Natural Gas-Based Coproduction of Power and H$_2$ with CCS

Chuck White[1] and Jess VanWagoner[1]

[1]KeyLogic Systems, LLC

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

Disciaimer and Acknowledgement

DISCLAIMER

"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

ACKNOWLEDGEMENT

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 H₂ with CCS

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
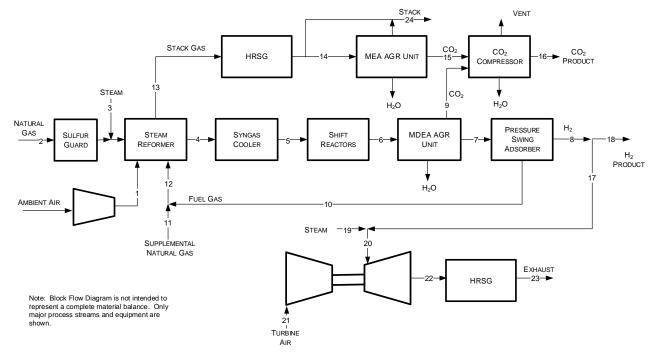
Highlights

- 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

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

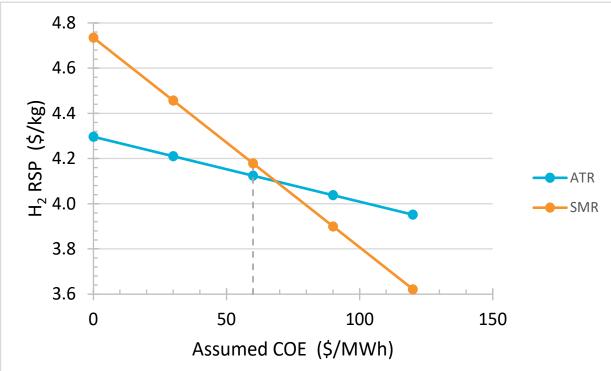# Natural Gas-Based Coproduction of Power and H_2 with CCS

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

U.S. DEPARTMENT OF ENERGY

Natural Gas-Based Coproduction of Power and H₂ with CCS

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

Chart: COE w/out T&S ($/MWh) and H2 RSP vs. Fraction oxidant as air; series COE and H2 RSP.

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)
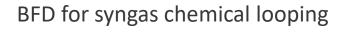- Explore more use cases for hydrogen storage

Data Resources and Project Coordination

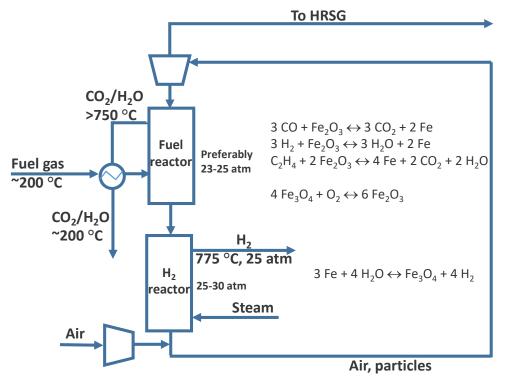- 2010 NETL/ESPA study on coal to H_2 with SMR reference case
- Cost data from prior studies (Baseline DPE, NG direct fired sCO_2)

Authors

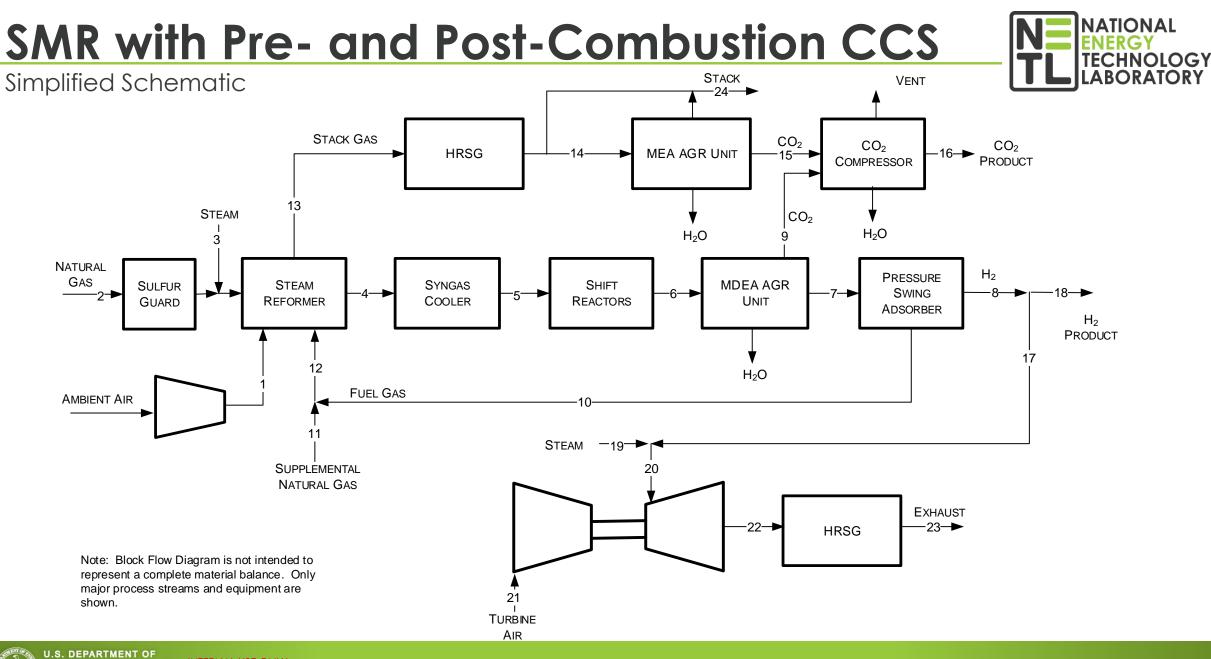- Jessica VanWagoner, KeyLogic
- Chuck White, KeyLogic

BFD for syngas chemical looping

To HRSG

CO_2/H_2O >750 °C

Fuel gas ~200 °C

Fuel reactor — Preferably 23-25 atm

$3\ CO + Fe_2O_3 \leftrightarrow 3\ CO_2 + 2\ Fe$
$3\ H_2 + Fe_2O_3 \leftrightarrow 3\ H_2O + 2\ Fe$
$C_2H_4 + 2\ Fe_2O_3 \leftrightarrow 4\ Fe + 2\ CO_2 + 2\ H_2O$

$4\ Fe_3O_4 + O_2 \leftrightarrow 6\ Fe_2O_3$

CO_2/H_2O ~200 °C

H_2 775 °C, 25 atm

H_2 reactor — 25-30 atm

$3\ Fe + 4\ H_2O \leftrightarrow Fe_3O_4 + 4\ H_2$

Steam

Air

Air, particles

Techno-economic Analysis

Baseline Steam Methane Reforming

INTERNAL USE ONLY – NOT APPROVED FOR PUBLIC RELEASE

Solutions for Today | Options for Tomorrow

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
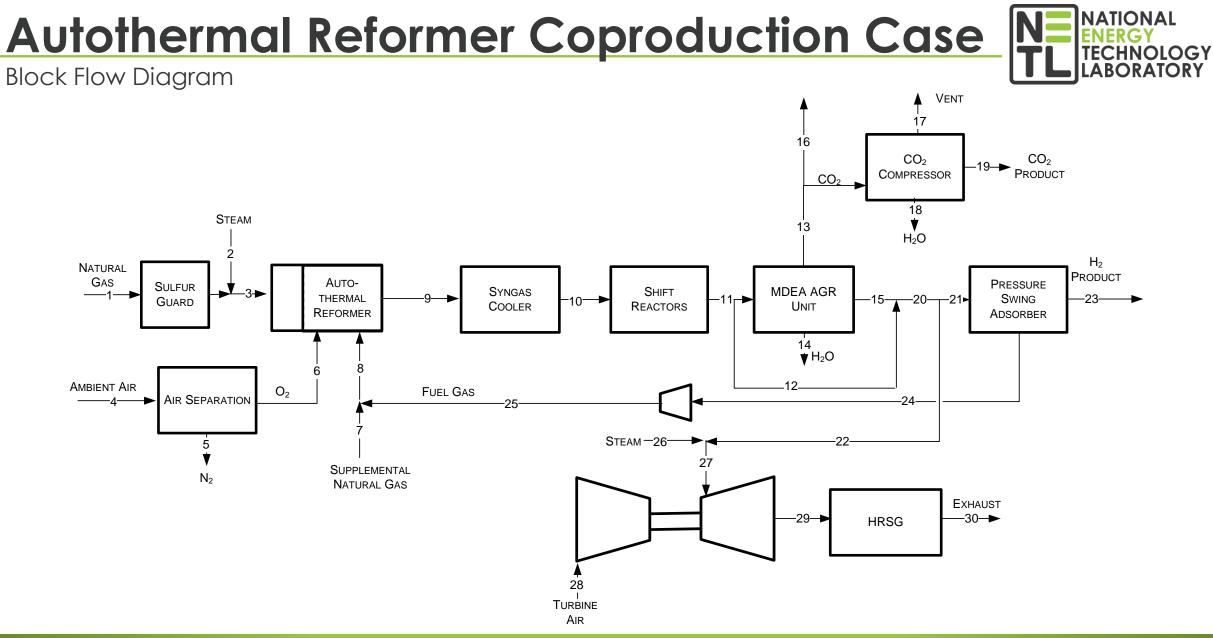
Autothermal Reformer Technology

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

Techno-economic Analysis

Design Basis

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

Site, Fuel and Hydrogen Characteristics

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	5.75×10^{-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)

U.S. DEPARTMENT OF ENERGY

INTERNAL USE ONLY – NOT APPROVED FOR PUBLIC RELEASE

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.

13

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

INTERNAL USE ONLY – NOT APPROVED FOR PUBLIC RELEASE

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

14

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

U.S. DEPARTMENT OF ENERGY

INTERNAL USE ONLY – NOT APPROVED FOR PUBLIC RELEASE

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.

15

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

U.S. DEPARTMENT OF ENERGY

INTERNAL USE ONLY – NOT APPROVED FOR PUBLIC RELEASE

[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.

16

Uncertainty Analysis and Data Gaps

ATR Case

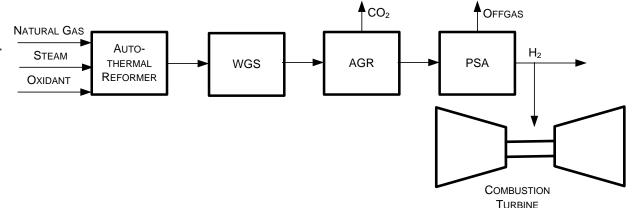- **Largest areas on uncertainty**
  - ATR capital cost
  - ATR temperature at which catalyst is no longer necessary
  - MDEA capital cost
- **Vendor quotes at target scale needed for:**
  - ATR
  - ASU
  - AGR
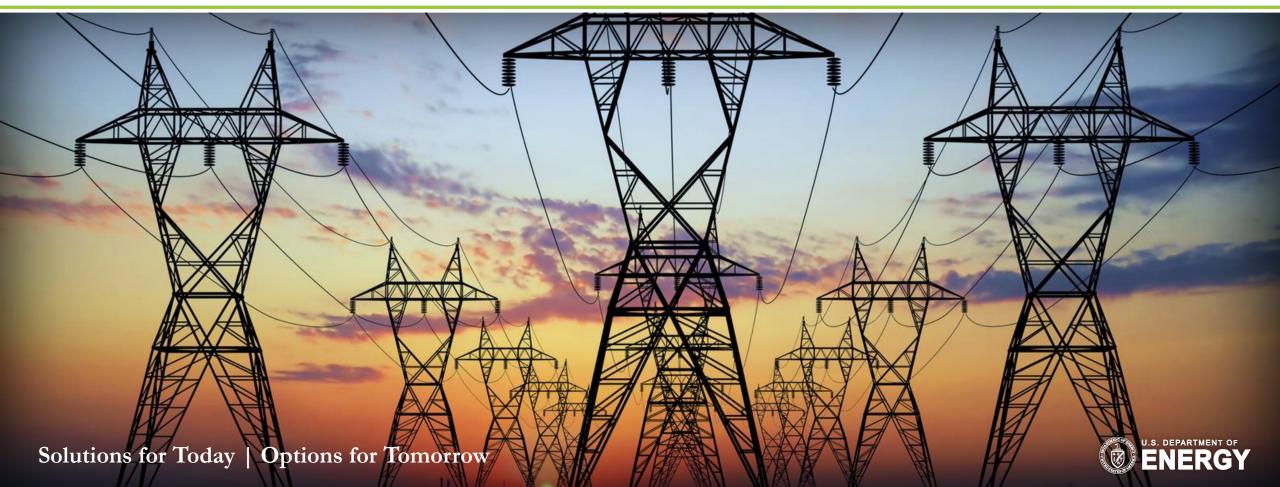- **Reduction in uncertainty unlikely to impact relative ranking of technologies**

Techno-economic Analysis

Performance Results

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF **ENERGY**

Plant Performance 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

[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		
	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**

[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.
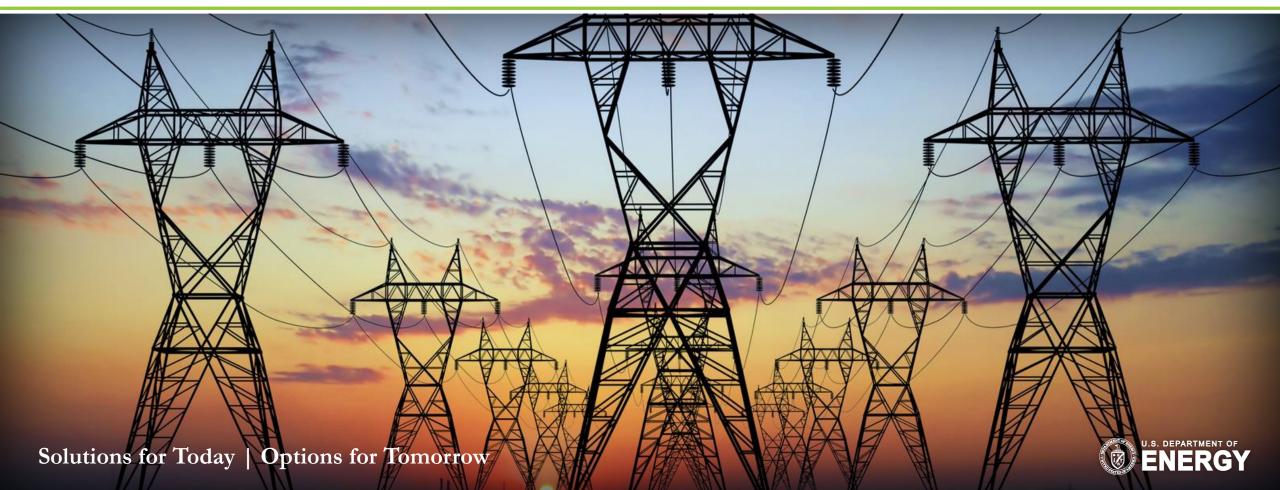
Techno-economic Analysis

Economic Analysis Results

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

Cost Results Summary
Capital Costs
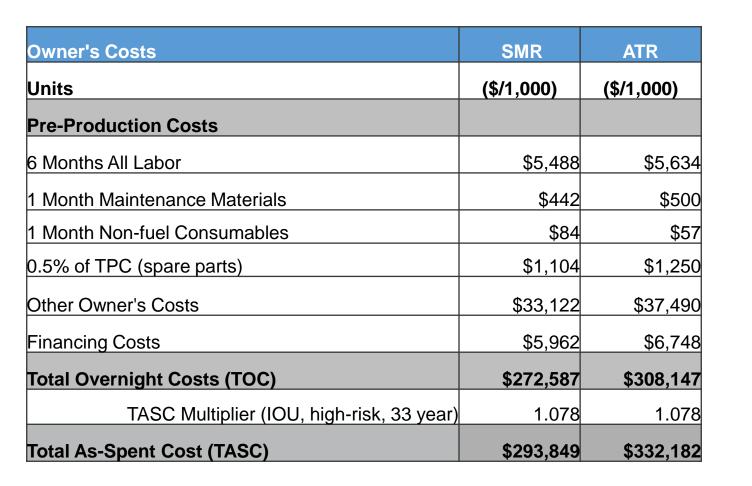
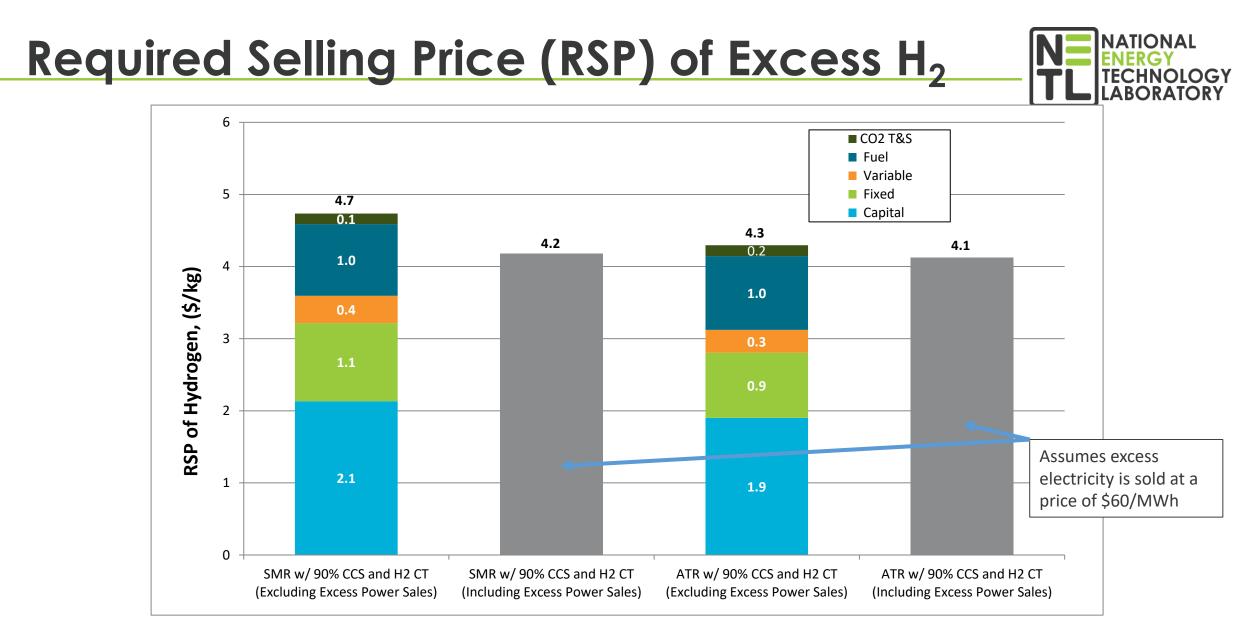| Account	Case 1 - SMR	Case 2 – ATR
	Total Plant Cost ($/1,000) (2018)	
Account 3: Feedwater and Miscellaneous BOP Systems	30,483	29,734
Account 5A: Gas Cleanup and Piping	4,899	6,190
Account 5B: CO_2 Removal and Compression	97,596	69,491
Account 6: Combustion Turbine and Accessories	11,691	11,691
Account 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
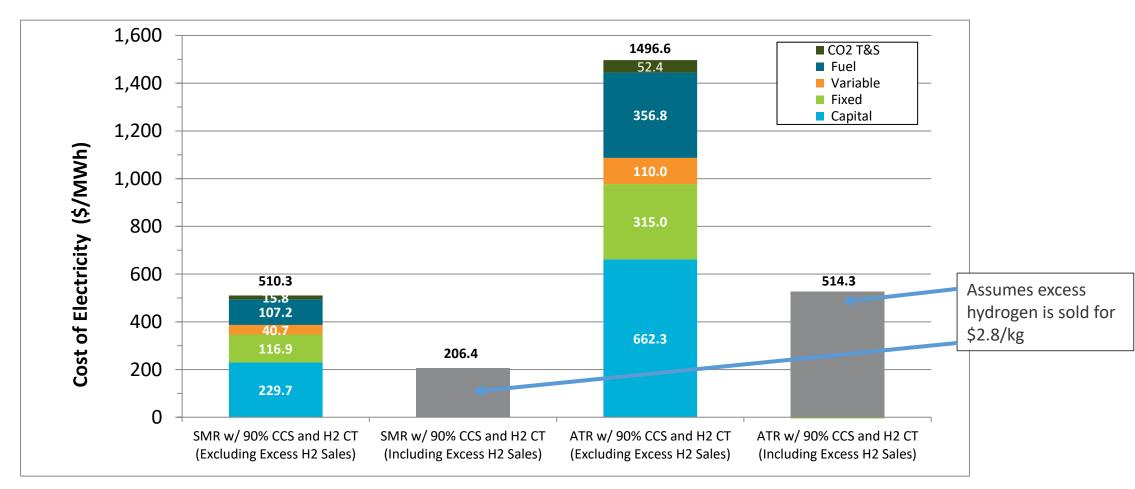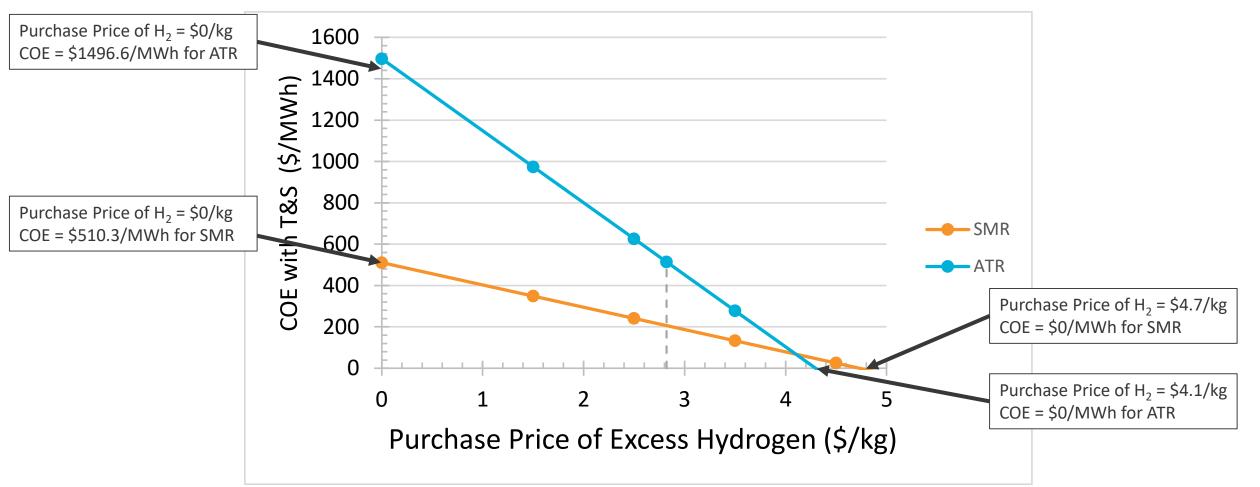
Cost of Electricity (COE)

H₂ T&S not included in RSP

Techno-economic Analysis

Additional Sensitivity Analyses

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF **ENERGY**

Additional Sensitivity Analyses

Direct-fired Reformer Coproduction Case
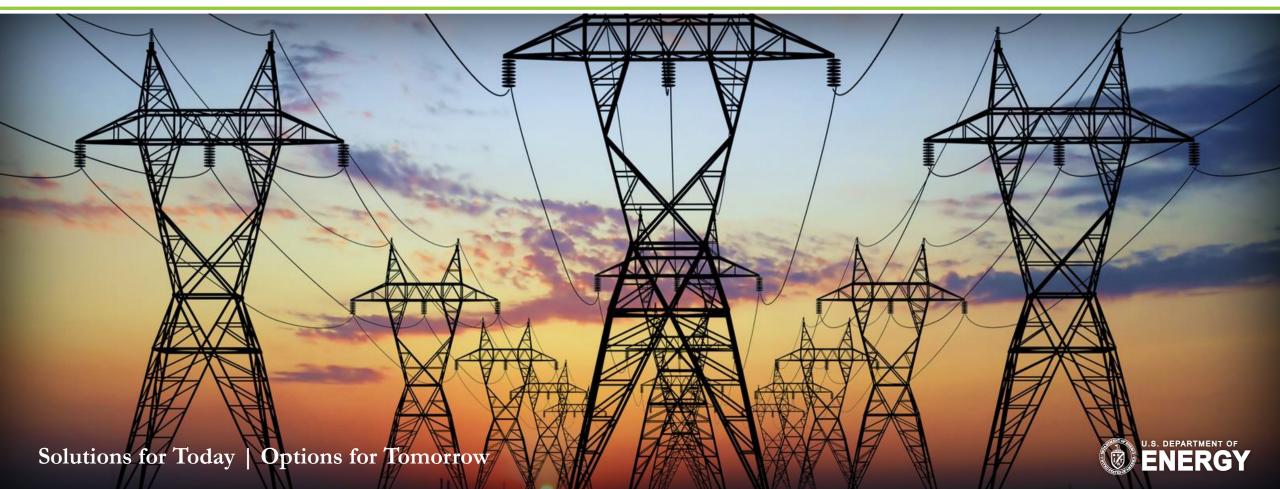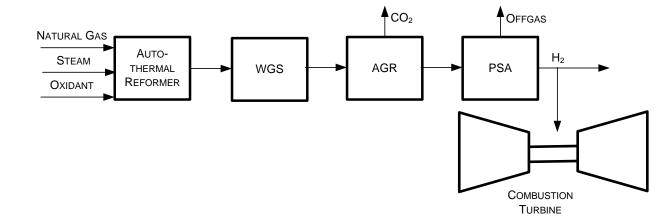
- **Sensitivity analyses performed to assess performance and economic impacts of:**
  - ATR temperature
  - ATR pressure
  - Oxygen purity (Oxygen:air ratio)
  - Hydrogen production rate
  - Assumed natural gas price
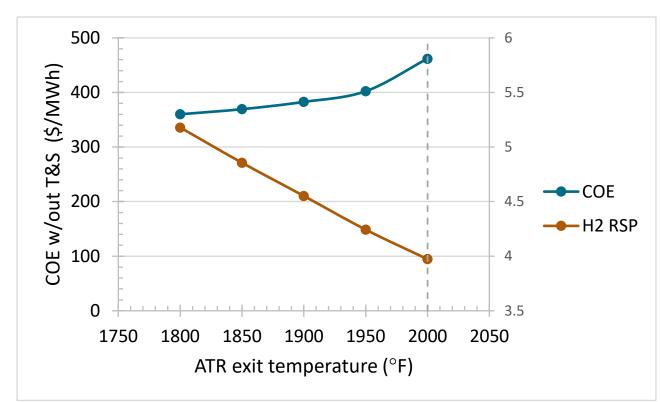
Range Sensitivity Analysis to ATR Temperature

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**

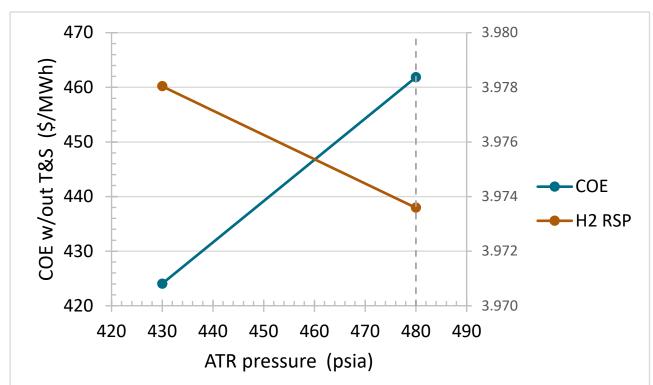- **H$_2$ RSP decreases with increasing temperature whereas COE increases**

Perturbation Sensitivity Analysis to ATR Pressure
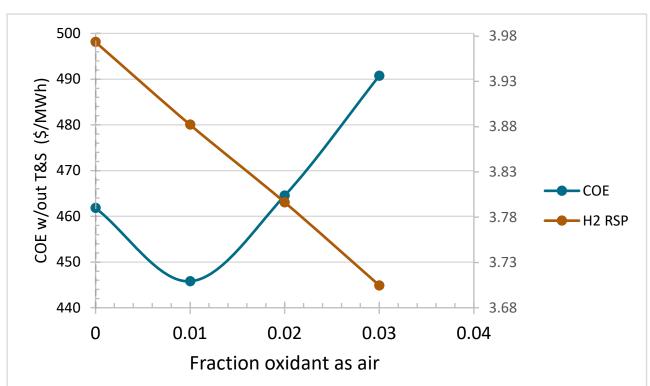
Direct-fired Reformer Coproduction Case

- **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**
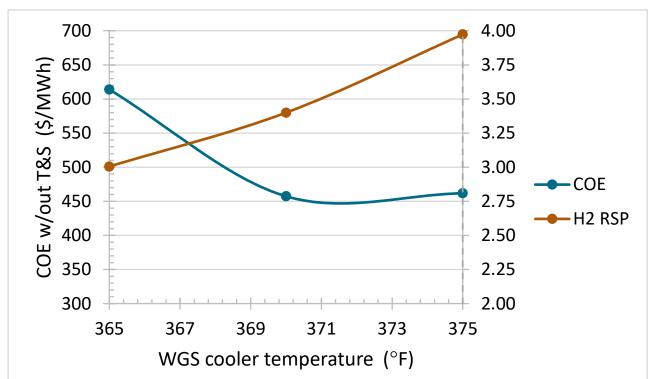
Small Range Sensitivity Analysis to Hydrogen Production

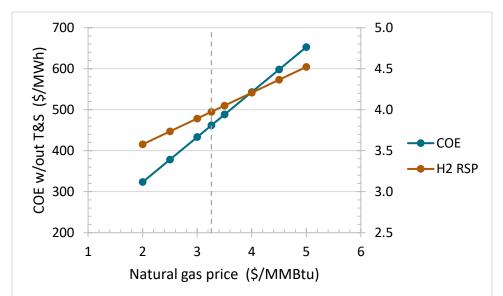Direct-fired Reformer Coproduction Case

- **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**

Direct-fired Reformer Coproduction Case

- **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?

Solutions for Today | Options for Tomorrow