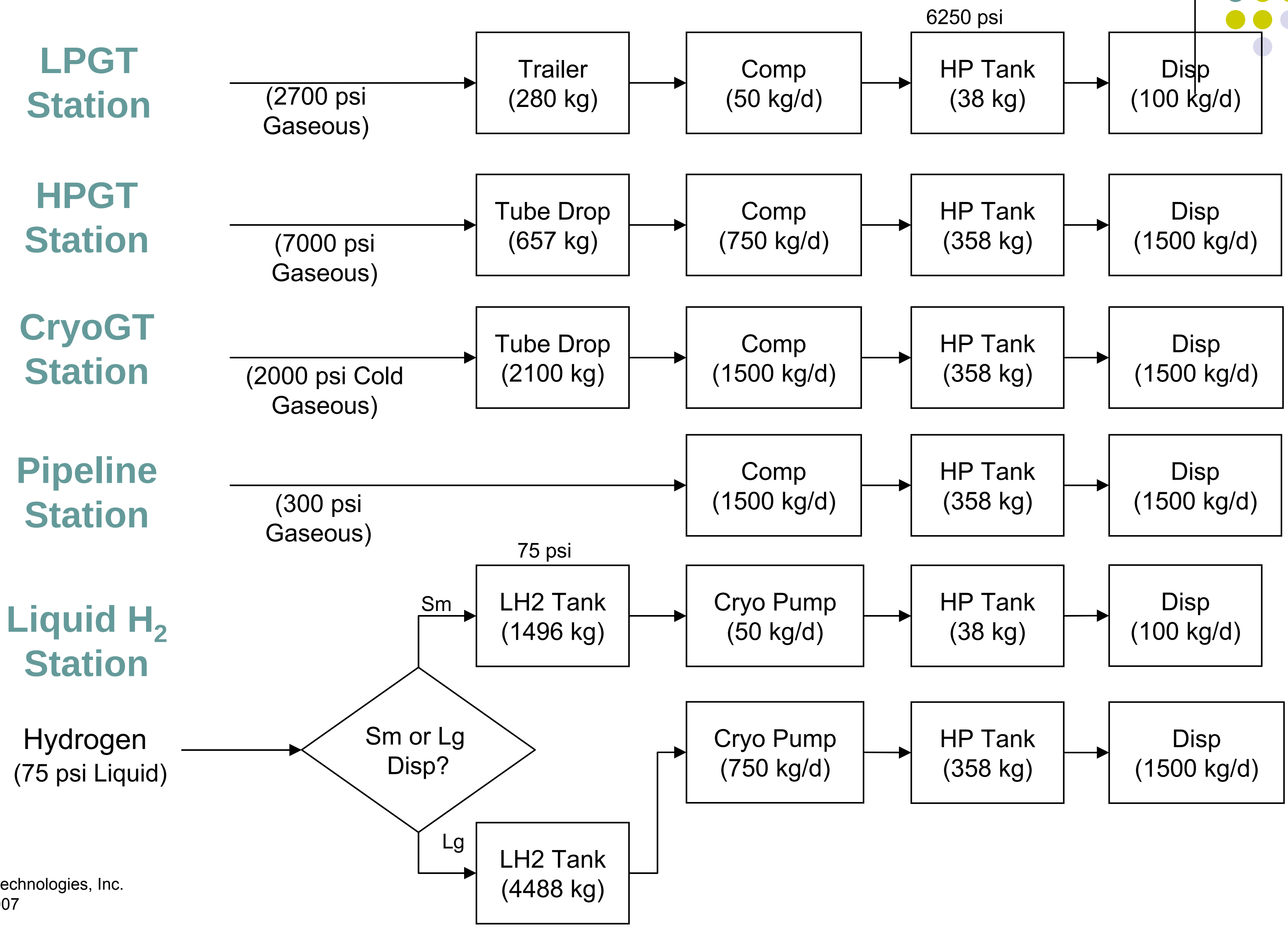
1.5 tpd Forecourt Station



Dispensing Parameters

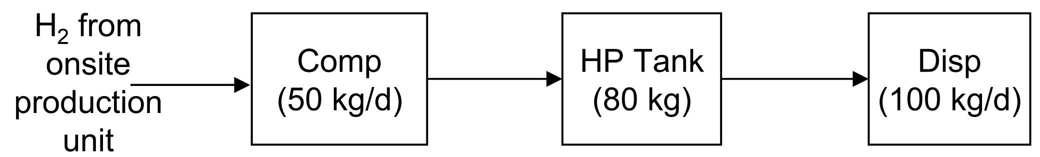
- **HP Storage**
  - 2005: $818/kg (steel tanks)
  - 2020: $355/kg (composite tanks)
- **Compressors**
  - 2005: 65% Efficient, 3 x 50%, 1 on standby,
  - 2005: $6300/kg/hr for 50 kg/d & $4580/kg/hr for 750 kg/d
  - 2020: 80% Efficient, 1 x 100%, no standby
  - 2020: $4100/kg/hr for 50 kg/d size & $3000/kg/hr for 750 kg/d
- **Dispensers**
  - 2005: 5,000 psi
  - 2020: 10,000 psi (assumes no cost impact)
- **Maintenance & Repair**
  - 2005: 1.8%/year of initial capital cost
  - 2020: 1.5%/year of initial capital cost
- **Initial Station Penetration set at 1% (40 stations for LA)**

Dispensing Options



Dispensing Options (cont.)

“Small” (0.1 tpd) Forecourt Station



“Large” (1.5 tpd) Forecourt Station