September 28, 2020

Natural Gas-Based Coproduction of Power and H_2 with CCS

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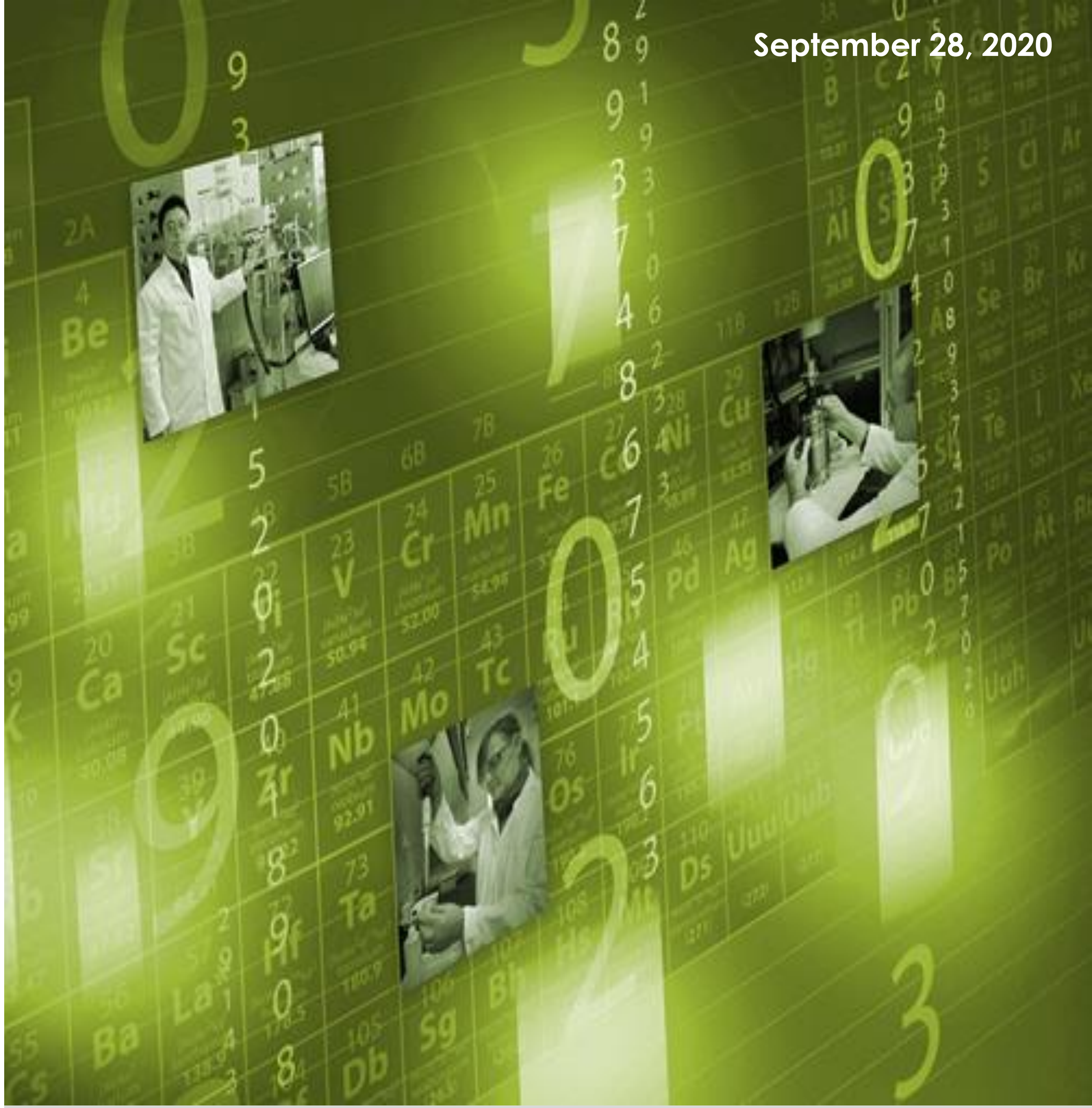

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ACKNOWLEDGEMENT

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Agenda

- **Project Summary**
- **Process Descriptions**
  - Baseline Steam Methane Reforming Case
  - Direct-fired Reformer
- **Design Basis**
  - Assumptions
  - Methodology
  - Uncertainty Analysis and Data Gaps
- **Performance Results**
- **Economic Analysis Results**
- **Additional Sensitivity Analyses**

Natural Gas-Based Coproduction of Power and H_2 with CCS

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Justification

- Hydrogen is an important chemical raw material and gaining growing attention for energy storage and low/zero carbon power applications
- Coproduction of hydrogen and power may allow fossil fuels to continue to play a critical role in a carbon constrained world

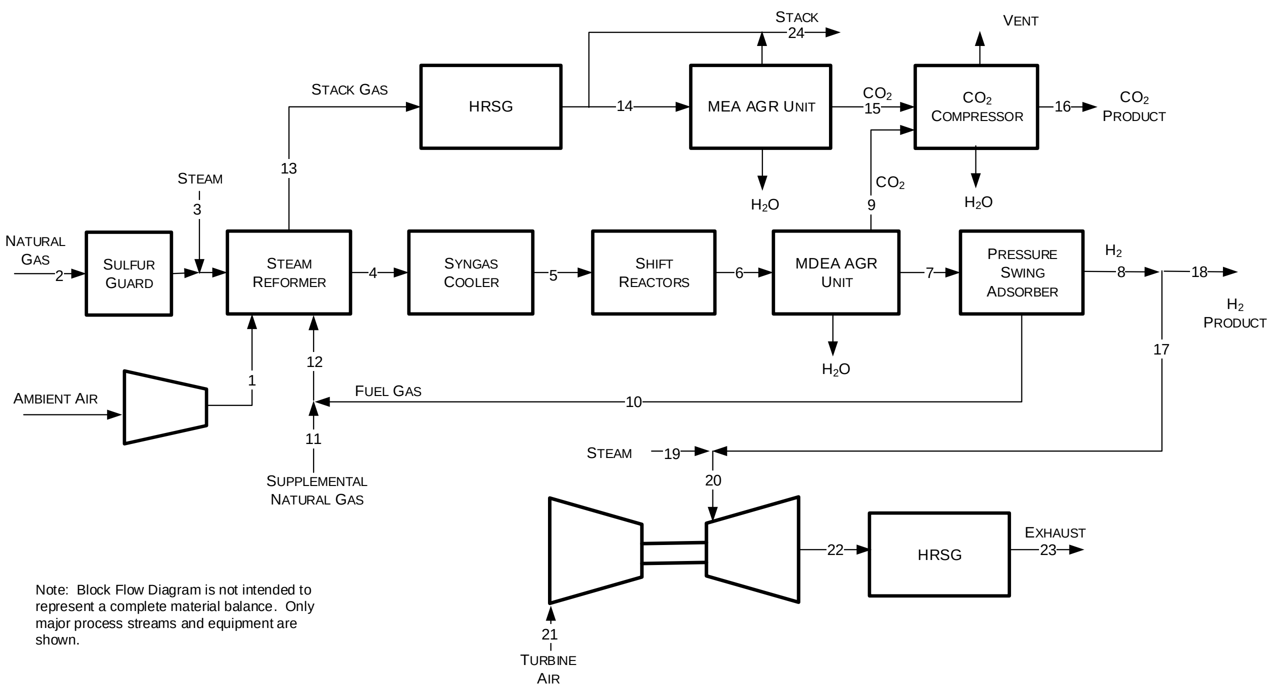
Highlights

- Coproduction of hydrogen and power is potentially economically viable
- Steam methane reforming (SMR) is the low-cost technology of choice for coproduction of hydrogen and power with 90% CCS
- Oxygen-blown autothermal reforming (ATR) appears competitive with SMR for hydrogen production at small scale but is not a superior process for hydrogen and power coproduction

Outcomes

- Update to accuracy and understanding of SMR technology
- Sensitivity analyses identifying possible optimization paths for ATR

BFD for SMR w/ CT and CCS



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Natural Gas-Based Coproduction of Power and H_2 with CCS

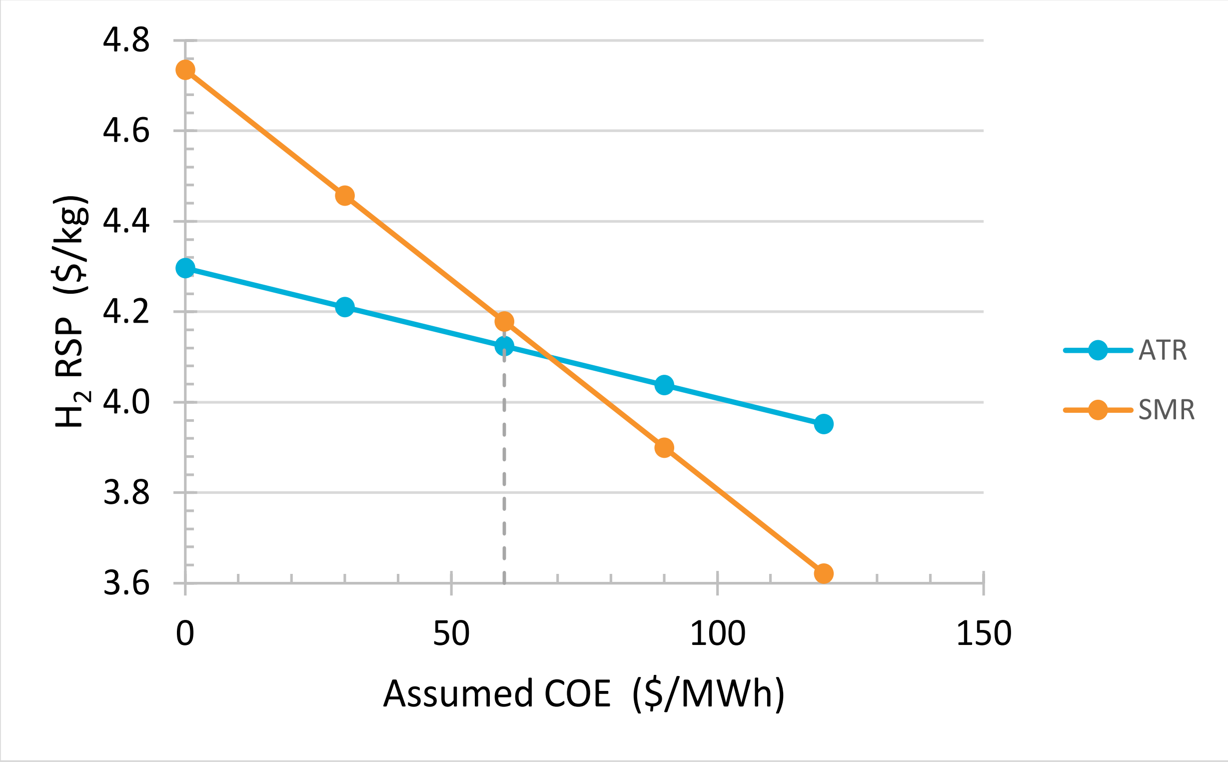
Approach

- Extensive literature survey performed
- Brainstorming sessions to identify potential co-production concepts of interest and proposed scale
- Spreadsheet level screening analysis used to down select most promising concepts
- Techno-economic analyses for 2 processes using Aspen Plus models

Results

Gross Plant Output, kWe		
	SMR	ATR
Gas Turbine Power	21,900	21,540
Steam Turbine Power	0	0
Total	**21,900**	**21,540**
Auxiliary Load, kWe		
Primary Air Fans / O_2 Compressor	210	2,600
CO_2 Compressor	2,420	3,120
Fuel Gas Recycle Compressor	---	1,520
Air Separation Unit	---	5,374
BFW and Ground Water Pumps	90	110
Circulating Water Pump	240	460
Cooling Tower Fans	120	230
CO_2 Capture/Removal Auxiliaries	1,030	1,060
Gas Turbine Auxiliaries[1]	0	0
Miscellaneous Balance of Plant[2]	20	20
Transformer Losses	80	110
Total	**4,210**	**14,604**

Sensitivity of H_2 RSP to electricity purchase price



Natural Gas-Based Coproduction of Power and H_2 with CCS

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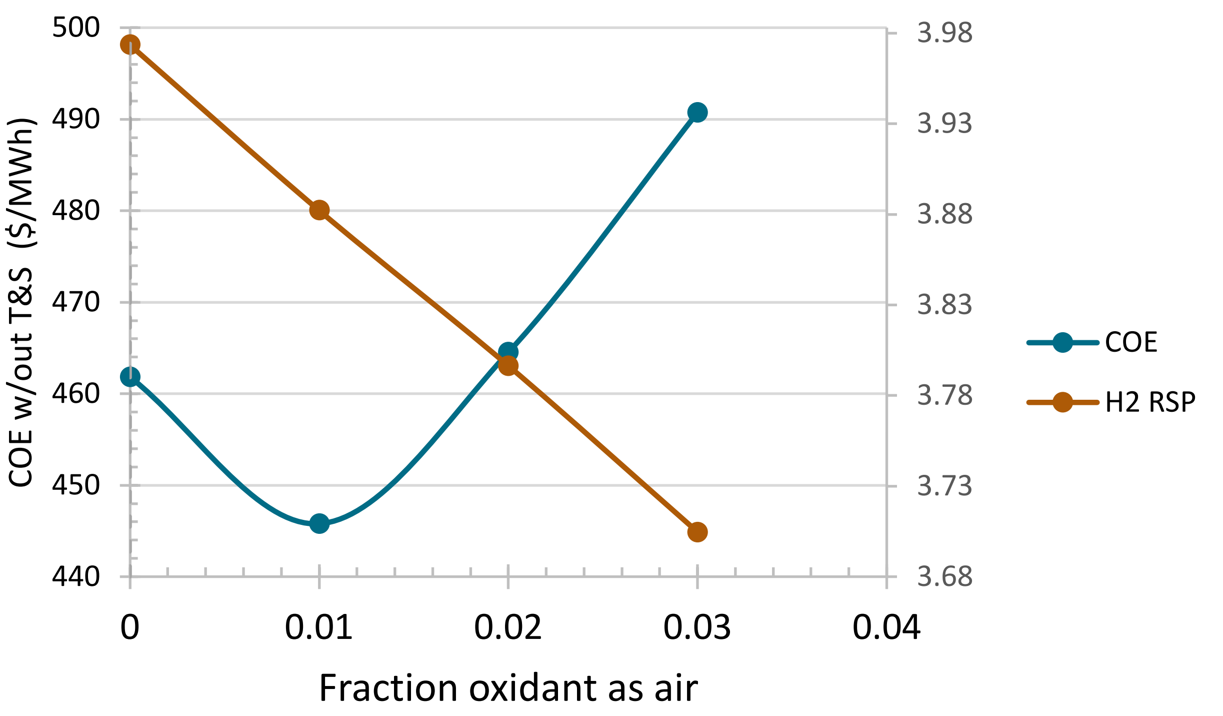
Results

Plant Performance Summary	SMR	ATR
Auxiliary Load, kW_e	4,210	14,604
Net Plant Power, kW_e	17,690	6,936
Natural Gas SMR Feed Flowrate, kg/hr (lb/hr)	11,706 (25,807)	15,268 (33,661)
Natural Gas SMR Thermal Input (HHV)[1], kW_{th}	172,381	224,845
Total Hydrogen Production, kg/hr (lb/hr)	3,583 (7,899)	2,416 (5,326)
Total Hydrogen Production (HHV)[2], kW_{th}	141,218	95,227
Hydrogen Production Efficiency (HHV)	79%	42%
Excess Hydrogen (Storage or Sale), kg/hr (lb/hr)	1,906 (4,203)	2,416 (5,326)
Hydrogen Fuel to Combustion Turbine, kg/hr (lb/hr)	1,676 (3,695)	1,659 (3,658)
Combustion Turbine Thermal Input (HHV), kW_{th}	66,071	65,400
Combustion Turbine Efficiency (HHV)[3]	33.1%	32.9%
Net Plant Efficiency (HHV)	54%	16%
CO2 Recovered, ton/day	739	962
CO2 Emissions, ton/day	82	57
Hydrogen Yield[4]	0.71	0.37
Raw Water Withdrawal, gpm	441	454

Sensitivity to feed ratio of air to oxidant in ATR



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Limitations

- Kinetic data for reformers not available
- TEAs limited to thermodynamic (equilibrium) analysis
- Cost algorithms extrapolated to a large degree
- Non-predictive models for AGR

Suggested Follow-On Work

- Vendor RFIs for cost quotes for small scale SMR, ATR, AGR units
- Enhance granularity of AGR models to allow process optimization
- Screening level TEAs for more advanced technologies (syngas chemical looping)
- Explore more use cases for hydrogen storage

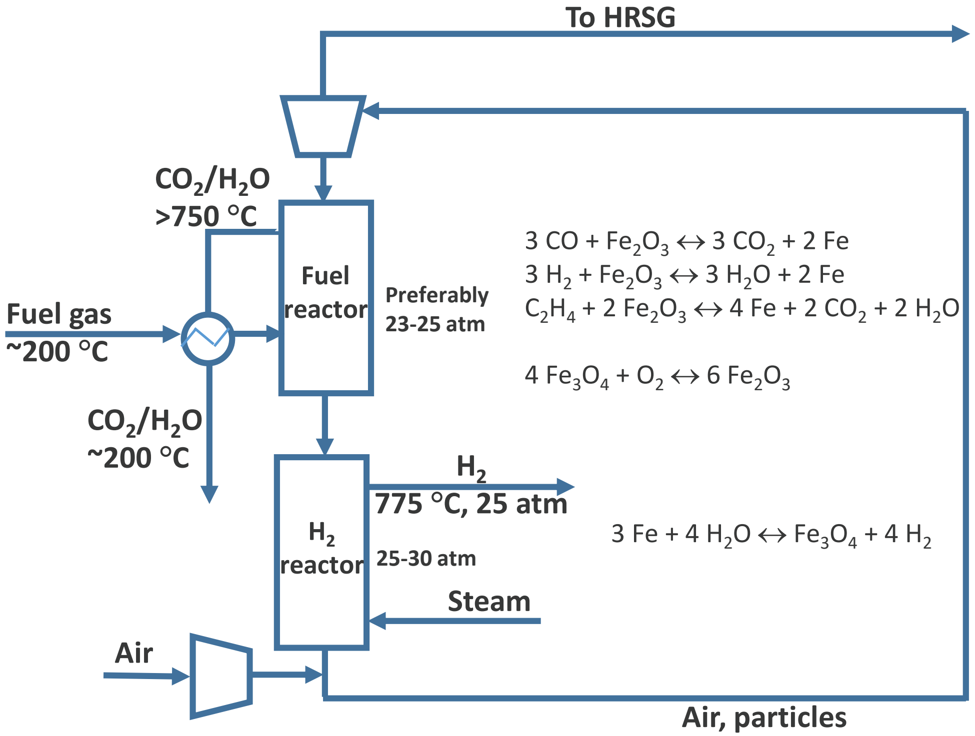
Data Resources and Project Coordination

- 2010 NETL/ESPA study on coal to H_2 with SMR reference case
- Cost data from prior studies (Baseline DPE, NG direct fired sCO_2)

Authors

- Jessica VanWagoner, KeyLogic
- Chuck White, KeyLogic

BFD for syngas chemical looping



Techno-economic Analysis

Baseline Steam Methane Reforming

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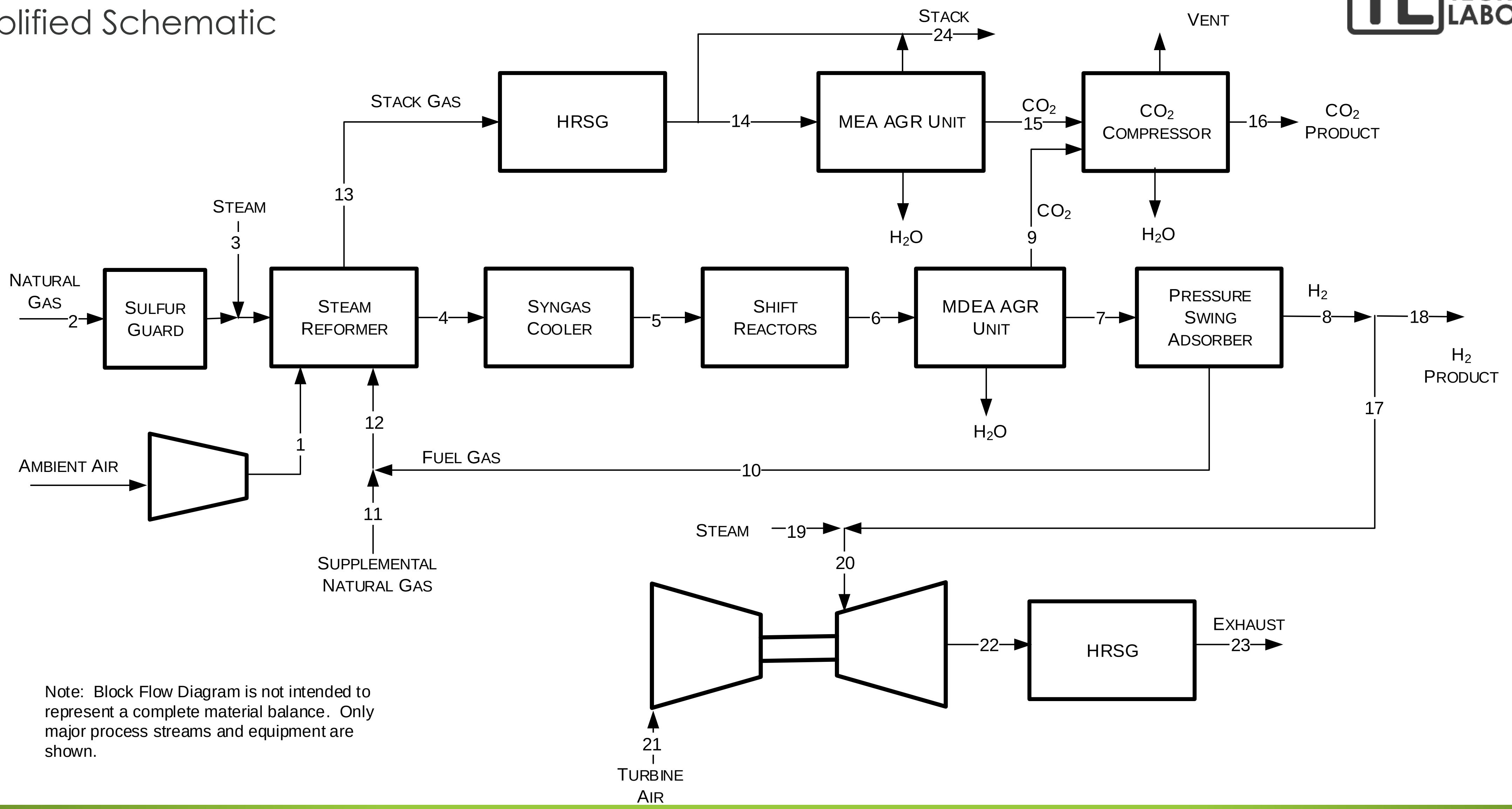
SMR with Pre- and Post-Combustion CCS

Simplified Schematic



Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

Techno-economic Analysis

Autothermal Reformer Technology

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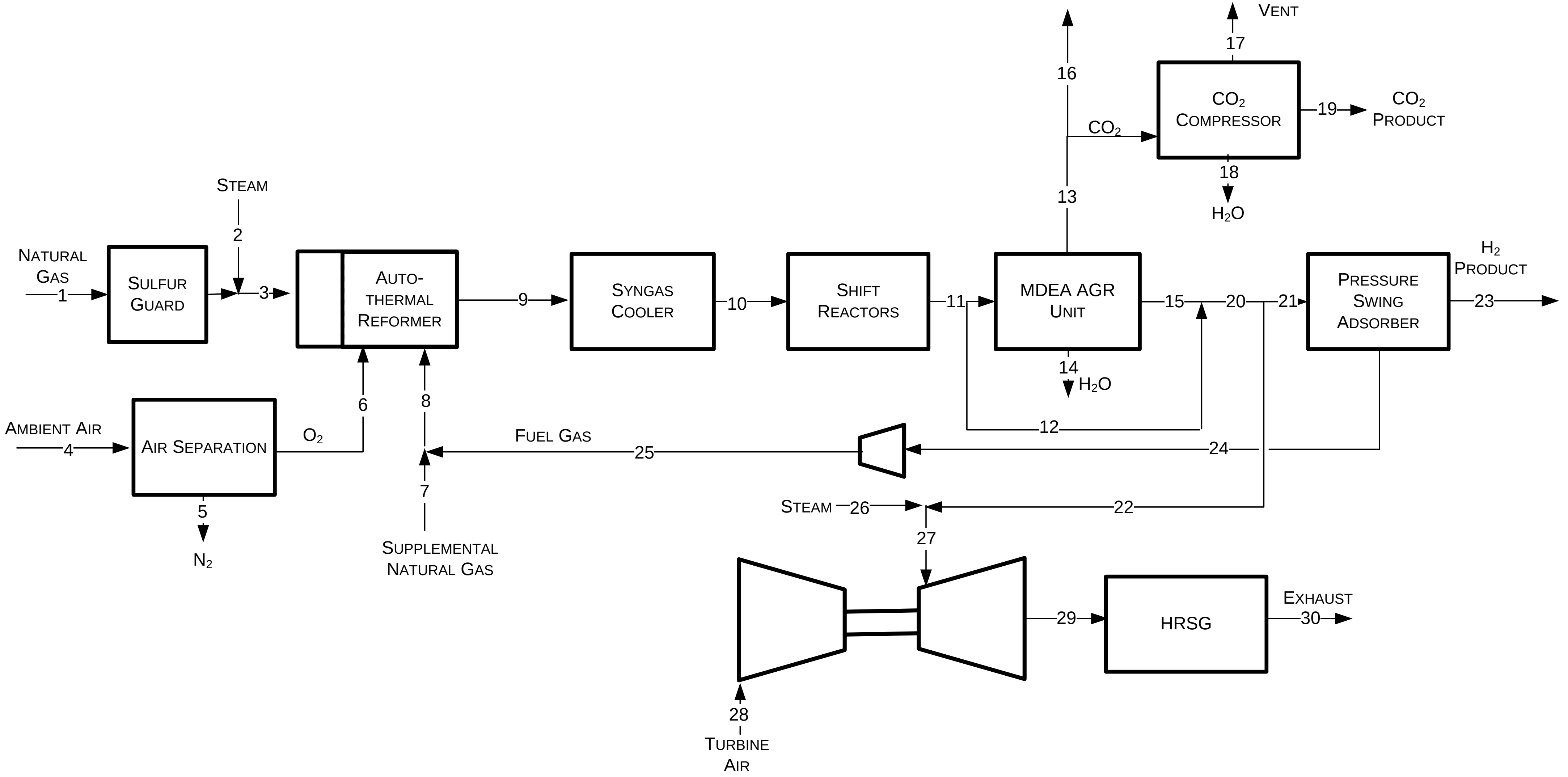
Autothermal Reformer Coproduction Case

Block Flow Diagram



Techno-economic Analysis

Design Basis

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Site, Fuel and Hydrogen Characteristics

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Site Characteristics[1]

Parameter	Value
Location	Greenfield, Midwestern U.S.
Water	50 % Municipal and 50% Ground Water
Elevation, ft	0
Barometric Pressure, MPa (psia)	0.101 (14.696)
Average Ambient Dry Bulb Temperature, °C (°F)	15 (59)
Average Ambient Wet Bulb Temperature, °C (°F)	10.8 (51.5)
Design Ambient Relative Humidity, %	60
Cooling Water Temperature, °C (°F)[A]	15.6 (60)
Air composition based on published psychrometric data, mass %	
N_2	74.97
O_2	23.03
Ar	1.30
H_2O	0.65
CO_2	0.05
Total	100.00

Fuel Characteristics[1]

Component		Volume Percentage
Methane	CH_4	93.1
Ethane	C_2H_6	3.2
Propane	C_3H_8	0.7
n-Butane	C_4H_{10}	0.4
Carbon Dioxide	CO_2	1.0
Nitrogen	N_2	1.6
Methanethiol[A]	CH_4S	$5.75x10^{-6}$
	Total	100.00
	LHV	**HHV**
kJ/kg (Btu/lb)	47,454 (20,410)	52,581 (22,600)

[A]The sulfur content of natural gas is primarily composed of added Mercaptan (methanethiol, CH_4S) with trace levels of H_2S (11). Note: Fuel composition is normalized and heating values are calculated

Hydrogen Characteristics[2]

Product Specification		Product Purity
Hydrogen	H_2	99.9
	LHV	**HHV**
kJ/kg (Btu/lb)	120,017(51,585)	141,936 (61,006)

Source: [1]NETL, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3," July 2015.
[2] NETL, "Assessment of Hydrogen Production with CO2 Capture, Volume 1: Baseline State-of-the-Art Plants, Revision 1," November 2011.

Design Basis

- **Environmental targets**
  - 90% CO_2 capture for all cases
  - Sulfur Oxides (SO_2) controlled by zinc oxide guard bed
  - Nitrogen Oxides (NO_x) controlled with low NO_x burners to meet the emission standard of 2.5 ppmv (dry) @ 15% O_2
- **SMR plant basis**
  - SMR case based on Case 1-2 from the Assessment of Hydrogen Production with CO_2 Capture Volume 1: Baseline State-of-the-Art Plants (NETL, 2011)
  - Scaled down to provide approximately equal amounts of hydrogen for sale and turbine fuel
- **ATR plant basis**
  - Similar to SMR scale but limited by desire to have export power

Source: NETL, "Assessment of Hydrogen Production with CO2 Capture, Volume 1: Baseline State-of-the-Art Plants, Revision 1," November 2011.

Cost Estimating Methodology

- Capital costs were scaled from NETL reference cases found in NETL's Bituminous Baseline (Revision 3) (BBR3)[1], legacy SMR cost models[2], and DPE TEA Report in preparation
- Costs based on the BBR3 were scaled according to methodology outlined in the Cost Scaling Quality Guidelines for Energy System Studies
- Costs were escalated to 2018$
- Cost of electricity (COE) and the required selling price (RSP) of hydrogen were calculated using the methodology outlined in Revision 3 of the Bituminous Baseline
  - Financial parameter assumptions match those of Case B31B from Revision 3

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Source: [1]NETL, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3," July 2015.
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Uncertainty Analysis and Data Gaps

SMR Case

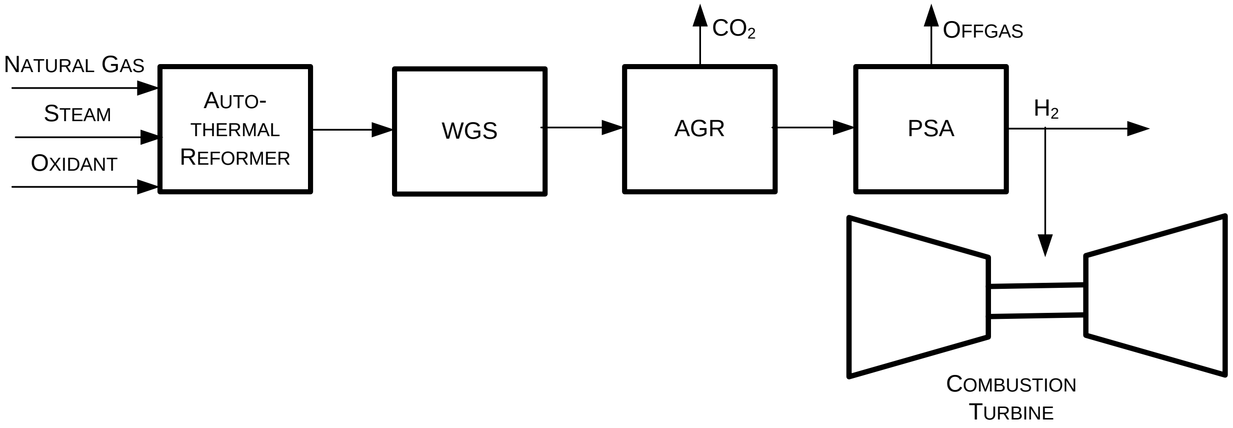
- **Capital costs associated with unit operations unique to the SMR process (reformer, PSA) were scaled using generic scaling factors, since scaling methodology for these accounts were not available**
- **Capital costs unique to the SMR process were scaled from costs in the legacy SMR cost models[1]**
  - These include capital costs for the reformer, PSA, and the MDEA system[2]
- **These capital costs may be outdated (2007$), and the original quote is not available**
- **The SMR scale in this study is ~7.2x smaller than the scale in the legacy SMR work**
- **Future work could aim to obtain updated SMR quotes and also quotes specific to the scale considered in this study**

[1] NETL, "Assessment of Hydrogen Production with CO2 Capture, Volume 1: Baseline State-of-the-Art Plants, Revision 1," November 2011.
[2] Although there are more recent estimates for MDEA systems, these are MDEA units for sulfur removal and quotes are based on a different set of operating conditions.

Uncertainty Analysis and Data Gaps

ATR Case

- **Largest areas on uncertainty**
  - ATR capital cost
  - ATR temperature at which catalyst is no longer necessary
  - MDEA capital cost
- **Vendor quotes at target scale needed for:**
  - ATR
  - ASU
  - AGR
- **Reduction in uncertainty unlikely to impact relative ranking of technologies**



Techno-economic Analysis

Performance Results

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Plant Performance Results

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CO2 Recovered, ton/day	739	962
CO2 Emissions, ton/day	82	57
Hydrogen Yield[4]	0.71	0.37
Raw Water Withdrawal, gpm	441	454

[1]HHV of Natural Gas is 53,014 kJ/kg (22,792 Btu/lb)
[2]HHV of Hydrogen is 141,900 kJ/kg (61,006 Btu/lb)
[3]Not including fuel dilution steam

Power Performance Summary

Gross Plant Output, kWe		
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Gas Turbine Power	21,900	21,540
Steam Turbine Power	0	0
Total	**21,900**	**21,540**
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CO_2 Capture/Removal Auxiliaries	1,030	1,060
Gas Turbine Auxiliaries[1]	0	0
Miscellaneous Balance of Plant[2]	20	20
Transformer Losses	80	110
Total	**4,210**	**14,604**

[1]Gas turbine auxiliary loads are accounted for in the gas turbine output power.

[2]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads.

Techno-economic Analysis

Economic Analysis Results

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Cost Results Summary

Capital Costs

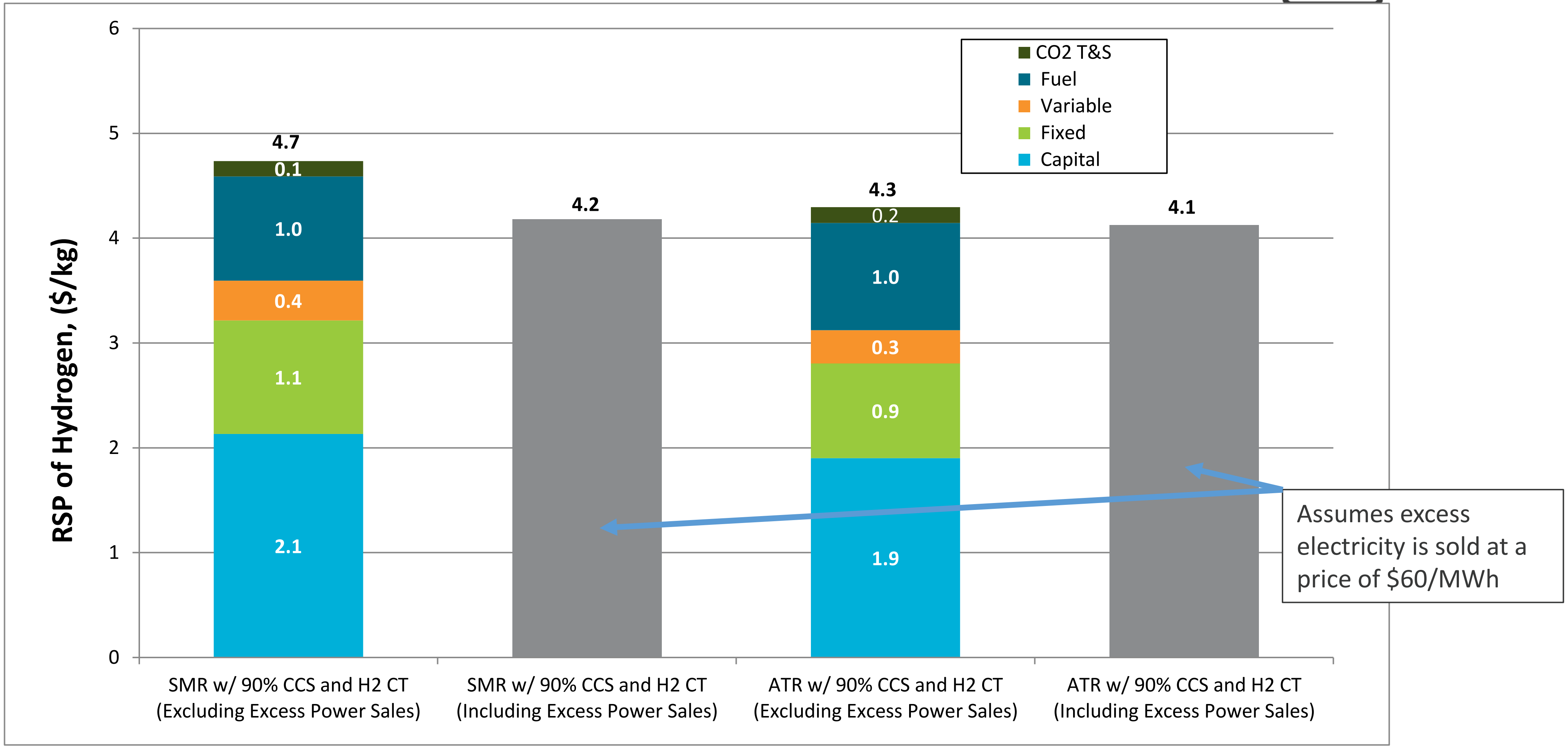
Account	Case 1 - SMR	Case 2 – ATR
	Total Plant Cost ($/1,000) (2018)	
Account 3: Feedwater and Miscellaneous BOP Systems	30,483	29,734
Account 5A: Gas Cleanup and Piping	4,899	6,190
Account 5B: CO_2 Removal and Compression	97,596	69,491
Account 6: Combustion Turbine and Accessories	11,691	11,691
Account 7: HRSG, Ductwork and Stack	7,070	8,476
Account 9: Cooling Water System	4,306	6,392
Account 11: Accessory Electric Plant	14,754	21,695
Account 12: Instrumentation and Control	4,026	8,492
Account 13: Improvements to Site	3,901	3,889
Account 14: Buildings and Structures	1,891	1,922
Account 15: Methane Reformer	29,893	74,445
Account 16: Pressure Swing Adsorber	10,301	7,516
Total	**220,811**	**249,933**

Cost Results Summary

Owner's Costs

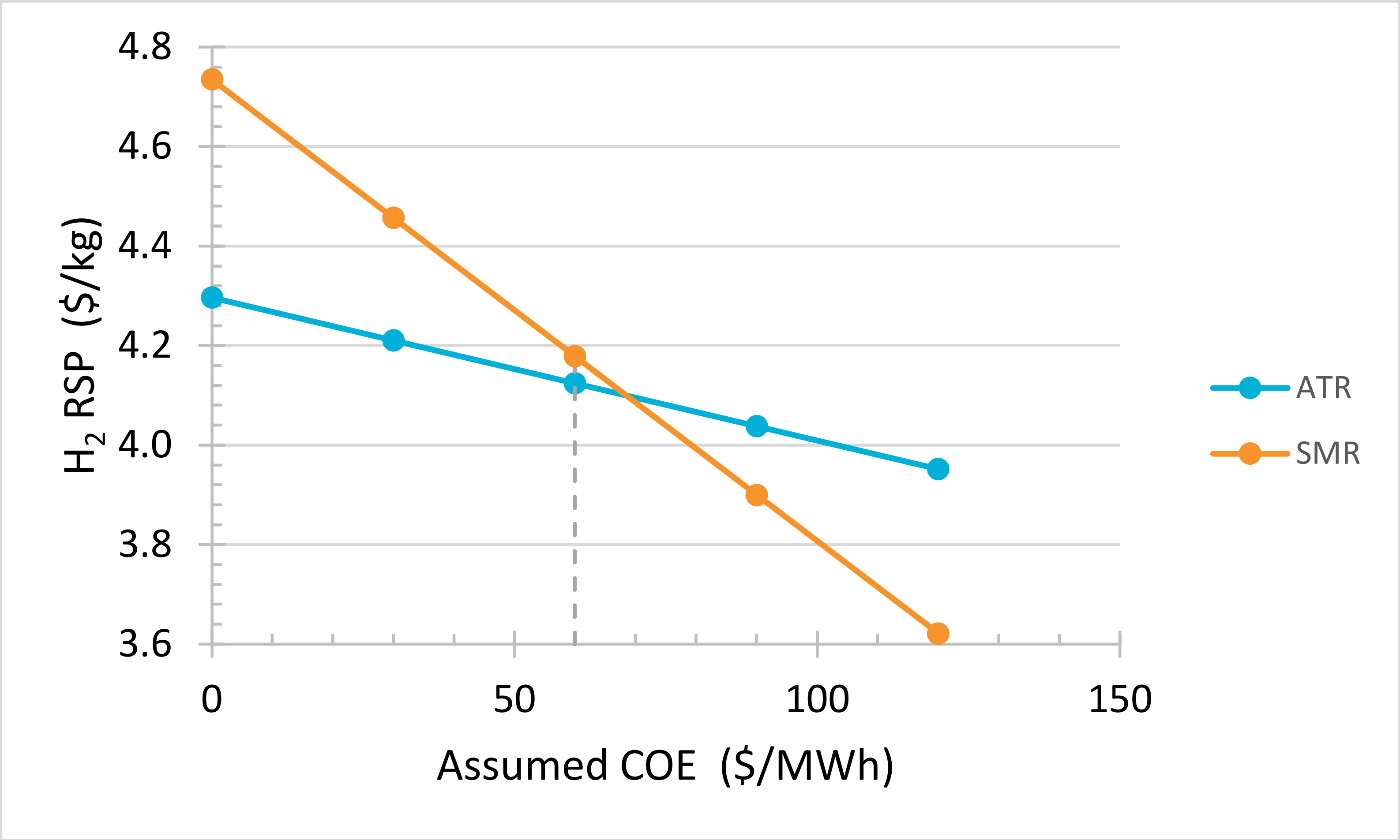
Owner's Costs	SMR	ATR
Units	**($/1,000)**	**($/1,000)**
Pre-Production Costs		
6 Months All Labor	$5,488	$5,634
1 Month Maintenance Materials	$442	$500
1 Month Non-fuel Consumables	$84	$57
0.5% of TPC (spare parts)	$1,104	$1,250
Other Owner's Costs	$33,122	$37,490
Financing Costs	$5,962	$6,748
Total Overnight Costs (TOC)	**$272,587**	**$308,147**
TASC Multiplier (IOU, high-risk, 33 year)	1.078	1.078
Total As-Spent Cost (TASC)	**$293,849**	**$332,182**

Required Selling Price (RSP) of Excess H_2

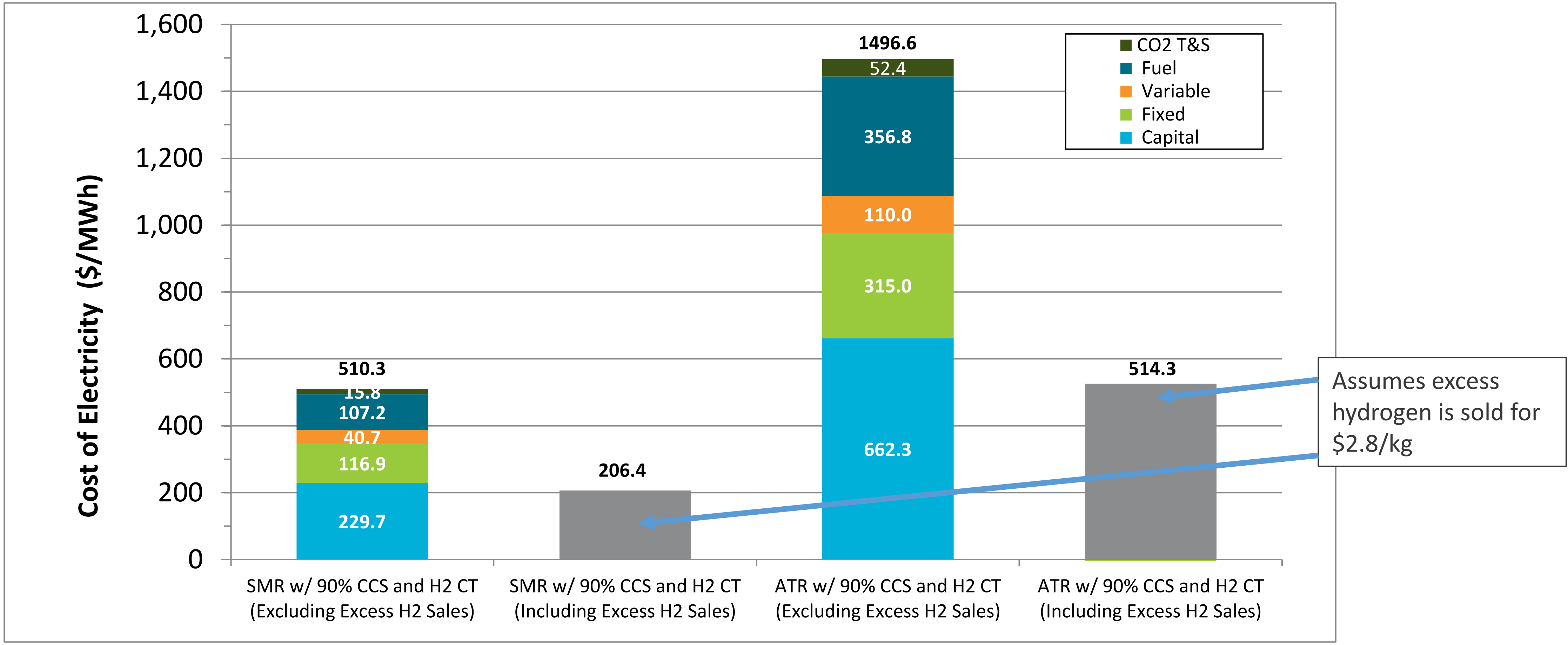


- H_2 T&S not included in RSP

RSP Sensitivity to Electricity Purchase Price



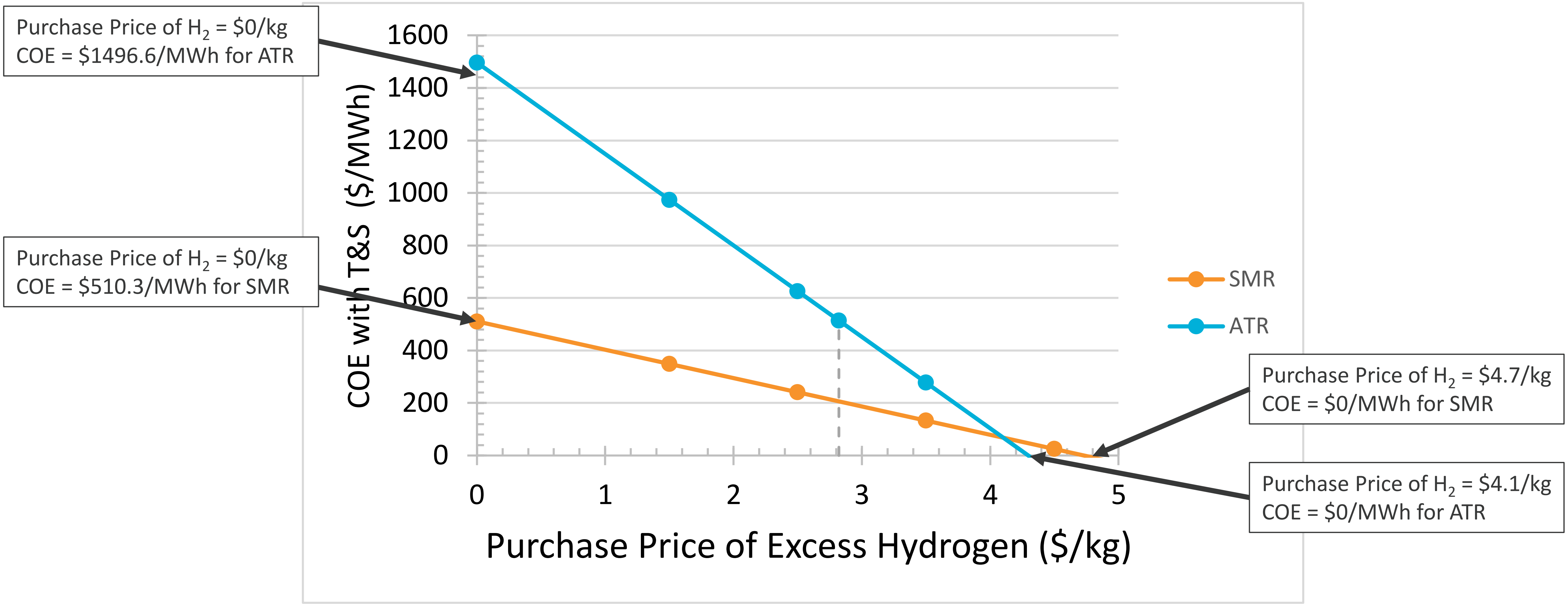
Cost of Electricity (COE)



- H_2 T&S not included in RSP

Direct-fired Reformer Coproduction Case

COE Sensitivity to Hydrogen Purchase Price



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Additional Sensitivity Analyses

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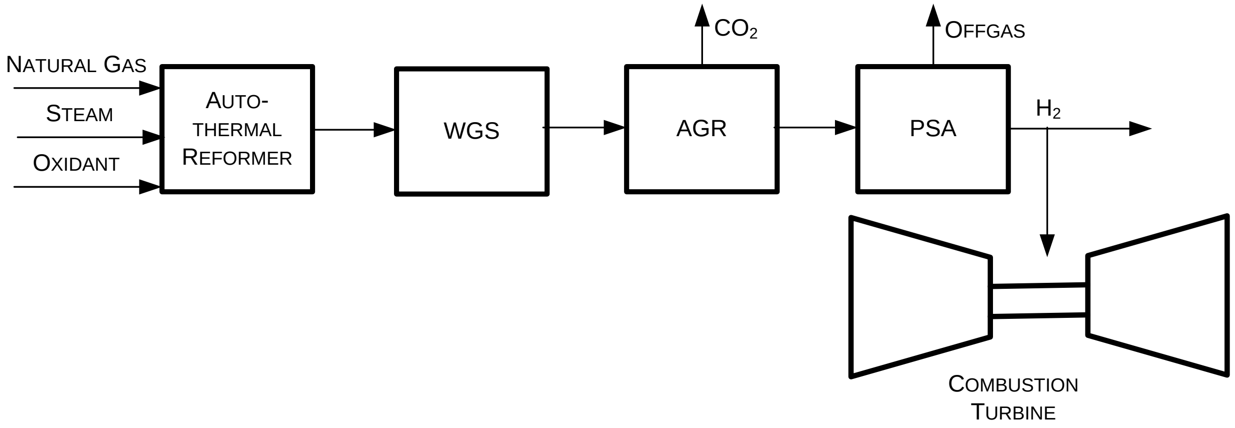
Additional Sensitivity Analyses

Direct-fired Reformer Coproduction Case

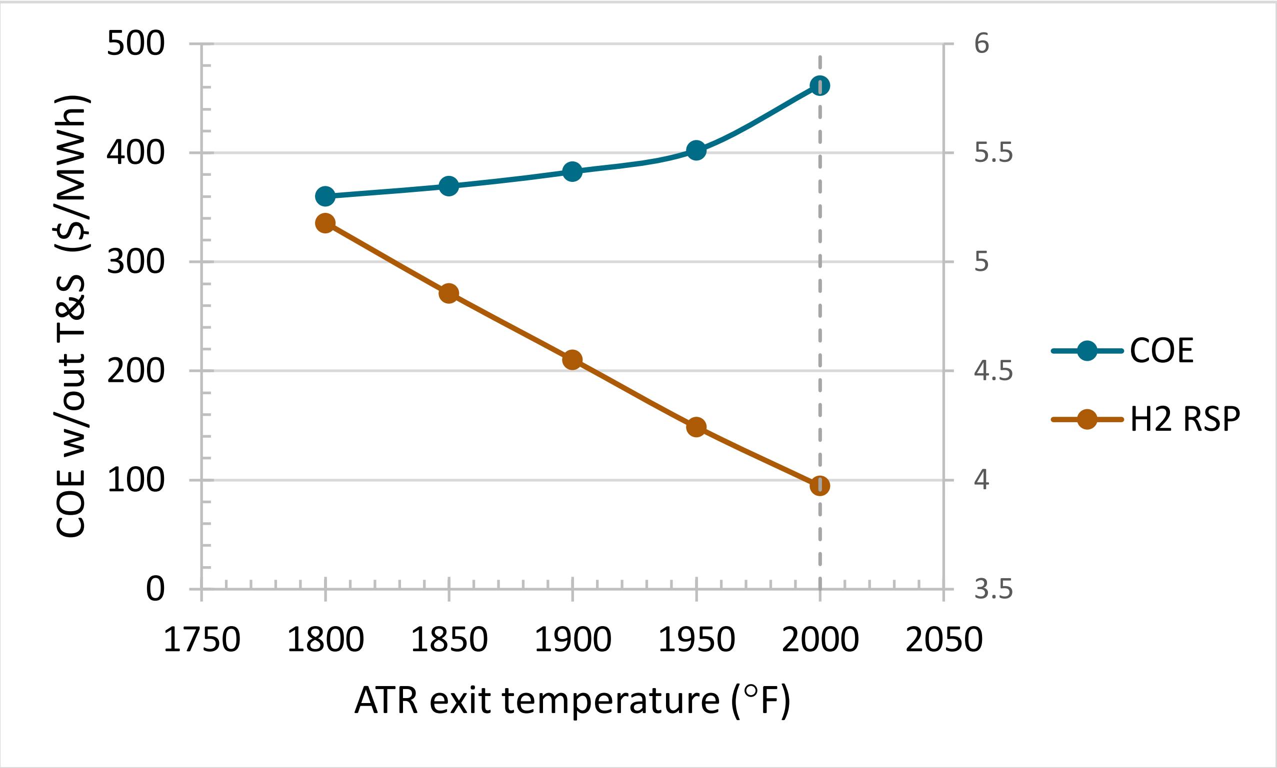
- **Sensitivity analyses performed to assess performance and economic impacts of:**
  - ATR temperature
  - ATR pressure
  - Oxygen purity (Oxygen:air ratio)
  - Hydrogen production rate
  - Assumed natural gas price



Range Sensitivity Analysis to ATR Temperature

Direct-fired Reformer Coproduction Case

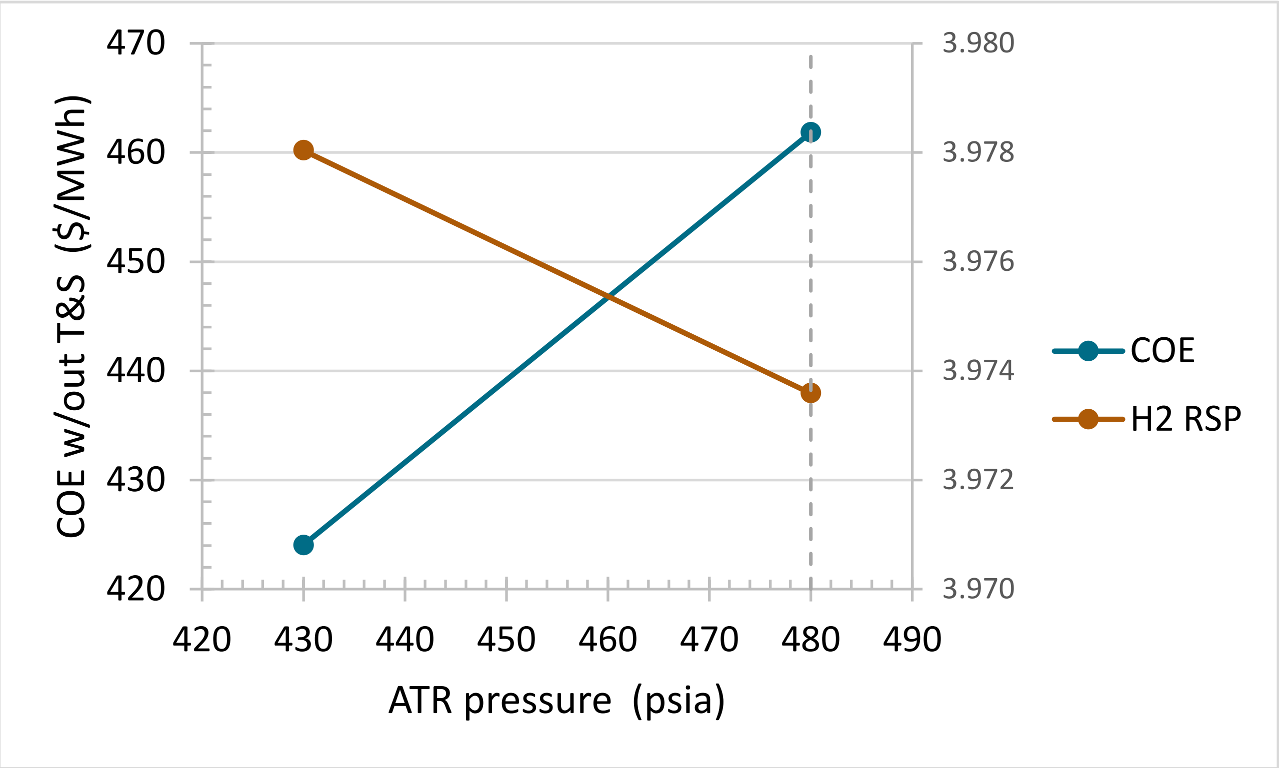
- **Plot shows estimated COE and H_2 RSP as a function of ATR exit temperature**
- **Temperature ranged from 1800 °F to 2000 °F (baseline)**
- **Assumed no catalyst required**
- **H_2 RSP decreases with increasing temperature whereas COE increases**



Perturbation Sensitivity Analysis to ATR Pressure

Direct-fired Reformer Coproduction Case

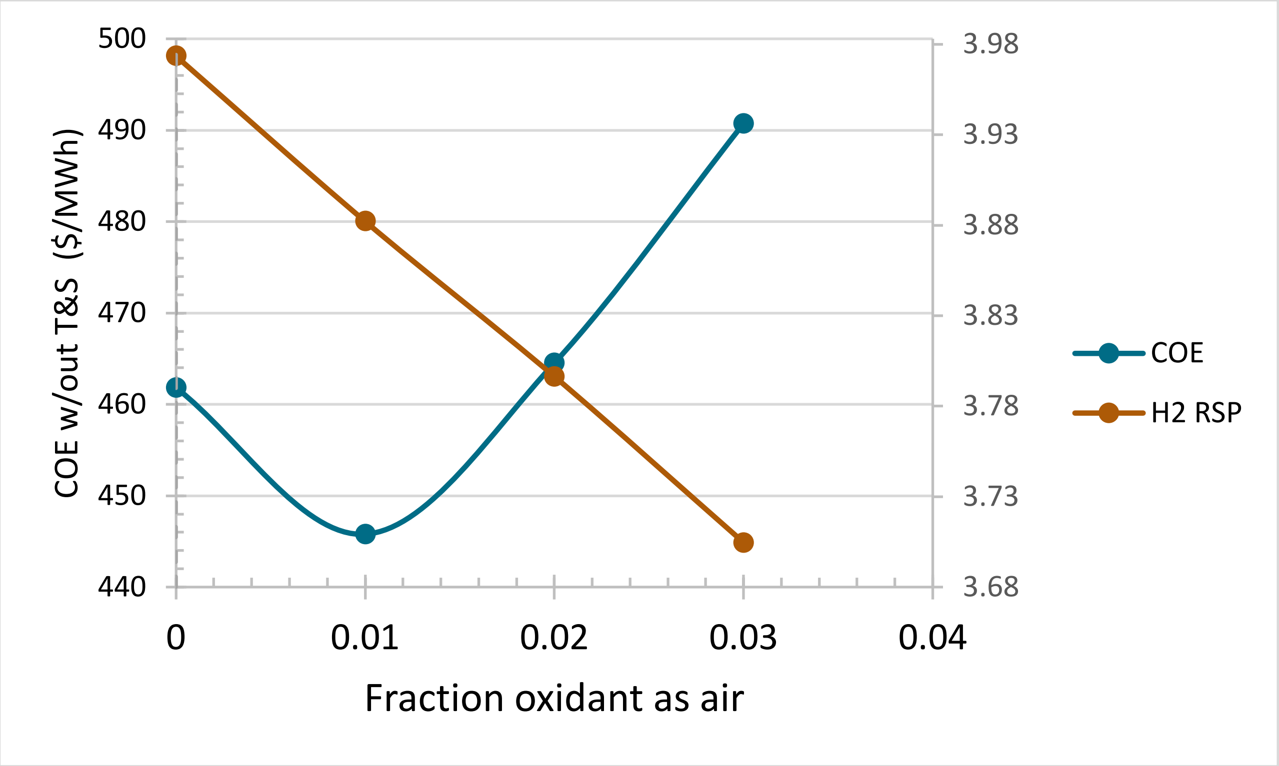
- **Plot shows estimated COE and H_2 RSP as a function of ATR inlet pressure**
- **Single pressure evaluated (430 psia) compared to baseline (480 psia)**
- **Process and computation constraints limited range**
- **H_2 RSP decreases slightly with increasing pressure whereas COE increases moderately**



Small Range Sensitivity Analysis to Oxygen:Air Ratio

Direct-fired Reformer Coproduction Case

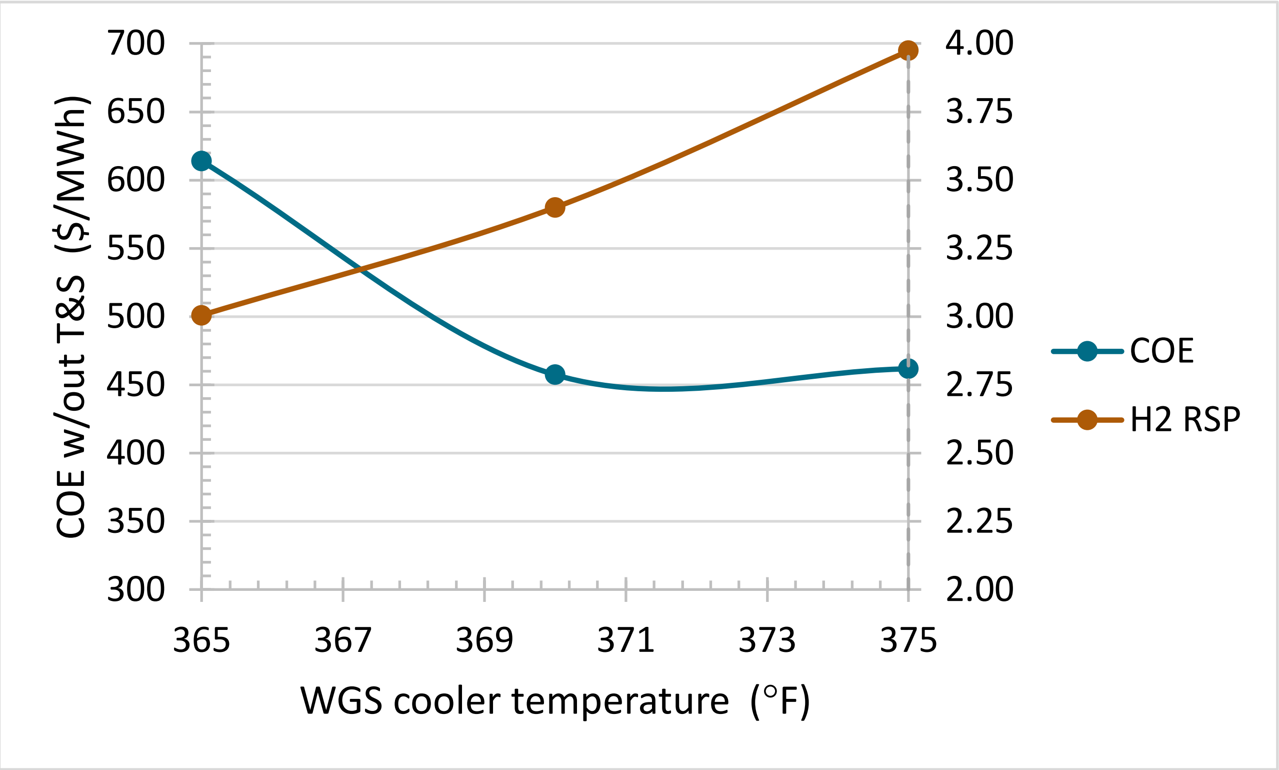
- **Plot shows estimated COE and H_2 RSP as a function of fraction of oxidant as air**
- **Air oxidant fraction ranged from 0.0 to 0.03**
- **Model computation constraints limited range**
- **H_2 RSP decreases slightly with increasing air whereas COE passes through a minimum and then rises rapidly**



Small Range Sensitivity Analysis to Hydrogen Production

Direct-fired Reformer Coproduction Case

- **Plot shows estimated COE and H_2 RSP as a function of WGS cooler temperature**
- **As WGS cooler temperature decreases, more H_2 produced**
- **Requirement to have excess power limited range**
- **As WGS cooler temperature decreases, H_2 RSP decreases whereas COE passes through a minimum and then rises rapidly**



Range Sensitivity Analysis to Assumed Price of Natural Gas

Direct-fired Reformer Coproduction Case

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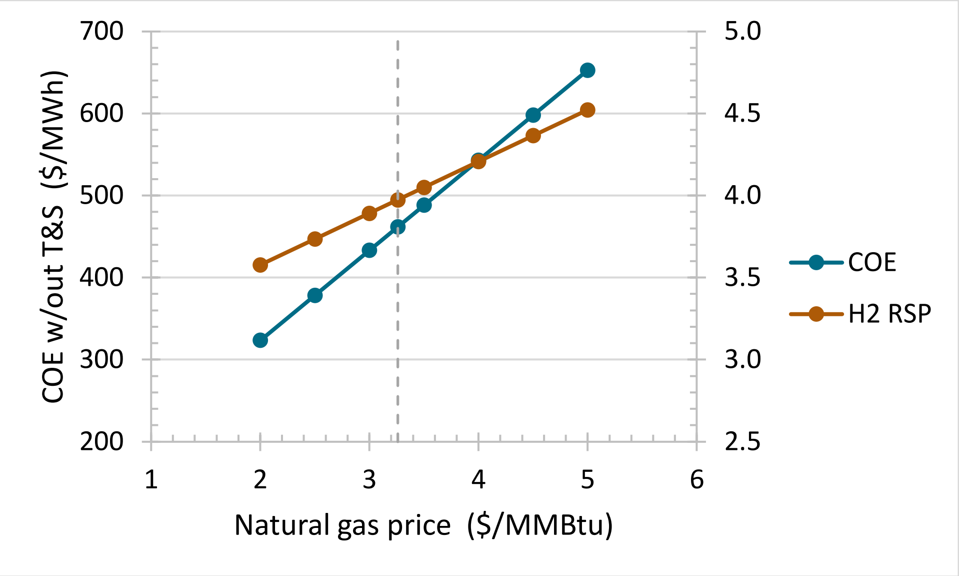
- **Plot shows estimated COE and H_2 RSP as a function of the assumed NG price**
- **NG price range 2-5 \$/MMBtu**
- **As NG price increases, both COE and H2 RSP increase monotonically**
- **Every \$1/MMBtu increase in NG price increases:**
  - COE by 110 \$/MWh
  - H_2 RSP by 0.315 \$/kg



Questions?

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