the Energy to Lead

Scalable, Economic Hydrogen Generation from Natural Gas

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Outline

- Background
- Compact Hydrogen Generator Description
- Cases Compared for power generation
- Key Assumptions & Metrics
- Results
- Technology Maturation & Issues
- Development Plan
- Summary & Recommendations

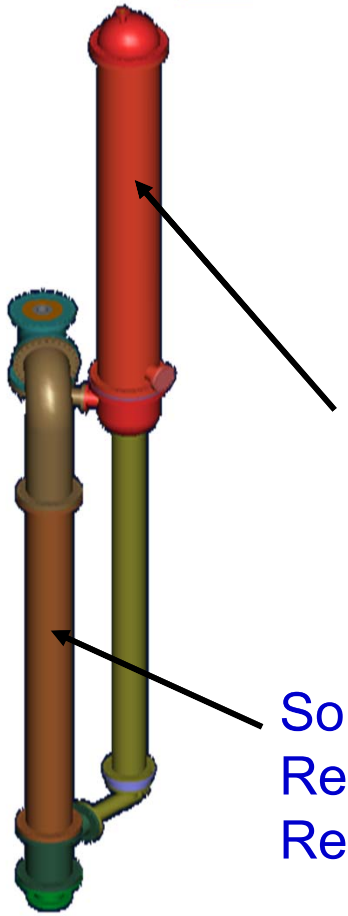
Background & Objective

Scalable, Economic H_2 Generation from NG

- GTI is piloting (.02 MMSCFD) a Compact Hydrogen Generator (CHG) technology for large-scale H_2 production (>2 MMSCFD)
  - Cost competitive against current Steam Methane Reformer (SMR) technology in traditional refinery and chemicals applications
- CHG has an inherent ability to capture CO_2
  - Enables cost-effective power generation with pre-combustion capture
  - Power generation can be accomplished with current-generation gas turbines
- DOE (FE) has been involved in development of hydrogen turbines for Integrated Gasification Combined Cycle (IGCC) plants to improve performance and reduce emissions
- <u>Objective</u>: Perform a techno-economic evaluation of current NG-fueled technologies to produce power with CO_2 capture (i.e., NGCCs and SMRs) and CHG with a conventional and advanced hydrogen turbine

CHG Process Chemistry

The SER process avoids the external heating of the SMR process. This is achieved by the exothermic nature of the carbonation reaction. Additionally, the SER process forces the water-gas shift reaction to occur in situ, thus enabling the heat from the water-gas shift reaction to be utilized within the hydrogen reactor.



Hydrogen Generation Reactions

Sorbent Regeneration Reaction

Chemistry	Heat
SMR Chemistry	
Reforming $CH_4 + H_2O \rightarrow 3H_2 + CO$	+206 KJ
WGS $CO + H_2O \rightarrow H_2 + CO_2$	-37.8KJ
Combined $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	+206 KJ/-37.8KJ
SER Process Chemistry	
$CH_4 + 2H_2O + CaO \rightarrow 4H_2 + CaCO_3$	None
$CaCO_3 \rightarrow CaO + CO_2$	+178 KJ

Closed loop operation produces hydrogen and regenerates calcium oxide

CHG: Principles of Operation

Product

- System for large-scale production of hydrogen from natural gas and other feedstock
- Replaces Steam Methane reformer

Benefits

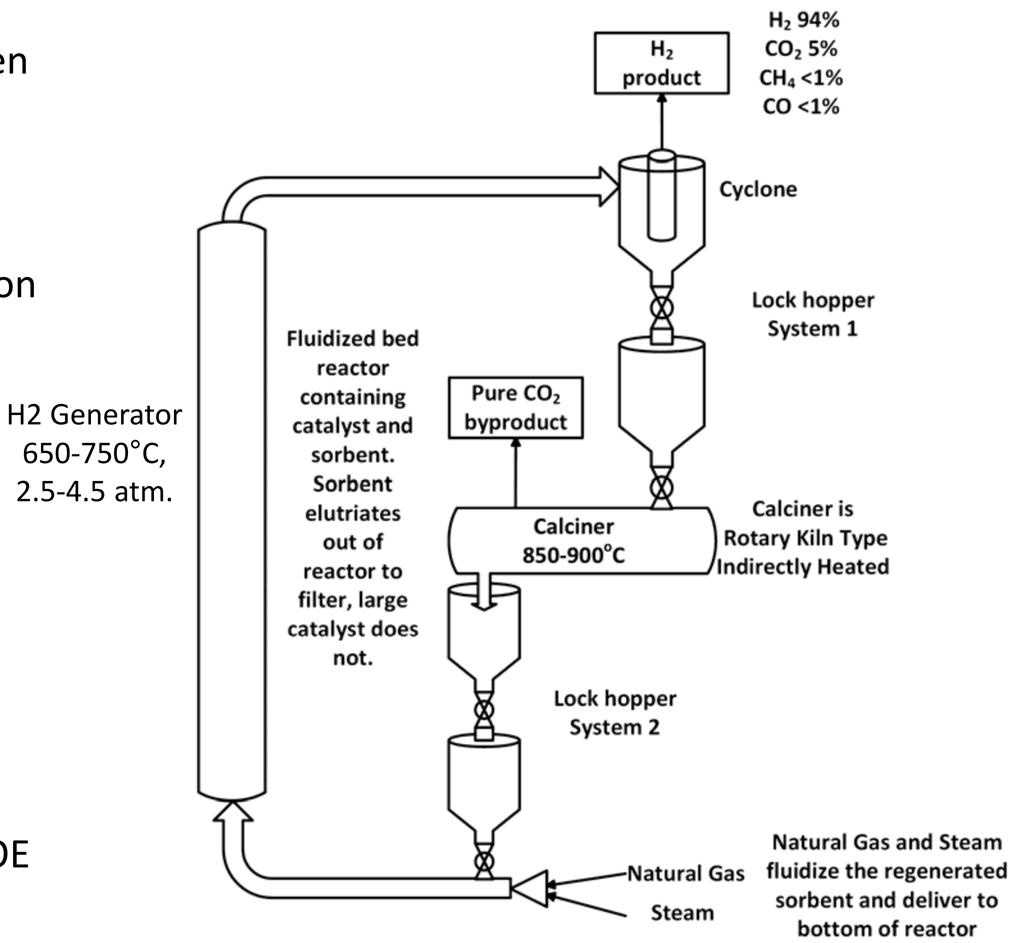
- Compact one-step process, 90% size reduction
- 20-40% lower equipment costs
- 10-20% increased H_2 efficiency
- Concentrated CO_2 byproduct

Markets

- H_2 for refineries, fertilizer and chemicals
- H_2 for field upgrading of oil and oil sands
- H_2 for power with low-cost CO_2 capture

Status

- Proof of Concept tests completed
- Pilot (20 MCFD) testing in progress under DOE contract
- Demo plant defined at 5.0 MMSCFD



H_2 product

H_2 94%
CO_2 5%
CH_4 <1%
CO <1%

Cyclone

Lock hopper System 1

H2 Generator 650-750°C, 2.5-4.5 atm.

Fluidized bed reactor containing catalyst and sorbent. Sorbent elutriates out of reactor to filter, large catalyst does not.

Pure CO_2 byproduct

Calciner 850-900°C

Calciner is Rotary Kiln Type Indirectly Heated

Lock hopper System 2

Natural Gas

Steam

Natural Gas and Steam fluidize the regenerated sorbent and deliver to bottom of reactor

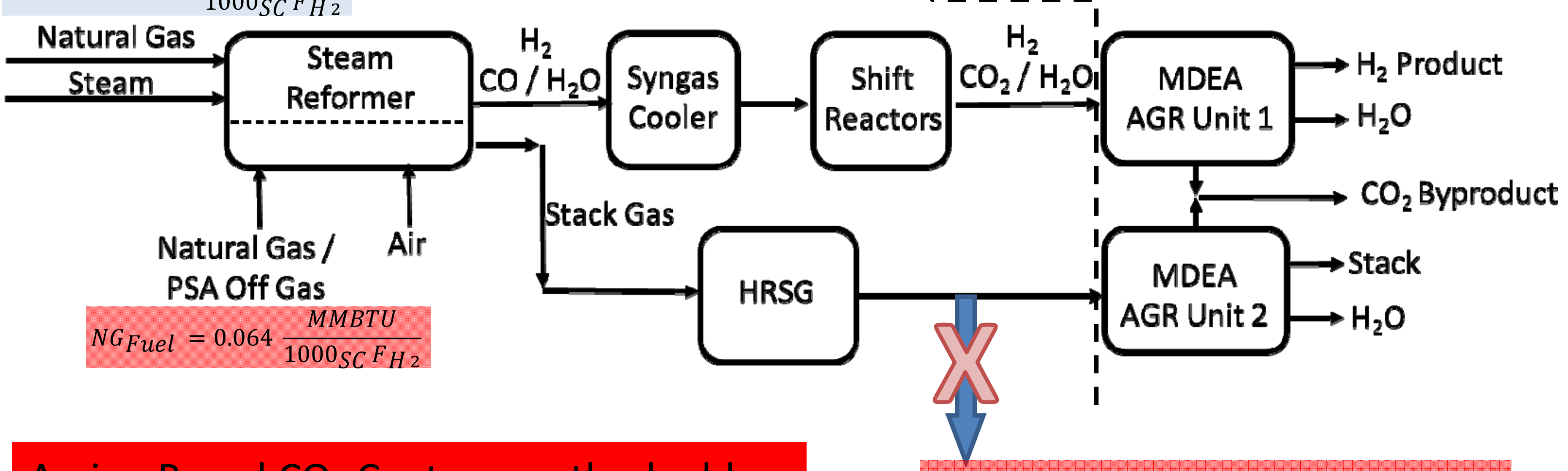
CO_2 Capture with SMR

Scalable, Economic H_2 Generation from NG

H_2 Production Percentage (%) of Total Plant Cost (TPC) = 45.6%

CO_2 Capture % TPC = 52%
CO_2 Compression % of TPC = 2.4%

$$NG_{Feed} = 0.335\ \frac{MMBTU}{1000_{SC}F_{H2}}$$



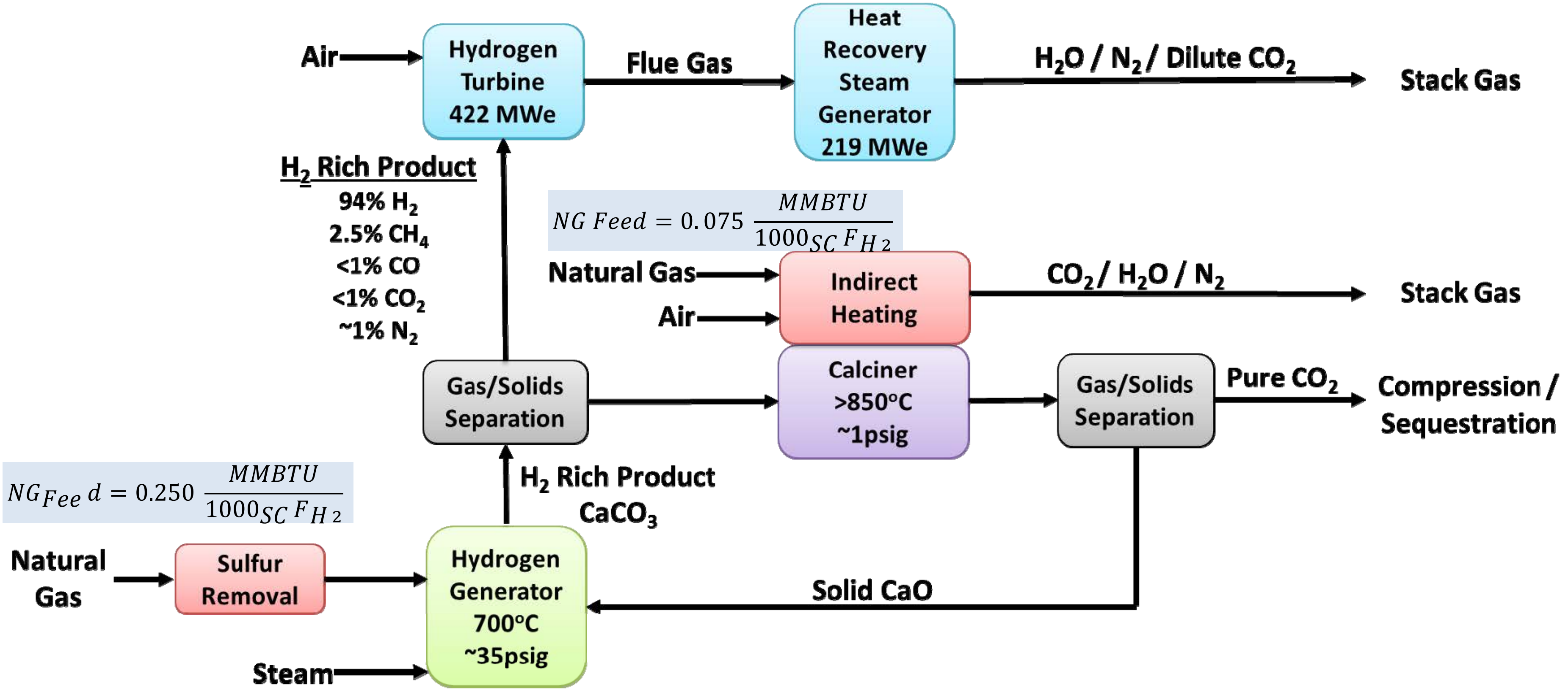
$$NG_{Fuel} = 0.064\ \frac{MMBTU}{1000_{SC}F_{H2}}$$

Amine Based CO_2 Capture method adds significant Capital Cost and Parasitic Loads means high CO_2 Capture Costs

Excess Heat Recovered and Sold as Steam. Amine based CO_2 Capture methods utilize 100% of this steam

Reference diagram according to NETL 2010/1434. PSA added for increased hydrogen purity

CO_2 Capture with CHG



Air
Hydrogen Turbine 422 MWe
Flue Gas
Heat Recovery Steam Generator 219 MWe
H_2O / N_2 / Dilute CO_2
Stack Gas

H_2 Rich Product
94% H_2
2.5% CH_4
<1% CO
<1% CO_2
~1% N_2

$NG\ Feed = 0.075\frac{MMBTU}{1000_{SC}F_{H2}}$

Natural Gas
Air
Indirect Heating
CO_2 / H_2O / N_2
Stack Gas

Gas/Solids Separation
Calciner >850°C ~1psig
Gas/Solids Separation
Pure CO_2
Compression / Sequestration

$NG_{Fee}d = 0.250\frac{MMBTU}{1000_{SC}F_{H2}}$

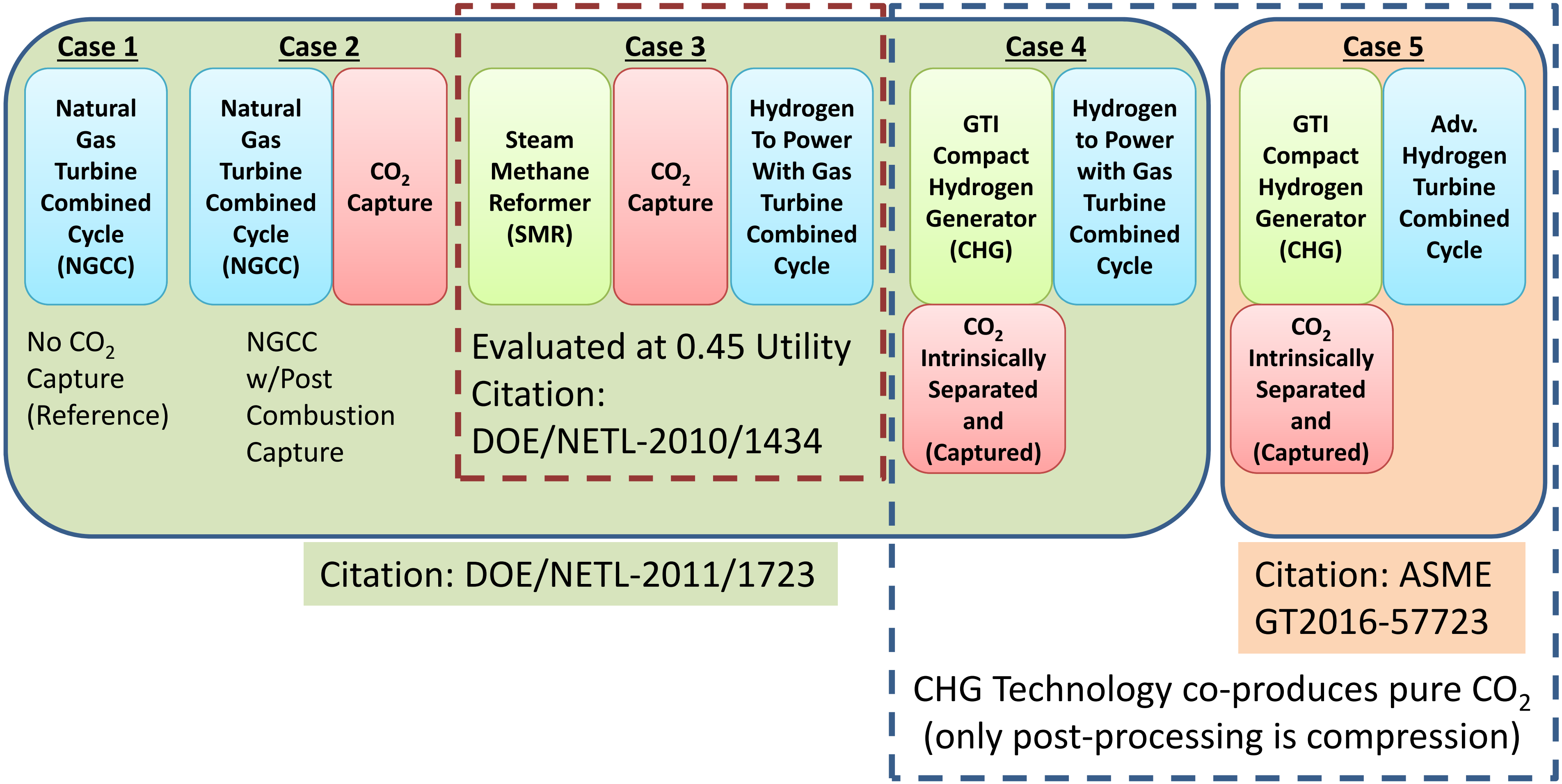
H_2 Rich Product
$CaCO_3$

Natural Gas
Sulfur Removal
Hydrogen Generator 700°C ~35psig
Solid CaO
Steam

Sorbent Enhanced Reforming captures CO_2 in a solid, enabling release in a pure form during sorbent regeneration and eliminating the expensive amine system

*PSA added (optional) for increased hydrogen purity

Study Cases Compared



Case 1

Natural Gas Turbine Combined Cycle (NGCC)

No CO_2 Capture (Reference)

Case 2

Natural Gas Turbine Combined Cycle (NGCC)

CO_2 Capture

NGCC w/Post Combustion Capture

Case 3

Steam Methane Reformer (SMR)

CO_2 Capture

Hydrogen To Power With Gas Turbine Combined Cycle

Evaluated at 0.45 Utility

Citation: DOE/NETL-2010/1434

Case 4

GTI Compact Hydrogen Generator (CHG)

Hydrogen to Power with Gas Turbine Combined Cycle

CO_2 Intrinsically Separated and (Captured)

Case 5

GTI Compact Hydrogen Generator (CHG)

Adv. Hydrogen Turbine Combined Cycle

CO_2 Intrinsically Separated and (Captured)

Citation: DOE/NETL-2011/1723

Citation: ASME GT2016-57723

CHG Technology co-produces pure CO_2 (only post-processing is compression)

Techno-Economics

~Assumptions & Metrics

Assumptions

1. Overall
   1. 90% CO_2 removal
   2. Natural gas at $6.13/MMBTU HHV
   3. H_2 purity =99.99%
   4. 10.3% Capital Charge
   5. CO_2 TS&M = $4/MWH 559MW basis
   6. 2.72 BBL/MT CO_2 EOR ratio
   7. 2 Turbines x 1 SSTG
2. F-Class turbine NGCC
   1. 641 MWe gross power
   2. Same Heat rate (HHV)
3. Advanced H2 Turbine (793 MWe)
   1. Pressure Ratio = 23.8
   2. η_c/η_t = 93%/90%
   3. Turbine Inlet Temp = 2640°F
   4. Steam Cycle Efficiency = 39.9%

Metrics

1. Cost of Electricity (COE)
2. Capital Investments
3. CO_2 Emissions
4. CO_2 Capture cost ($/MT)
5. Plant Efficiency (LHV)
6. Sensitivity to Fuel Price

Results

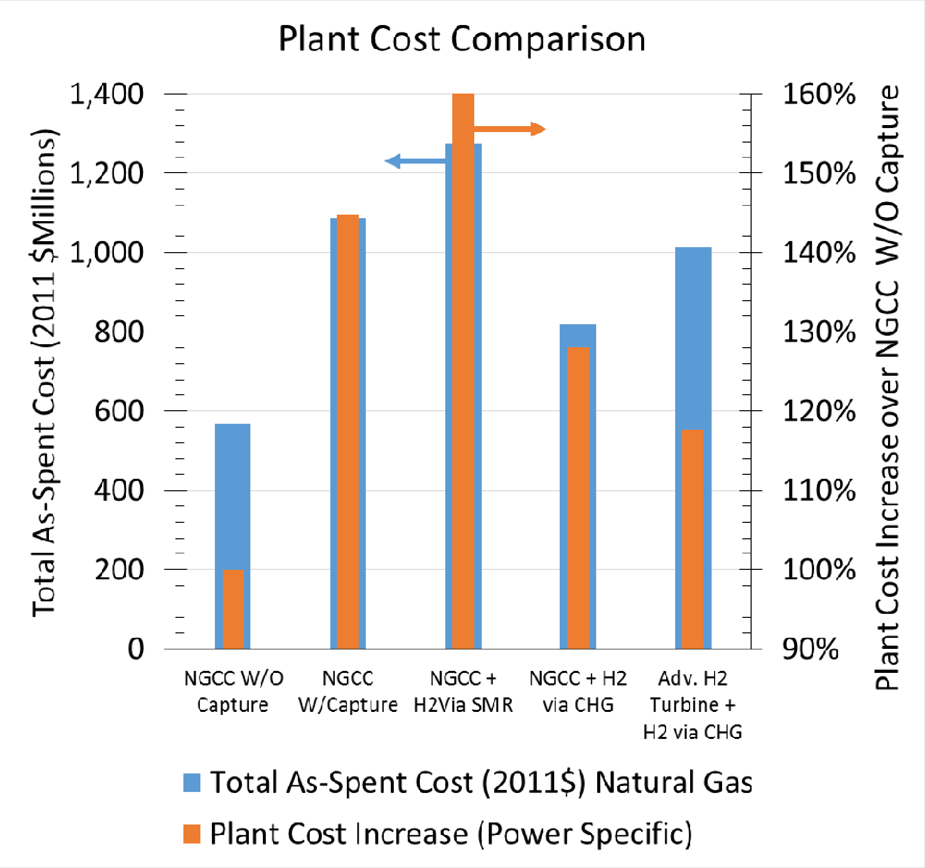
Scalable, Economic H_2 Generation from NG

	NGCC w/o Capture	NGCC w/ Capture	H_2 Via SMR HTCC	H_2 via CHG HTCC	CHG w/Adv. H_2 Turbine HTCC
Total Plant Power (MW)	630	559	596	604	761
Percent of CO_2 Captured	0%	90%	90%	90%	90%
Total Plant Cost, Capital Costs ($M)	431	828	949	623	771
Total Overnight Cost ($M)	525	1,008	1,156	759	938
Total As-Spent Cost ($M)	567	1,087	1,247	818	1012
Annual Costs (excluding TS&M)($M)	270	347	433	331	384
COE ($/MWh) (including TS&M)	58	87	101	77	73
Plant Efficiency (%) – LHV basis	56.93	50.48	38.84	51.06	56.41
Cost of CO_2 capture ($/MT)	N/A	47	82	40	33
Total CO_2 Emitted (MT/day)	5,394	492	682	526	533
BBL of Oil Recovered per Day	N/A	12,041	16,700	12,878	13,059

CHG-based power via hydrogen with pre-combustion capture offers lower COE than: (1) SMR and (2) NGCC with post-combustion capture

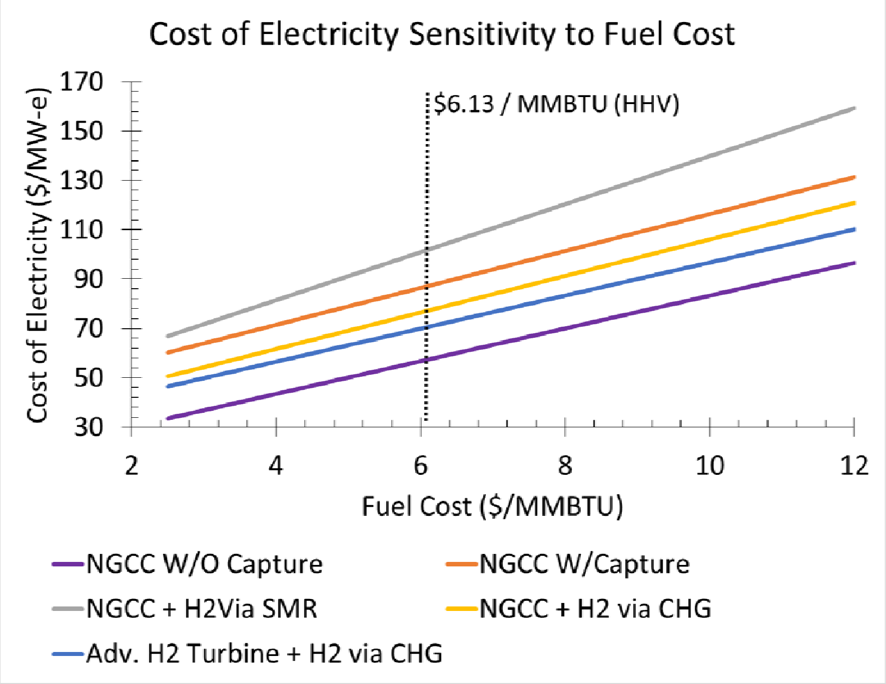
Impact of CAPEX and Fuel Costs

- The biggest cost driver is the CAPEX



Plant Cost Comparison

- COE is proportional to fuel costs
- Plant efficiency effects slope



Cost of Electricity Sensitivity to Fuel Cost

Component Technology TRLs

1. **Gas Turbine and HRSG system – TRL 9**
2. **Advanced H_2 Gas Turbine –TRL 4**

   DOE (FE) program is currently working towards 3100°F turbine inlet temperature, applicable to H2 and NG fuels. Supports IGCC and NGCC platforms with 65% combined cycle efficiency
3. **CHG System – TRL 4**

   DOE (EERE) currently supporting technology development by updating pilot plant with indirect-fired, atmospheric calciner
4. **Indirect-fired Atmospheric Calciner – TRL 6**
5. **High Temperature lock hoppers – TRL 4**

   Will be developed as part of the CHG System
6. **CO_2 Capture and compression – TRL 6**

Maturing component TRLs & Operation of components as a system requires demonstration

Summary & Recommendations

- **GTI's Compact Hydrogen Generator (CHG) offers a cost-effective approach to power generation with pre-combustion capture**
  - **Approx. 19% improvement in COE over NGCC and 30% over SMRs**
- **CHG is being matured through a DOE (EERE)-funded Pilot program**
- **Extending technology elements developed for hydrogen turbines by DOE (FE) will further improve the value proposition for CHG-based power with capture**
- **A novel variant would enable lower electricity production, enabling excess H_2 to support the hydrogen grid concept**
- **Recommend initiating a phased program to: further define the system; determine associated component maturities; re-validate cost-benefits; and, develop and demonstrate technology**