DOE Hydrogen Program

Hydrogen Pathway Analysis using HyPro

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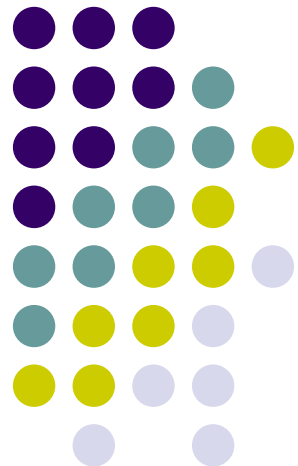
Directed Technologies, Inc.
17 May 2007



Project ID #
AN1

Overview

Timeline

- Start: ~May 2005
- End: September 2007
- 77% complete

Budget

- Total project funding: $750,000
- FY05: $110,000
- FY06: $350,000
- FY07: $290,000

Barriers

- Lack of understanding of the transition of a hydrocarbon-based economy to a hydrogen-based economy.
- Lack of prioritized list of analyses for appropriate and timely recommendations.
- Stove-piped/Siloed Analytical Capabilities.

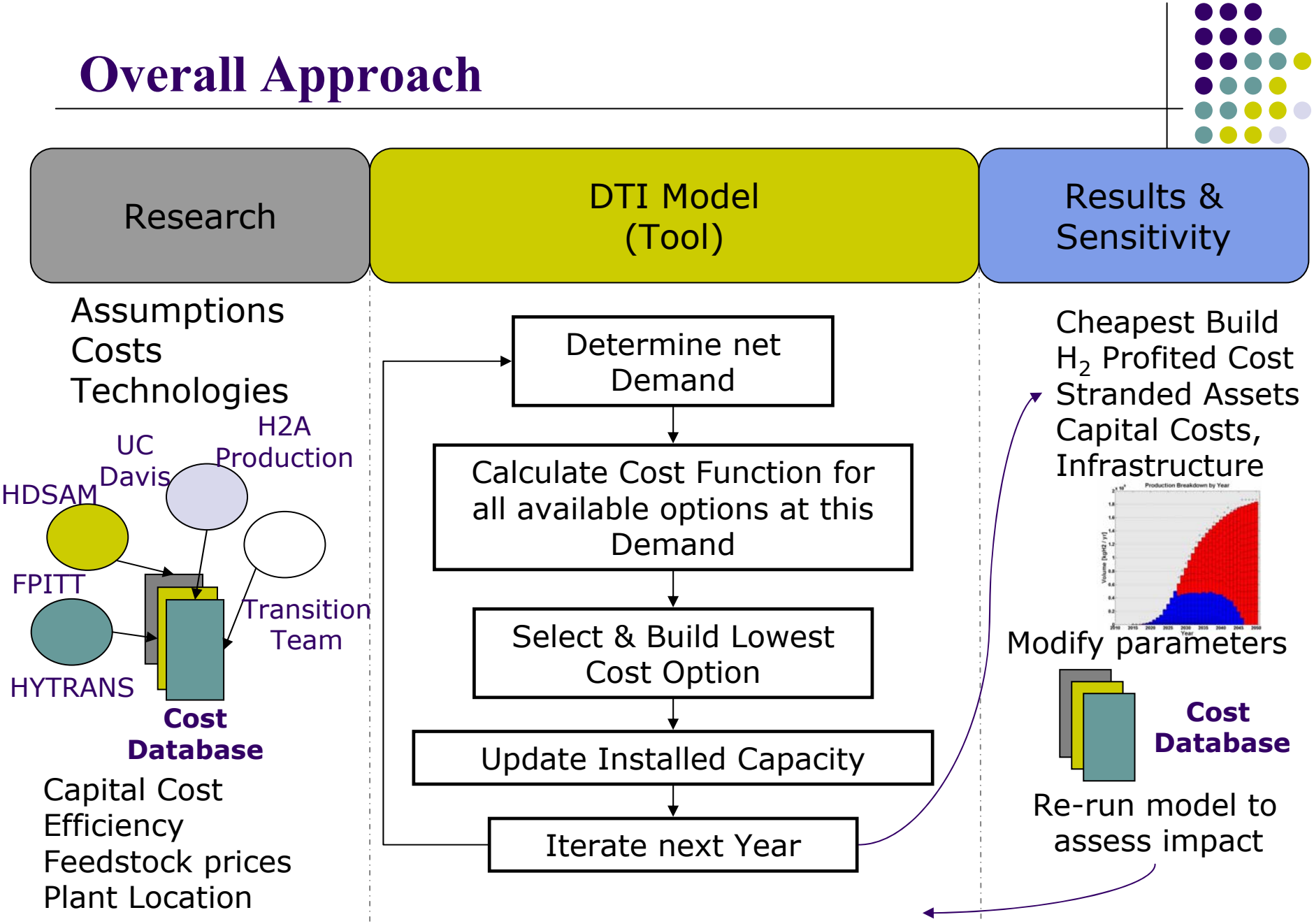
Partners

- Sentech, Inc.
- Advisory Board:
  - H_2Gen Innovations
  - ChevronTexaco
  - Teledyne Energy Services
  - Air Products
  - Sentech, Inc.

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



Key Analysis Assumptions

- **Yearly hydrogen demand is entered by the user**
- **Model evaluates regions (e.g. cities) as opposed to the whole nation**
- **Build decisions made with perfect foresight**
- **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**

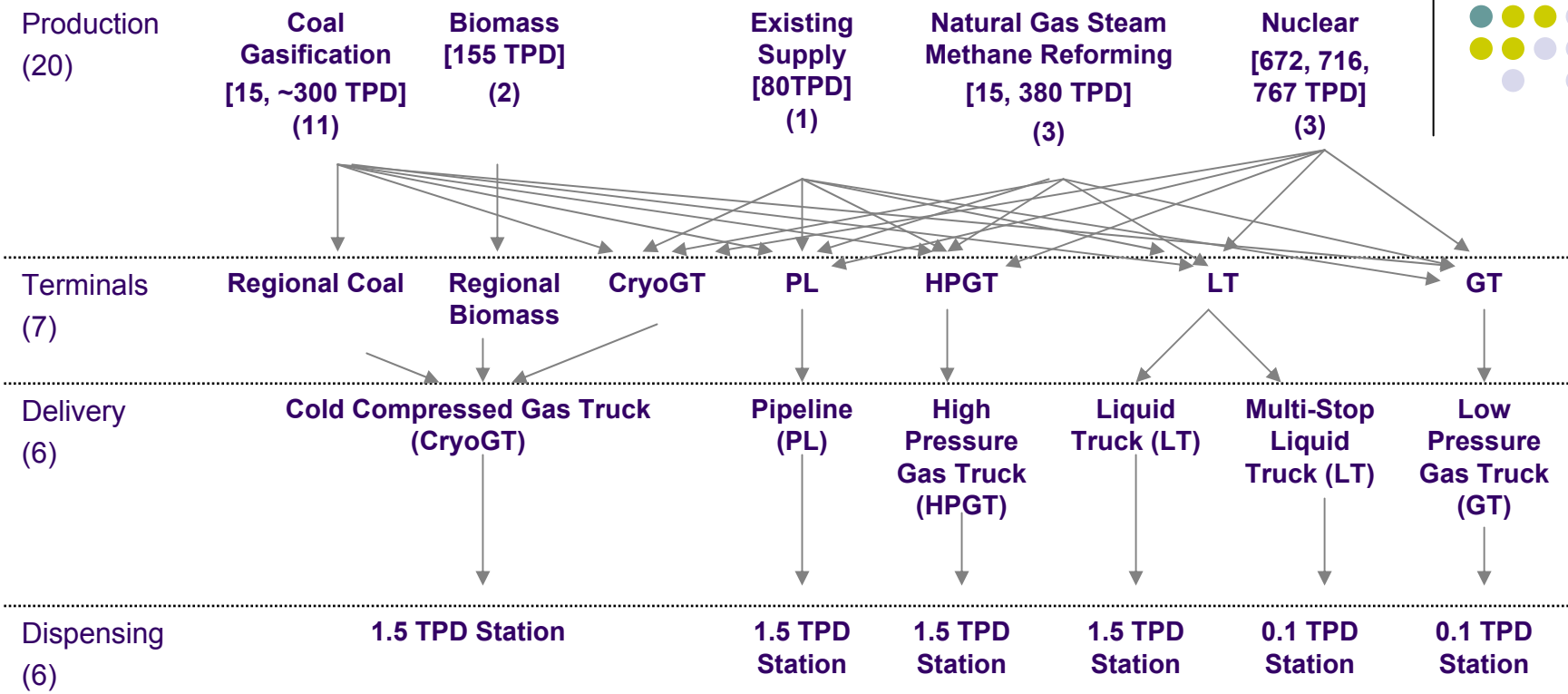
Objective Cost Function

Cost of Hydrogen [$/kg] at Pump =

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

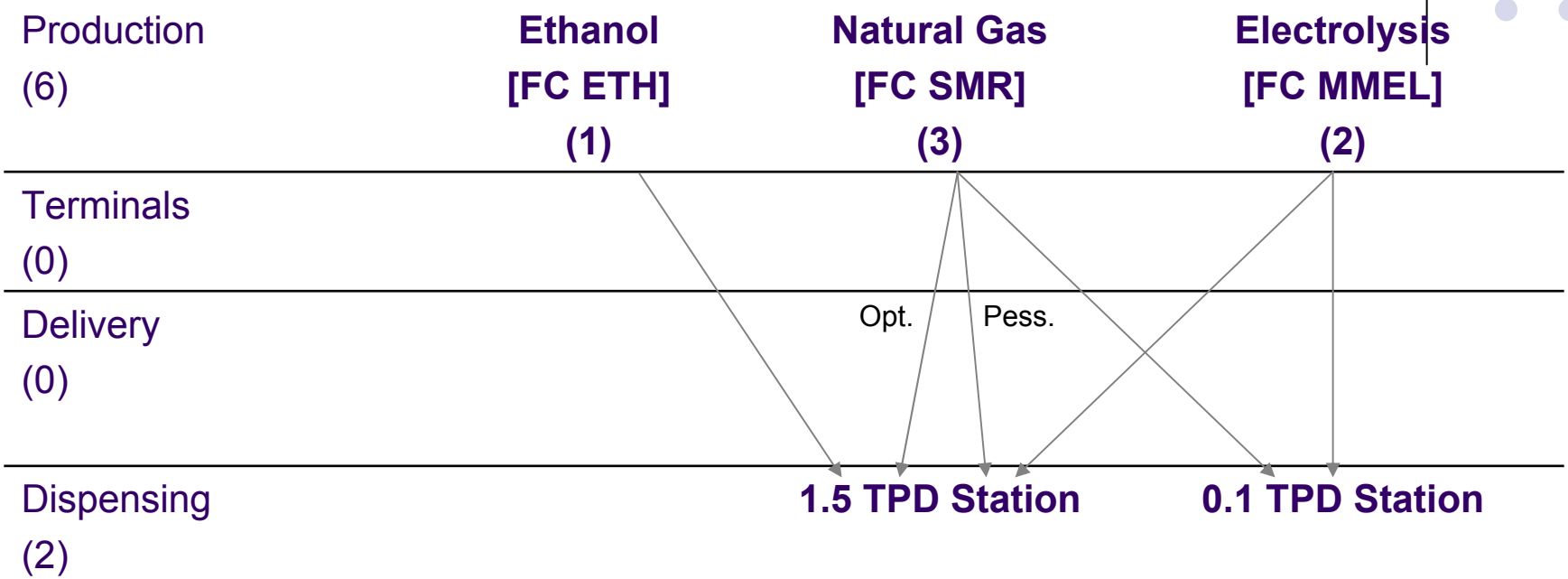
- **All component costs are determined by NPV calculations performed dynamically.**
- **Component costs include effects from;**
  - State of technology development,
  - Infrastructure capacity, and
  - Varying plant utilization
- ***Production*** **includes feedstock, capital, and O&M.**
- ***Terminals*** **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.**

Database Refinements

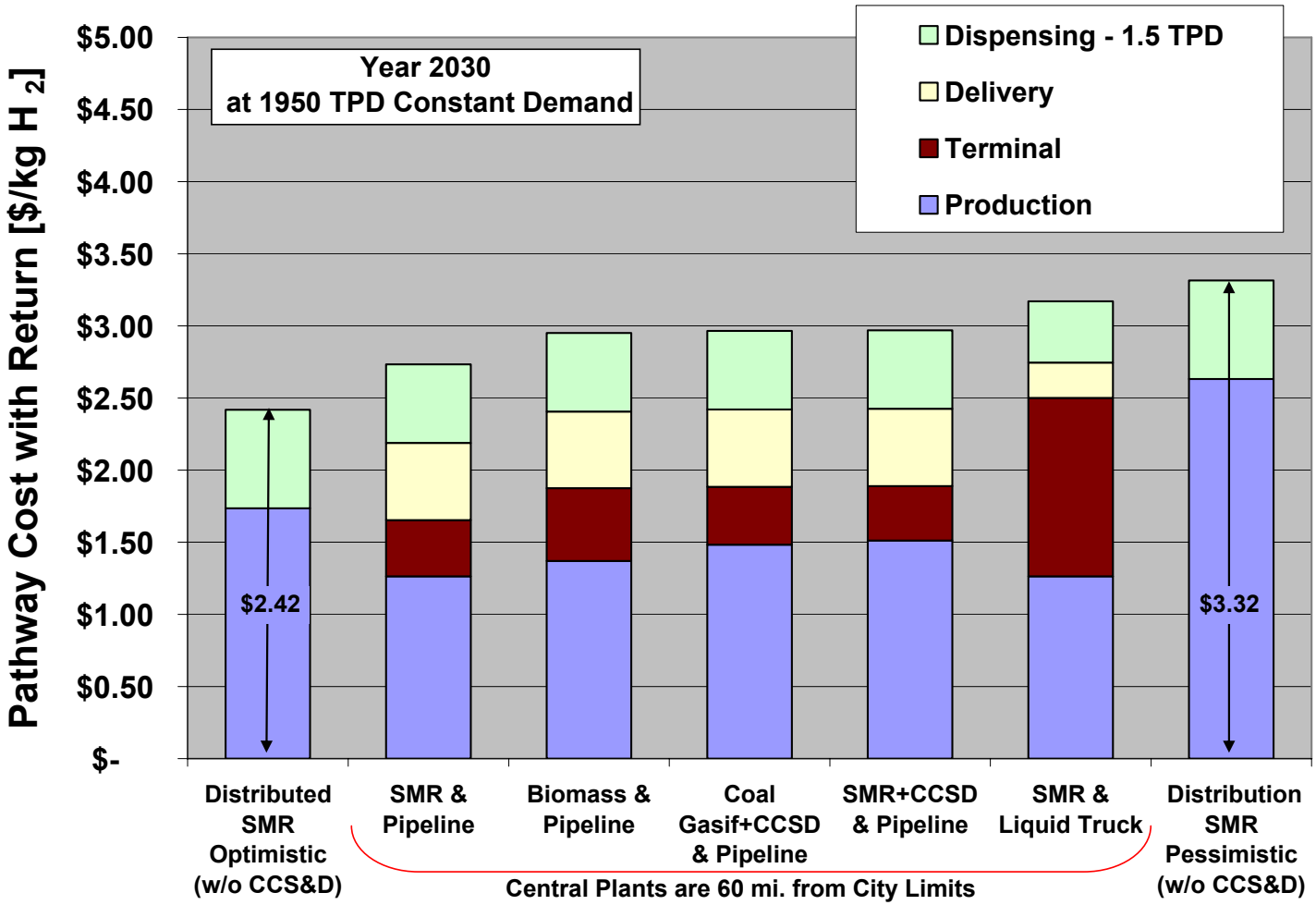
- **Production**
  - Added FC Ethanol
  - Added Regional 2015 Coal Plant in Wyoming
  - Located Biomass Plant at Regional rice fields
  - Increased scope of Carbon Capture, Sequestration and Disposal Costs
- **Terminal**
  - 1 to 1 ratio of terminal to remote plants
  - Incorporated 5-days of bulk H_2 storage & 10% Liquefier for outages
  - Added terminals for mixed-mode delivery from regional plants
- **Delivery**
  - Introduce component costs for DCF analysis
  - Eliminated Pipeline to small distributed dispensing station
  - Added Cryogenic H_2 trucks option for large dispensing station
- **Dispensing**
  - Introduce component costs for DCF analysis
  - Match storage & compressors to delivery method
  - Incorporated technology improvements in 2020

Process flow diagrams were developed for infrastructure options and the appropriate size and cost was attributed to each component in a particular pathway.

Model Improvements

Feature	H_2Sim 1.0 "Old"	HyPro "New"
Pathways in Each Year	One pathway built each year	Multiple pathways allowed each year
Delivery Evolution	Delivery method is fixed to production plant	Prod. plant can change delivery methods (e.g. Central plant that trucks H_2 initially, then switches to pipeline)
Stranding	Entire pathways	Strands individual portions (e.g. Prod., Term., Del., Disp.)
Dispensing Stations Build-Out	Disp. stations capacity = Prod. Capacity, all built in same year	Dispensing stations built as required by demand
Delivery & Dispensing Cost Algorithm	Lookup tables of H2A data	Discounted Cash Flow
Pipelines	Optimized Ring Structure used in HDSAM (Rev. 22 Apr 06)	Minimum Spanning Tree Approach as suggested by UC Davis
Trucking Distances	Lookup tables populated with city-specific H2A data	Average Manhattan Distance for inner city travel distances
CO_2 Emissions (for CO_2 tax)	None	Included
Carbon Capture and Sequestration (CCSD)	H2A Costs (Capture Only)	Detailed Model based on UC Davis Studies

Fully Utilized Remote Pathway Costs

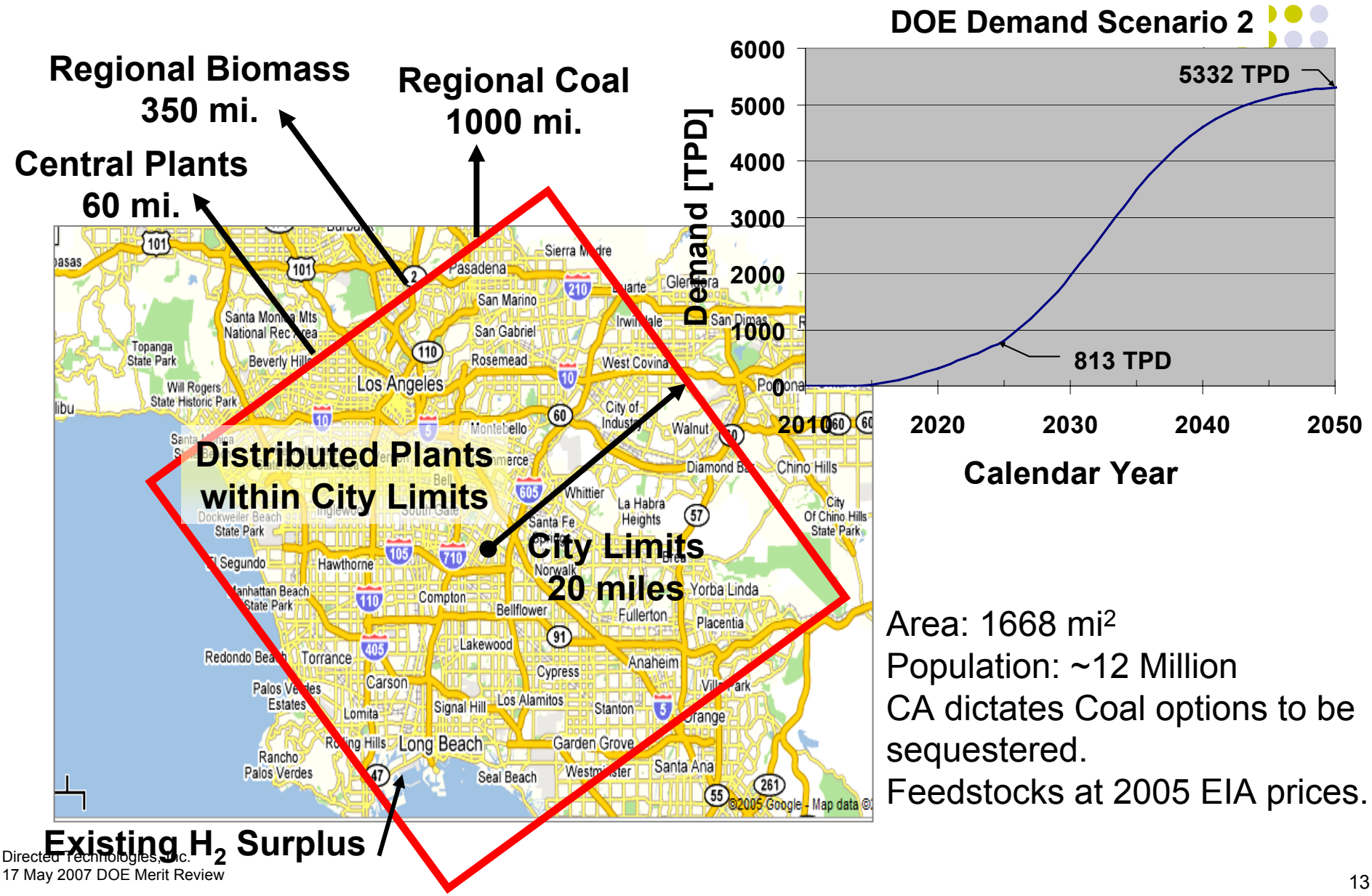


Difference in cost projections for Distributed SMR means several options are competitive.

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**

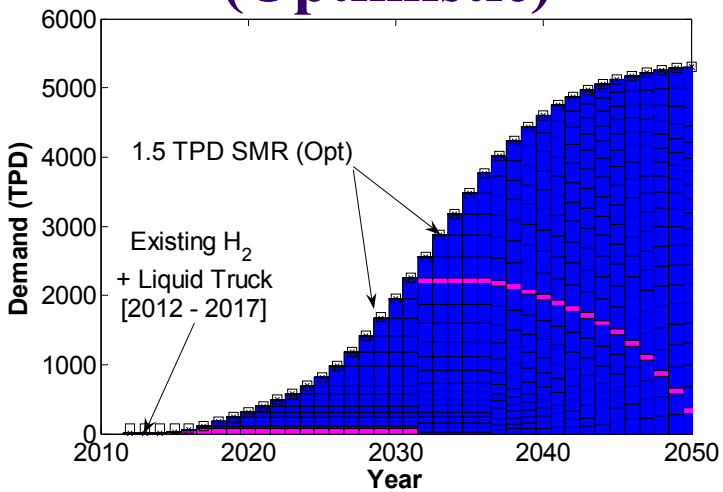
Baseline Case



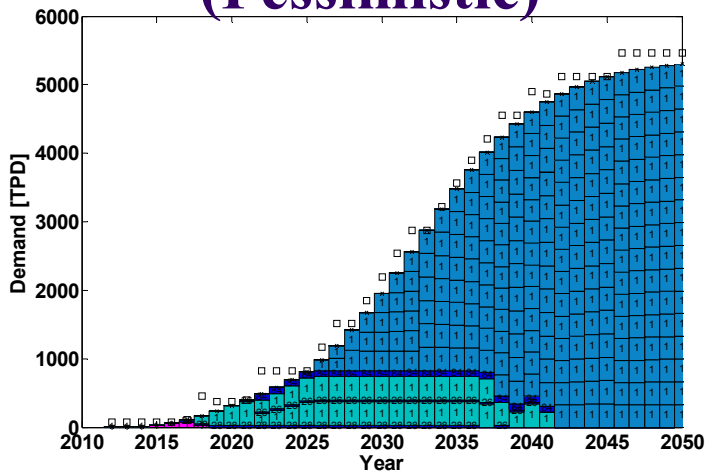
Area: 1668 mi^2
Population: ~12 Million
CA dictates Coal options to be sequestered.
Feedstocks at 2005 EIA prices.

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.

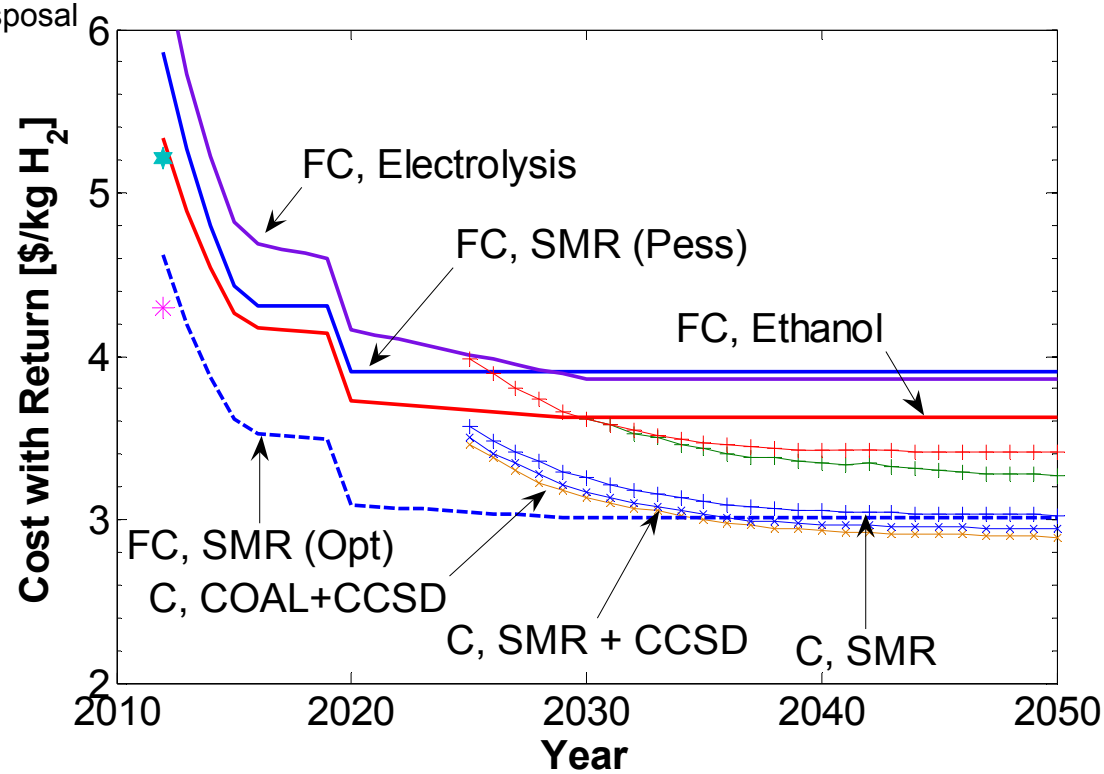
Sensitivities Evaluated

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
Entry date of Pipeline into market	2025	2005	Build out unchanged (Yearly demand increase insufficient for PL)
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

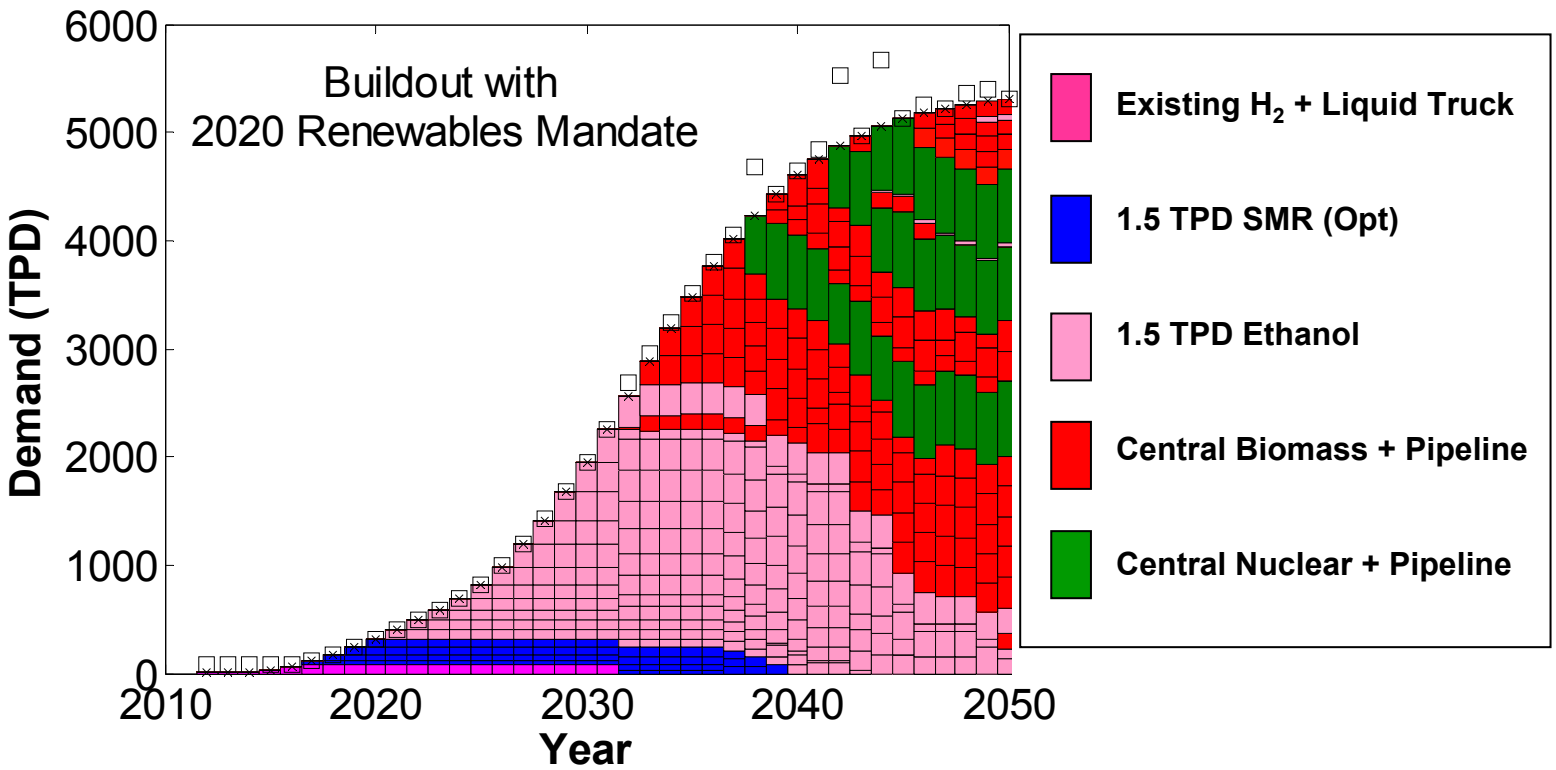
Impact of CCSD and CO_2 Emission Tax ($50/ton)

		w/o CCSD	w/ CCSD
CCSD Cost Adder [$/kg H_2]	Forecourt SMR		0
	Central SMR		~$0.24
	Central Coal		~$0.43
Carbon Tax Cost Adder at $50/ton CO_2 [$/kg H_2]	Forecourt SMR	~$0.58	0
	Central SMR	~$0.53	~$0.43
	Central Coal	~$1.38	~$0.60

CCSD = Carbon Capture, Sequestration and Disposal



2020 Renewables Mandate

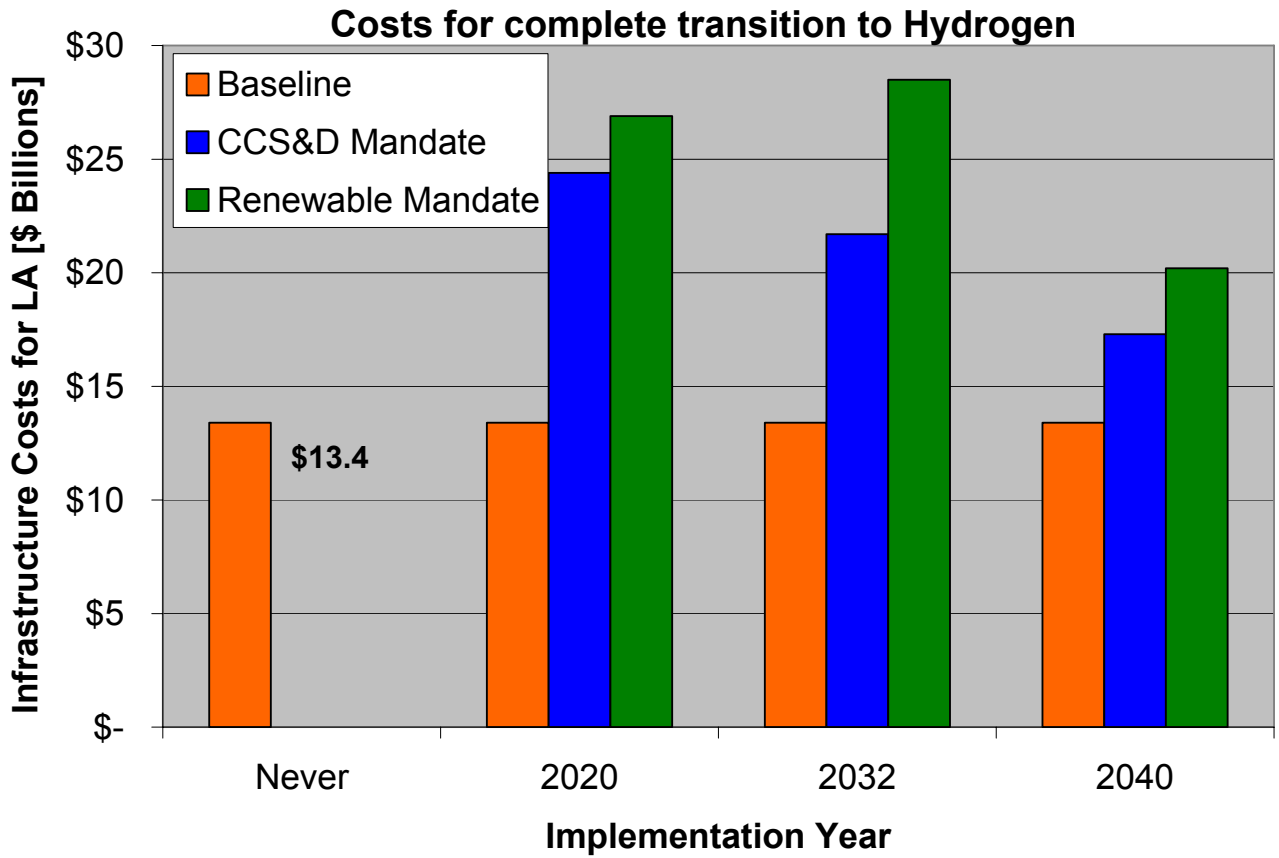


- **2020 Renewables Mandate:**

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.

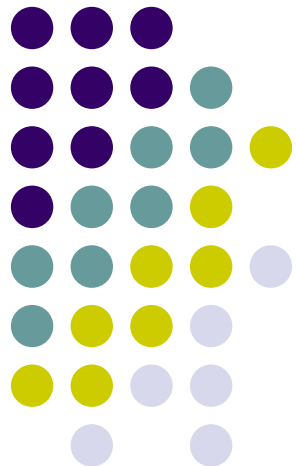
Future Work, FY07

- **Model upgrades**
  - Update database with latest HDSAM Dispensing parameters
  - Incorporate manufacturing learning curves
  - Evaluate 3.0 TPD Distributed Stations
- **Further sensitivity analyses**
- **Analyze different scenarios**
  - Run model on other lighthouse cities such as New York
  - Evaluate DOE Transition Scenario 1 & 3 in these cities
- **Document results**
  - Write analysis report
  - Identify incentives required to meet various DOE cost targets
  - Suggest to DOE areas of further research

Summary

- **Relevance:**
  - Analysis is important to the planning of the H_2 transition and useful for making decisions on which options are most likely to succeed.
- **Approach:**
  - Calculate an objective cost function which is evaluated regularly to determine build out
- **Technical Progress & Accomplishments:**
  - DCF calculation of complete pathway, sensitivity studies has lead to H_2 drivers
- **Infrastructure Drivers:**
  - Capital Cost of Forecourt Stations
  - Feasibility of pipelines in the future
  - CO_2 Policies
  - Feedstock Prices (Ethanol, Natural Gas)
- **Future Work:**
  - Analyze other demand scenarios
  - Model other cities
  - Suggest areas of further research

Other Results

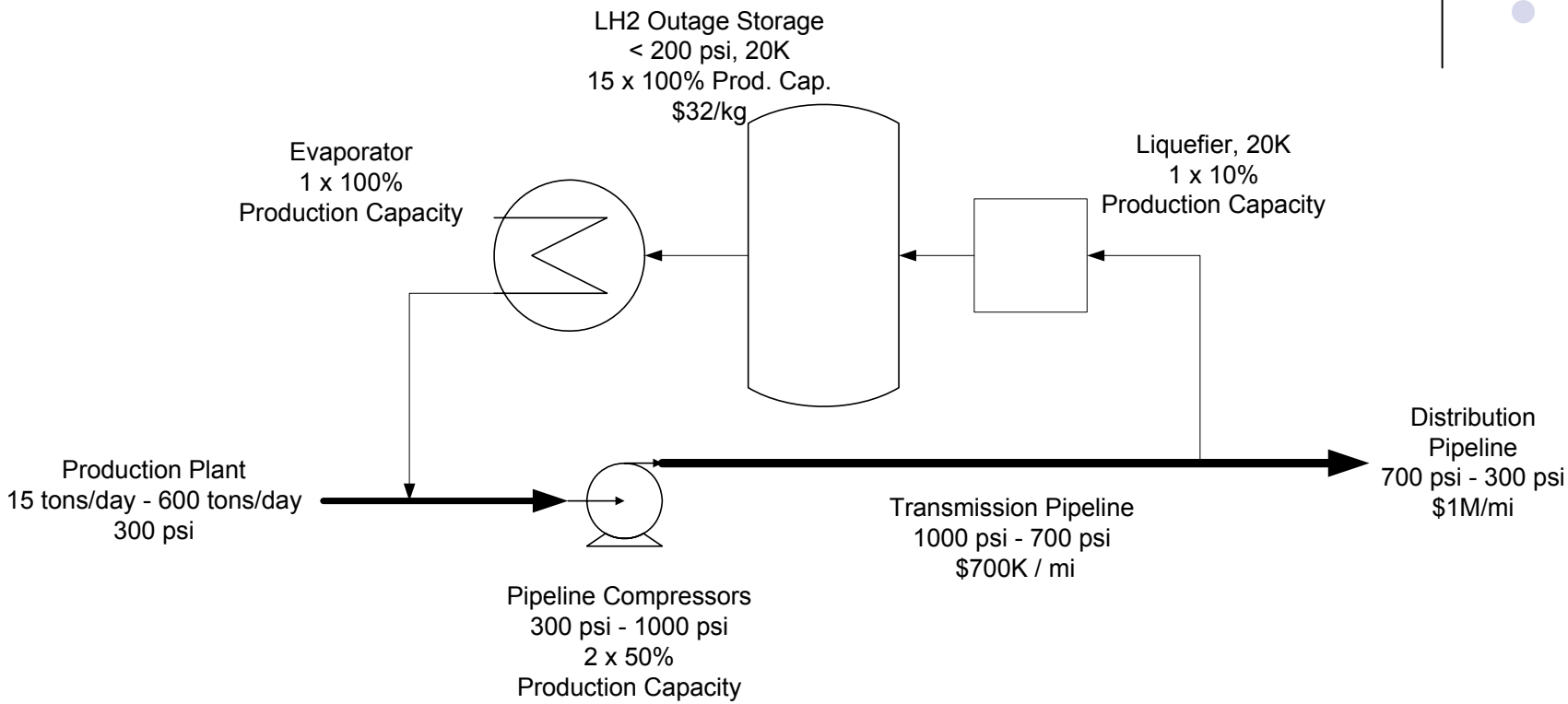


2005 Feedstock Prices

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.**

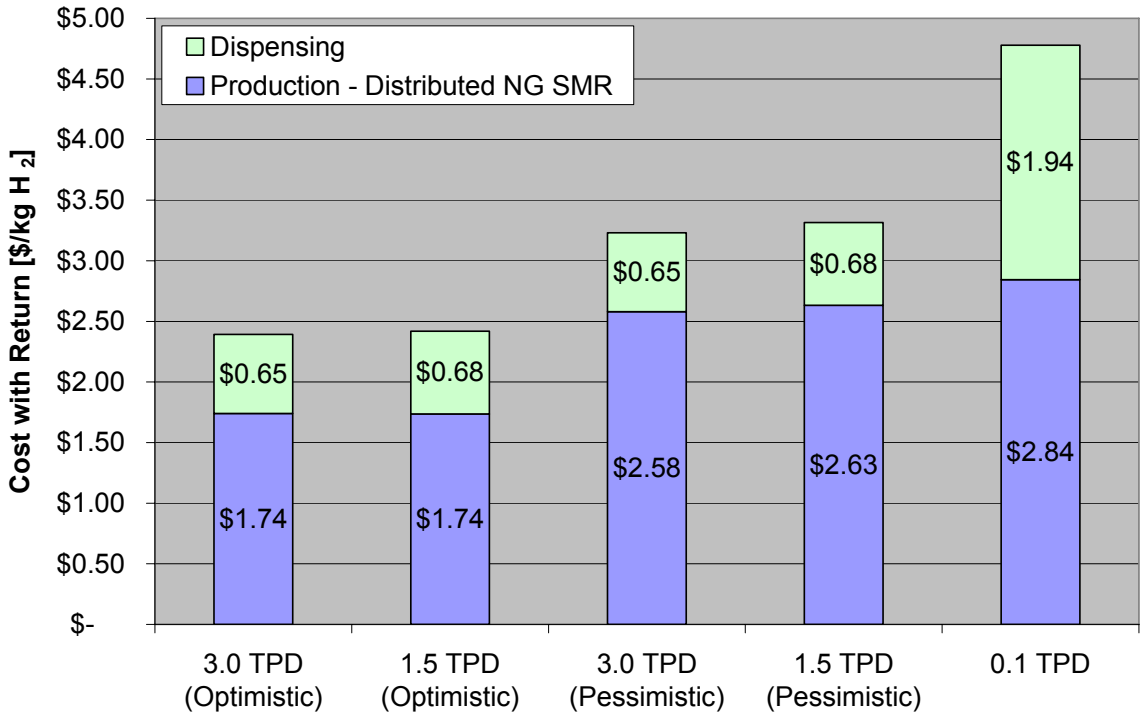
Terminal Components for Pipeline Delivery



Gaseous Terminal
for
Pipeline

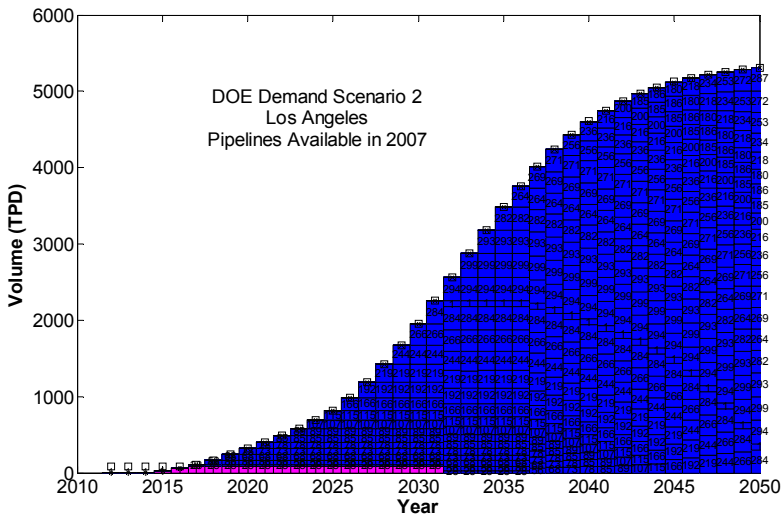
Subsystem schematics available for all 7 terminals.

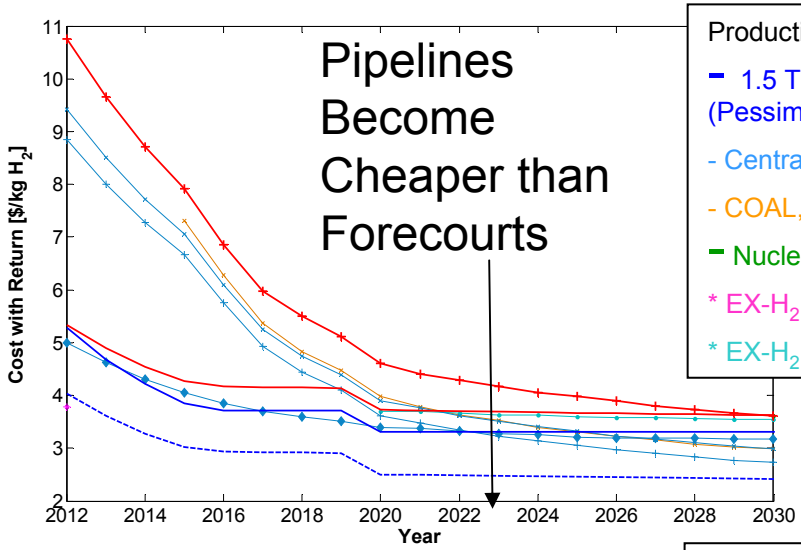
What about smaller stations?



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

What if pipelines were available sooner?





Production LEGEND
- 1.5 TPD NG SMR (Pessimistic)
- Central NG SMR
- COAL, GASIF.
- Nuclear
* $EX\text{-}H_2$ with LT
* $EX\text{-}H_2$ with HPGT

Delivery LEGEND
♦ LT
◊ CCSD & LT
\+ PL
x CCSD & PL

- **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**