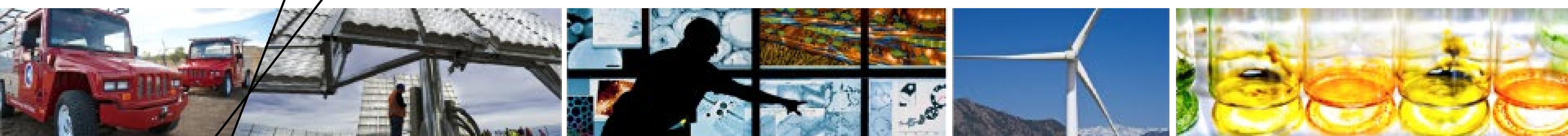
Analysis of SMR Thermal Augmentation with CHP Turbine Exhaust



Michael Penev

August 21, 2013

NREL/PR-5400-66836

Relevant Characteristics of Typical CHP Turbine

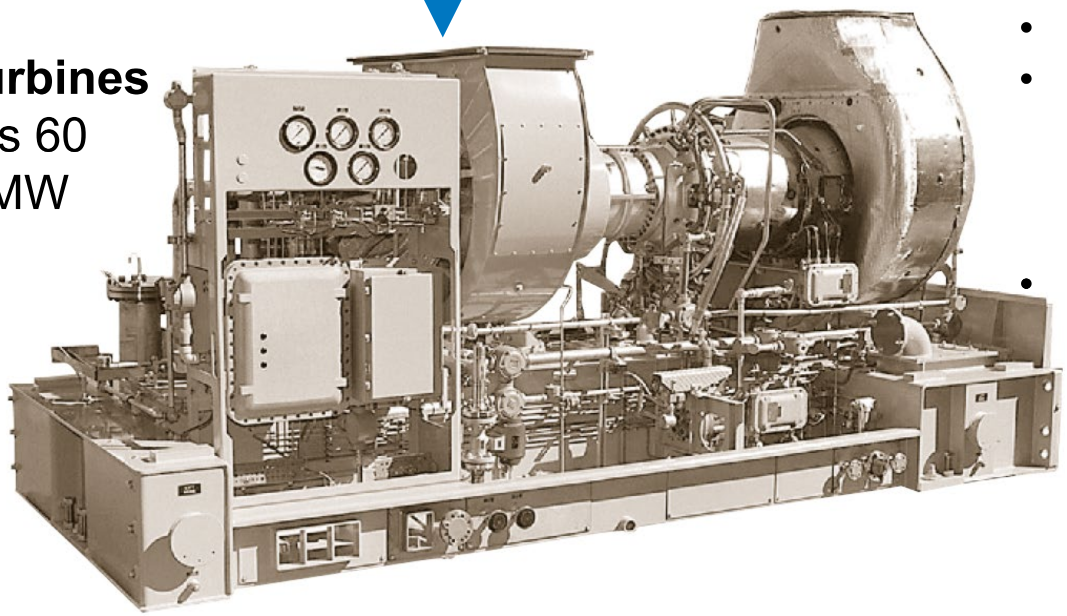
Air intake

Exhaust:

- Temperature: 510°C (950°F)
- Mass flow: 171,690 lb/h
- Back-pressure allowance: sufficient for steam generator heat exchanger (inches water column)
- Oxygen content: 15 vol%

Solar Turbines

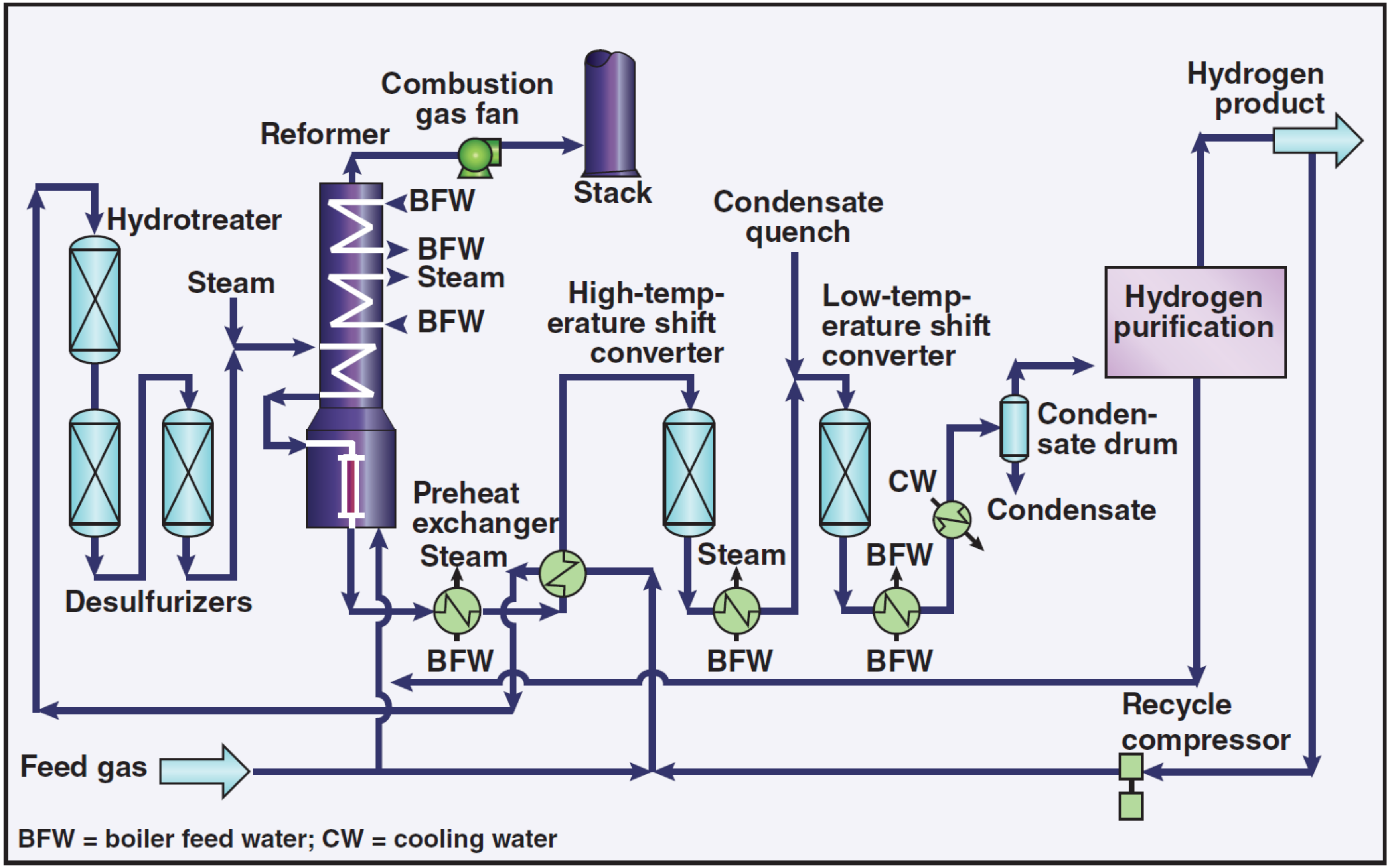
- Taurus 60
- 5.74 MW



Sources:

- "Technology Characterization: Gas Turbines", Energy and Environmental Analysis, Prepared for: Environmental Protection Agency, 2008
- Solar turbines performance specifications: Taurus 60, 5.74 MW turbine
- R. Pravi, G. Moore, "Gas Turbine Emissions and Control", GE Power Systems, March, 2001, GER-4211

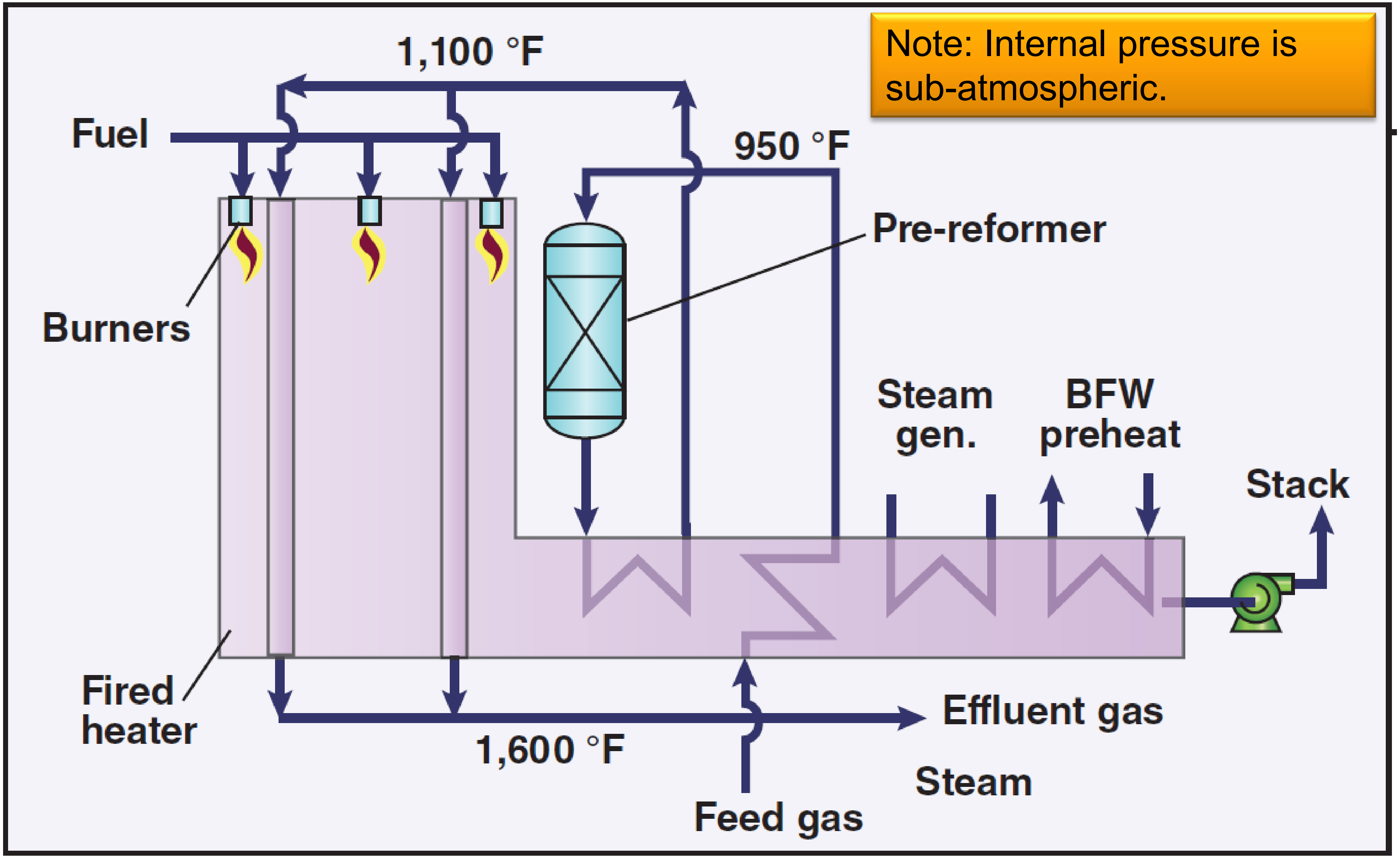
Typical SMR System Configuration



Sources:

- R. Elshout, "Hydrogen Production By Steam Reforming", Chemical Engineering www.che.com, May 2010 issue, page 34

Typical SMR System Configuration



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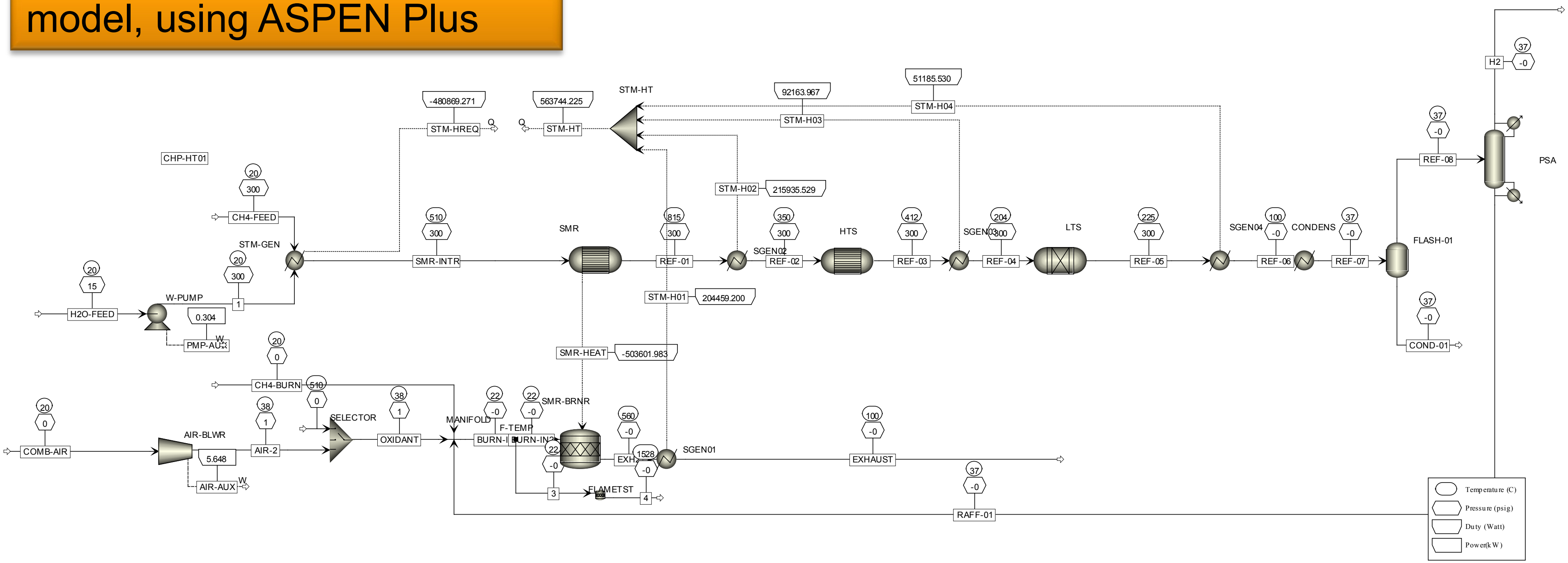
Modeling of Typical SMR System

NREL replicated typical SMR model, using ASPEN Plus



Efficiency: 76.3% LHV (without utilities)

Production scale: 1,000 kg/day

Key observations:

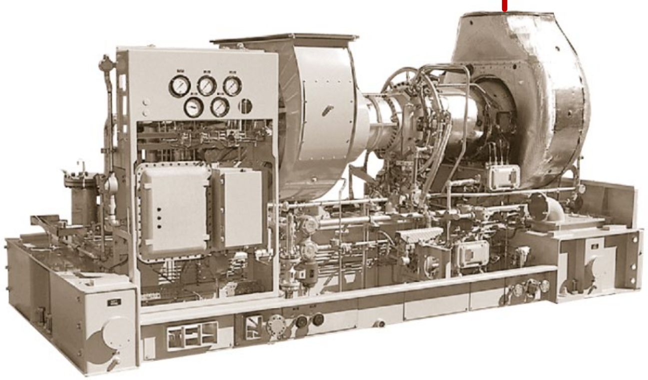
- **high quality heat drives gas consumption for process heat**
- **low quality heat exceeds steam generation demand**
- **gas consumption reduction can be achieved by high quality heat > 880°C**

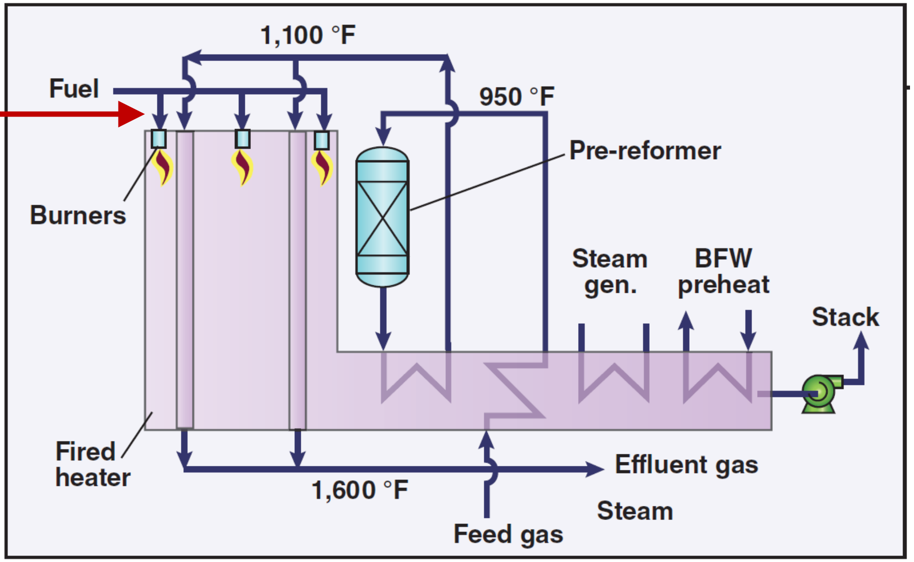
Process conditions source:

Nexant Inc., “Equipment Design and Cost Estimation for Small Modular Biomass Systems, Synthesis Gas Cleanup, and Oxygen Separation Equipment”, May 2006

Integration Concept

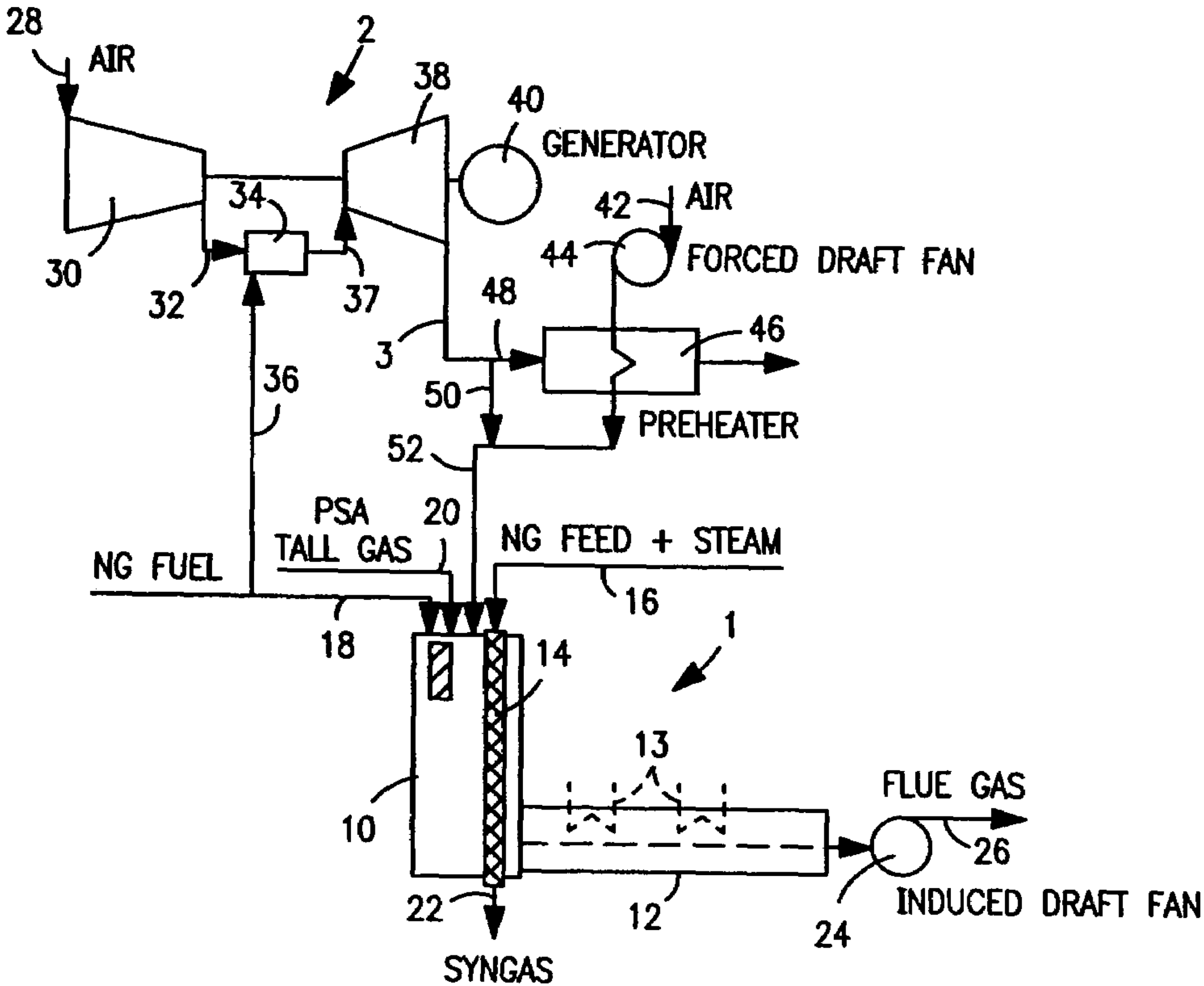
CHP Exhaust
15% O_2
510°C



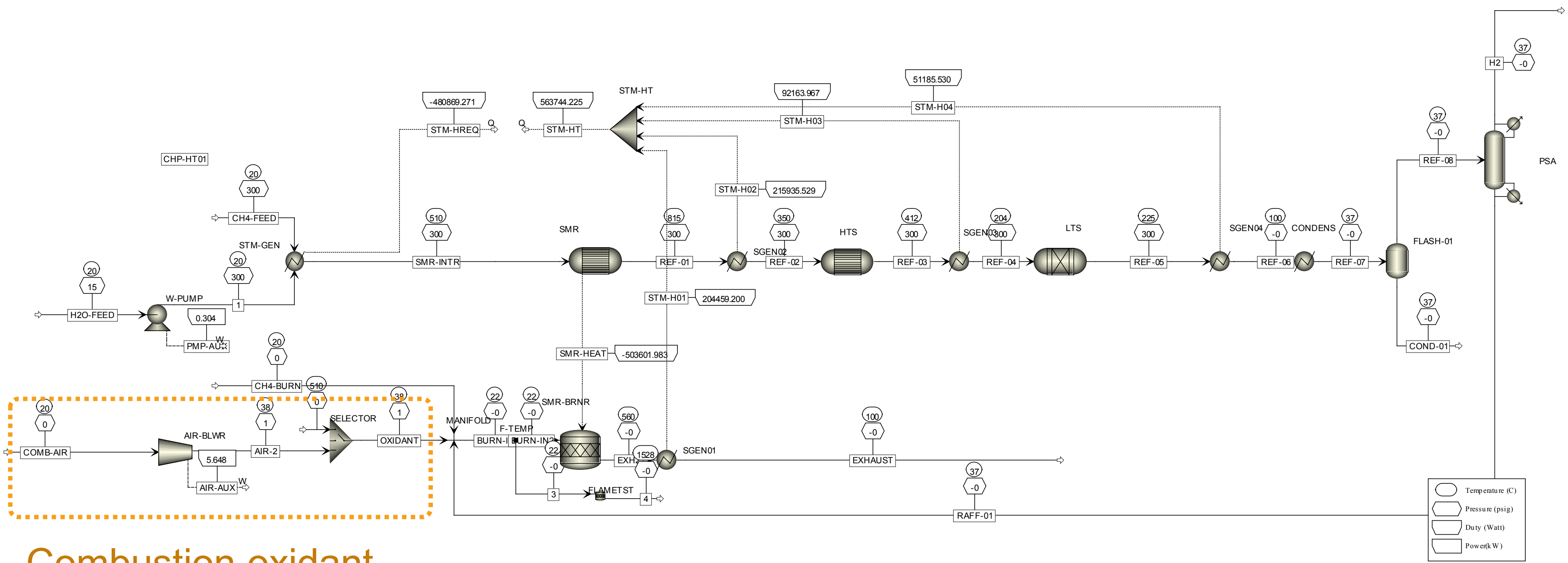


- SMR combustion air intake is manifolded to accept CHP exhaust
- Fuel is combusted into CHP exhaust to increase heat quality
  - adiabatic flame temperature ~1470°C
- Hand-off pressure = ambient (consistent with SMR construction)

PraxAir Patent US 7043923 B2, May 16, 2006



SMR Model in ASPEN Plus



Combustion oxidant can be either fresh air or CHP exhaust

Operating conditions examined:

- Reactor outlet temperature 815°C, 880°C
- PSA hydrogen recovery extent: 90%, 97%

Performance metrics:

- Natural gas consumption (process & combustor)
- Low quality heat impact
- Hydrogen production impact

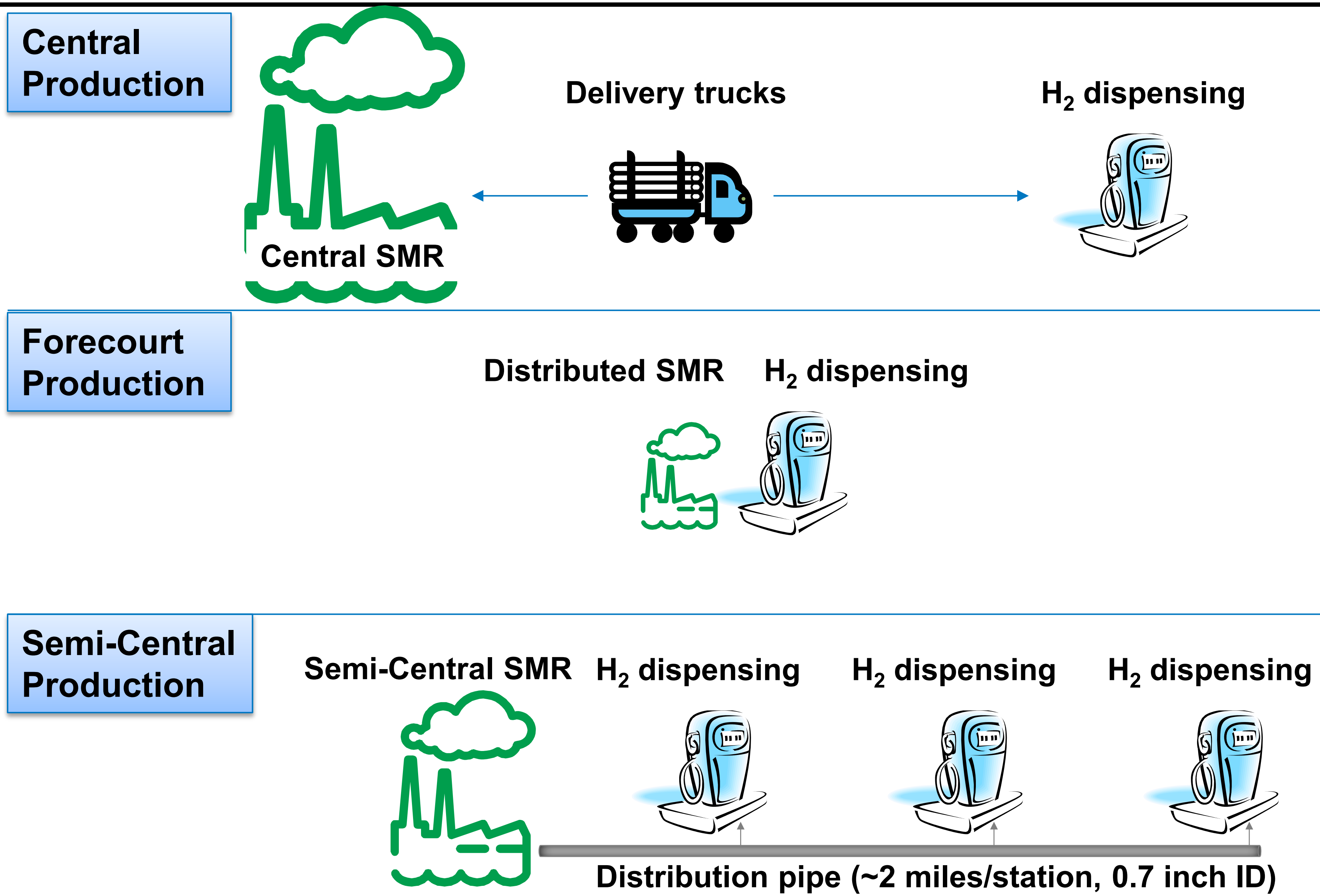
Performance Summary

SMR Configuration	Units	Baseline	CHP+SMR Config. A	CHP+SMR Config. B	CHP+SMR Config. C	CHP+SMR Config. D
SMR-out temperature	°C	815	815	880	815	880
PSA H_2 recovery %	mol/mol	90%	90%	90%	97%	97%
High quality heat requirement	kW-thermal	563,744	616,786	673,342	585,414	678,731
Steam generation heat required	kW-thermal	480,869	480,869	480,869	480,869	480,869
Low quality heat available (steam generation)	kW-thermal	503,602	503,602	606,113	503,602	606,113
Methane used in production stream	mmBTU HHV/kgH2	0.156	0.156	0.133	0.144	0.123
Rafinate used in combustion stream	mmBTU HHV/kgH2	0.054	0.054	0.032	0.041	0.020
Fresh methane used in combustion stream	mmBTU HHV/kgH2	0.010	0.001	0.022	0.008	0.030
Total methane use	mmBTU HHV/kgH2	0.165	0.156	0.155	0.152	0.153
Feedstock use efficiency (excluding CHP heat & electricity)	HHV	81.3%	86.0%	86.8%	88.4%	87.9%
Feedstock use efficiency (excluding CHP heat & electricity)	LHV	76.3%	80.7%	81.5%	83.0%	82.5%
Total CH4 consumption reduction		**0.0%**	**5.5%**	**6.3%**	**8.1%**	**7.5%**

Initial indication shows as much as 8% fuel consumption reduction.

Integration ratio: 1 MW CHP can augment 14,000 kg/day SMR

Supply Chain Models Examined

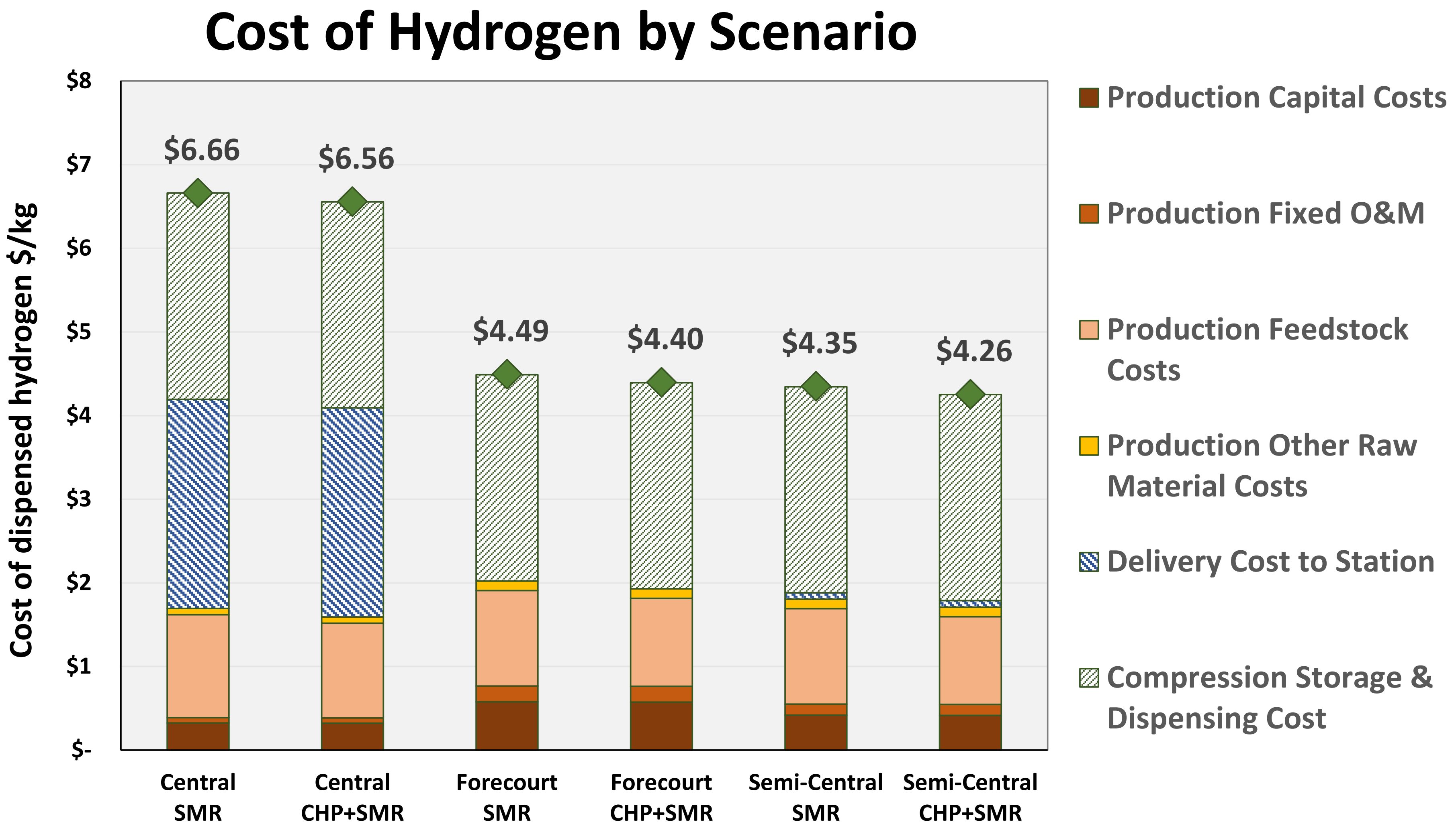


H2A Analysis, Current Technology, Central SMR Basis

Case	Central SMR	Central CHP+SMR	Forecourt SMR	Forecourt CHP+SMR	Semi-Central SMR	Semi-Central CHP+SMR
Production Capacity (kg/day)	379,387	379,387	1,500	1,500	4,500	4,500
Per-Station Dispensing Capacity (kg/day)	1,500	1,500	1,500	1,500	1,500	1,500
Production Costs ($/kg)						
Capital Costs	$ 0.32	$ 0.32	$ 0.58	$ 0.57	$ 0.42	$ 0.42
Fixed O&M	$ 0.06	$ 0.06	$ 0.19	$ 0.19	$ 0.13	$ 0.13
Feedstock Costs	$ 1.23	$ 1.13	$ 1.14	$ 1.05	$ 1.14	$ 1.05
Other Variable Costs (including utilities)	$ 0.07	$ 0.07	$ 0.11	$ 0.11	$ 0.11	$ 0.11
Total	$ 1.70	$ 1.59	$ 2.03	$ 1.93	$ 1.81	$ 1.72
Delivery Costs ($/kg)						
Delivery Cost to Station	$ 2.50	$ 2.50	$ -	$ -	$ 0.08	$ 0.08
Dispensing Costs ($/kg)						
Compression Storage & Dispensing	$ 2.46	$ 2.46	$ 2.46	$ 2.46	$ 2.46	$ 2.46
Total Cost	**$ 6.66**	**$ 6.56**	**$ 4.49**	**$ 4.40**	**$ 4.35**	**$ 4.26**

- **H2A Production Model values are used for production and CSD costs (N'th plant assumption in effect)**
- **ANL input was used for truck delivery costs**
- **H2A Components Model values were used for pipeline costs (2 miles, 0.7 inch ID pipeline per station)**

H2A Analysis, Current Technology, Central SMR Basis



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H2A Analysis: Benefit of Semi-Central SMR Architecture (Preliminary Results without CHP augmentation)

- Economies of scale benefits to SMR > cost of pipeline
- H2A Production Model values are used for production and CSD costs (N'th plant assumption in effect)
- H2A Components Model values were used for pipeline costs (2 miles, 0.7 inch ID pipeline per station)

Discussion

10¢/kg is not trivial – it is in the order of magnitude of investor rate of return

8% fuel reduction = 8% reduction in GHG emissions

H_2 can be distributed to nearby fueling stations (lowest cost delivery method)

- Less delivery GHG emissions & trucks on the road
- Semi-central SMR can get lower cost Natural Gas (industrial vs. commercial)

Leverage of economies of scale

- on-site technical support (no travel time and expense for service)
- higher up-time due to on-site technician support
- available infrastructure (natural gas, utilities, cooling)
- industrial zoning may allow easier permitting

Adiabatic flame temperature reduction = reduction in NOx emissions

Reduced market entry cost for renewables:

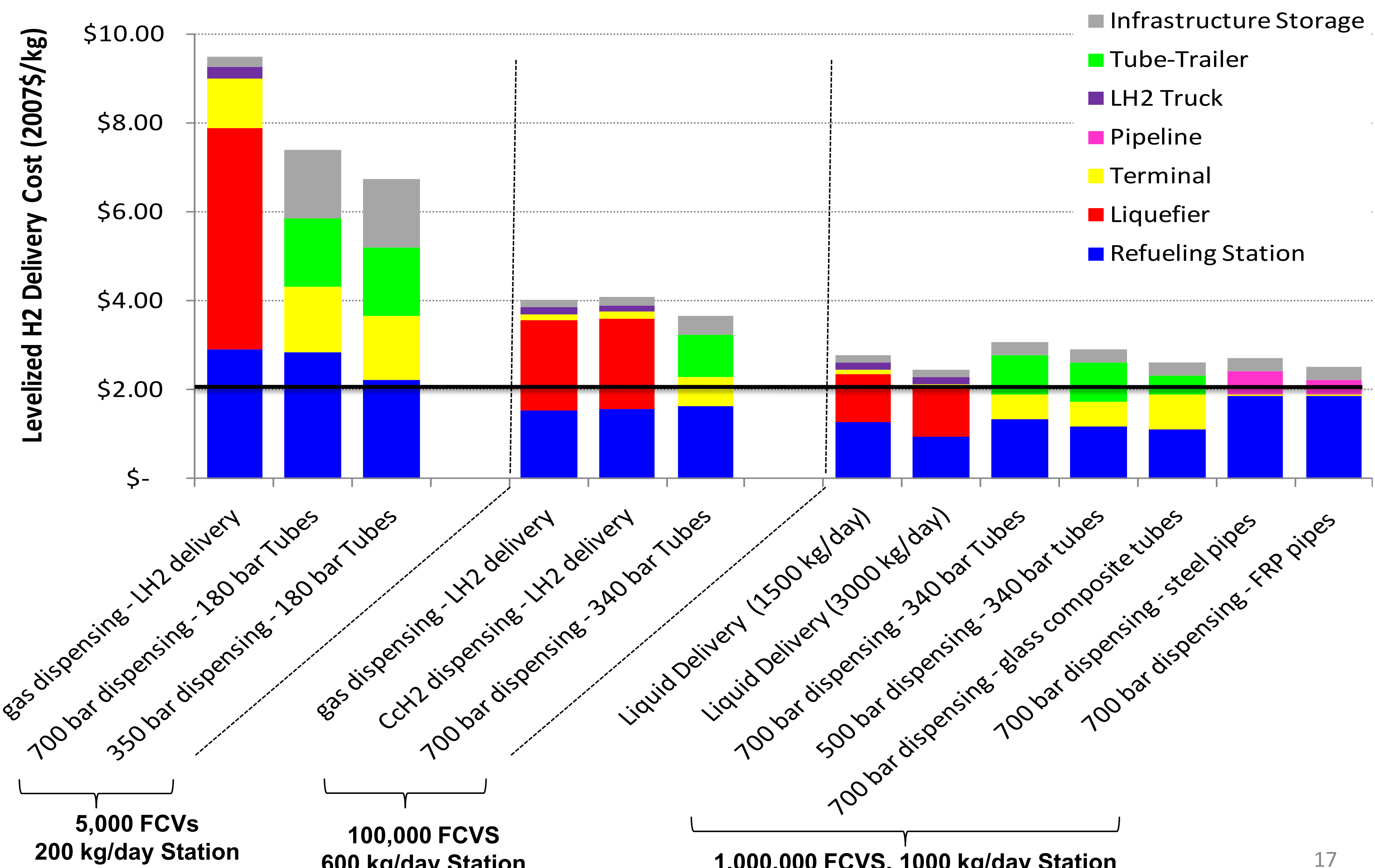
- Power to Gas (P2G) can sell high-value H_2 into network
- MSW gasifiers can feed into network with lower distribution cost

Questions?

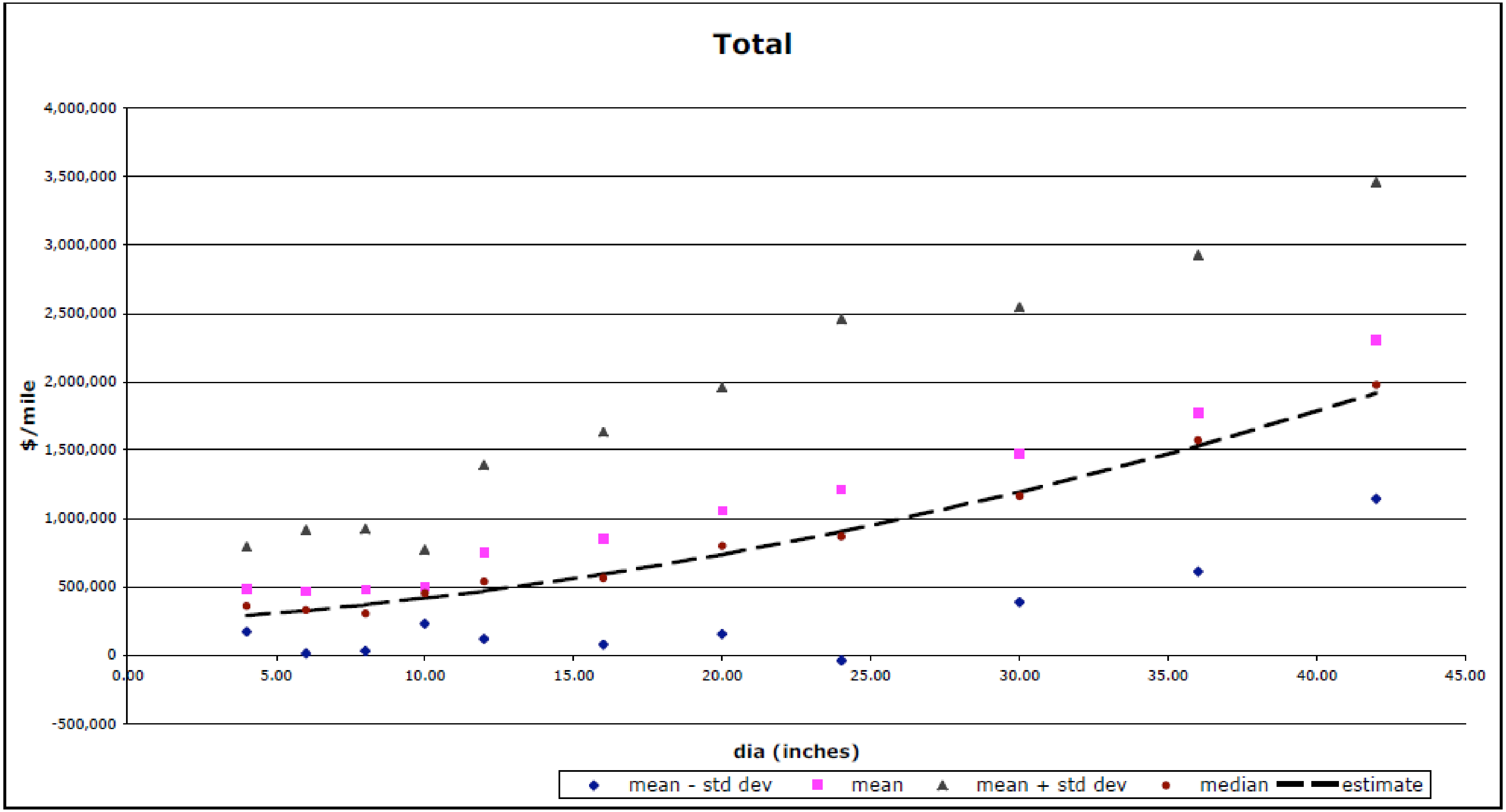
Backup Slides

Levelized Hydrogen Delivery Cost Reduction Path

(Input from Amgad Elgowainy, ANL)



Pipeline Cost Distribution
(Total Installed Cost)



Source: Parker, Nathan. "Using Natural Gas Transmission Pipeline Costs to Estimate Hydrogen Pipeline Costs," Technical Report No. UCD-ITS-RR-04-3, Institute of Transportation Studies, University of California, Davis, January 2005.