

Hydrogen from Coal

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- **Coproduction of hydrogen and power from coal**
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- **Advanced SOFC configuration for hydrogen and power production from coal**
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- **Challenges**

Issues & Drivers for Hydrogen

- **ISSUES:**
 - low volumetric energy content (storage)
 - Infrastructure for Hydrogen Delivery
 - Carbon capture & Sequestration
 - Resources for Mass Production
- **DRIVERS:**
 - energy security
 - petroleum resource depletion
 - climate change & pollution

Hydrogen Storage



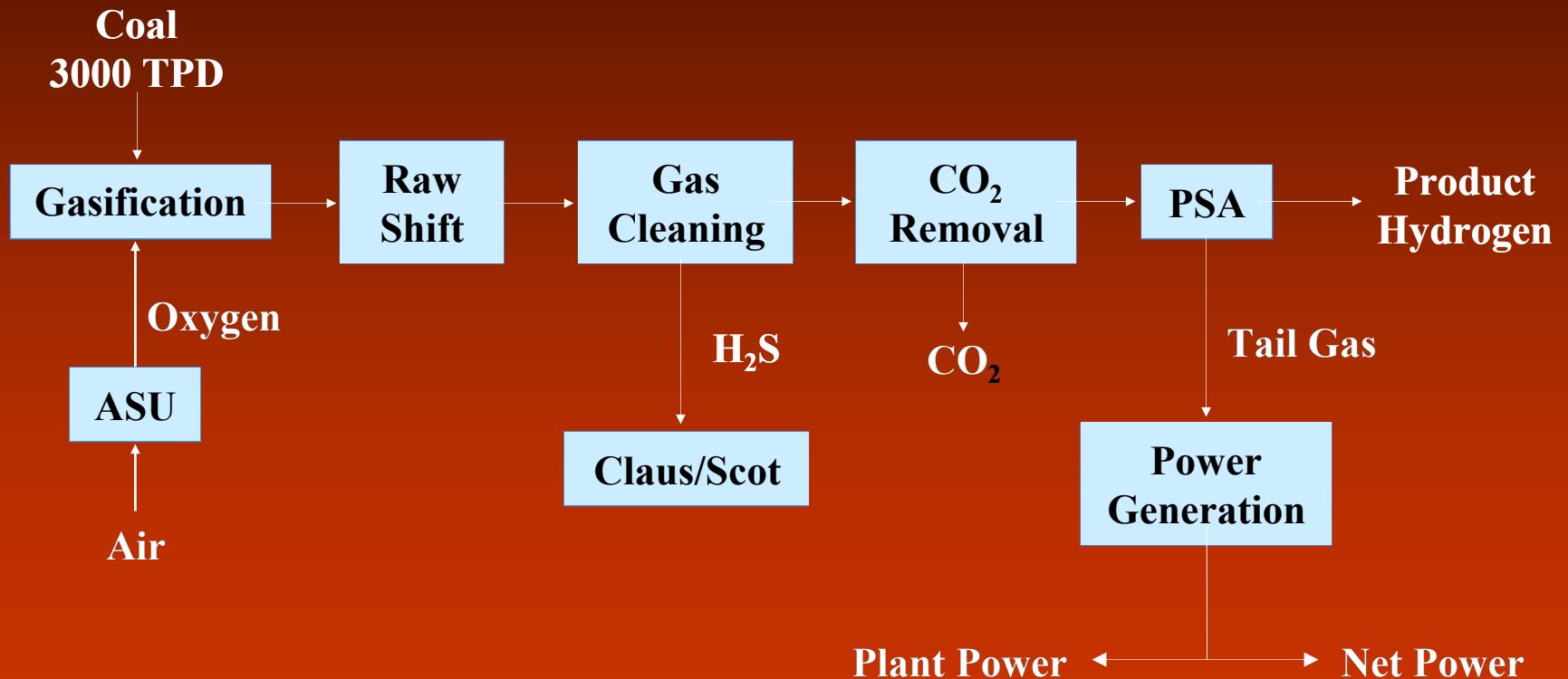
Coal Analysis

- **Illinois #6 Old Ben #26 Mine:**
- **Proximate as-received (wt %)**
 - **Moisture 11.12**
 - **Ash 9.7**
 - **Volatile matter 34.99**
 - **Fixed carbon 44.19**
 - **HHV Btu/# 11,666**
- **Ultimate as-received (wt %)**
 - **Moisture 11.12**
 - **Carbon 63.75**
 - **Hydrogen 4.5**
 - **Nitrogen 1.25**
 - **Chlorine 0.29**
 - **Sulfur 2.51**
 - **Ash 9.7**
 - **Oxygen (bd) 6.88**

Financial Assumptions

- **25 year plant life**
- **67/33 % debt/equity financing**
- **15 % return on equity**
- **8 % interest, 16 year term**
- **3 % inflation (coal de-escalation of 1.5 % per annum below general inflation)**
- **16 year DDB depreciation**
- **40 % combined Federal and State tax rate**
- **3 year construction, 50 % output in start-up year**
- **Sequestration of high pressure CO₂ stream costs \$10/ton carbon**

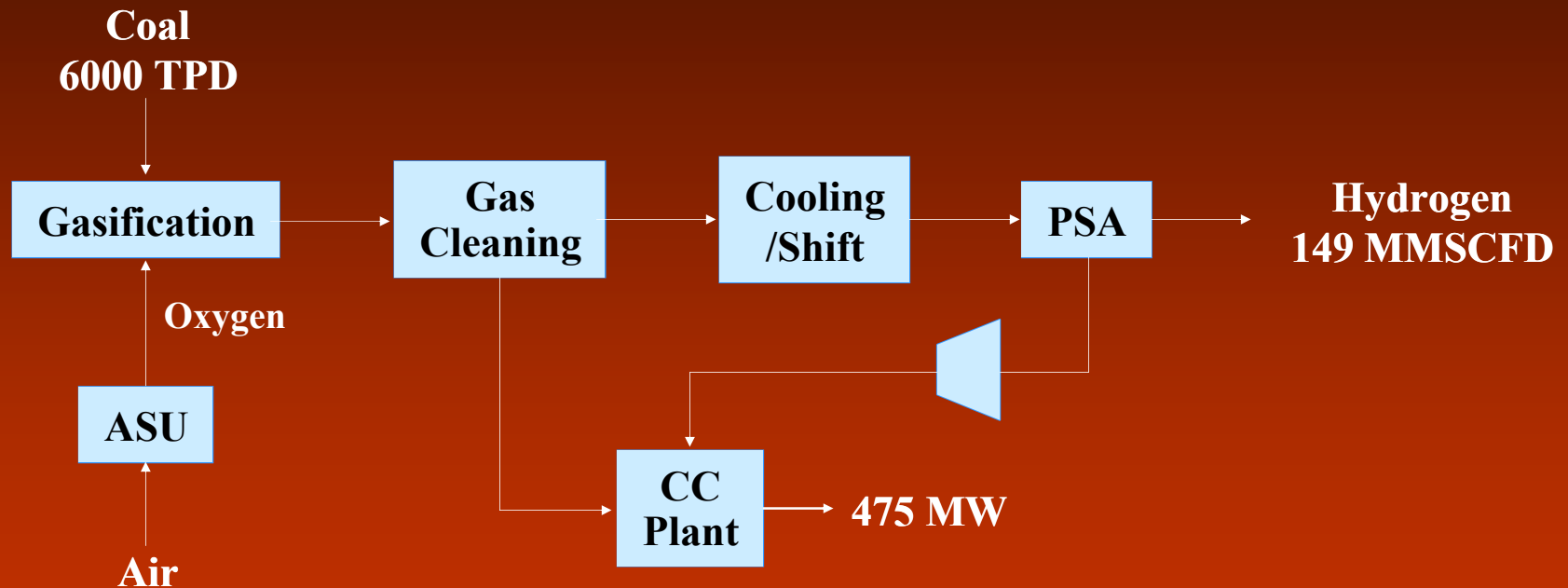
Cases 1 and 2: Hydrogen from Coal



Summary of Hydrogen from Coal Cases

	Case 1	Case 2
Carbon Sequestration	NO	YES (87%)
Hydrogen MMSCFD	131	119
Coal T/D (AR)	3000	3000
Efficiency (% HHV)	63.7	59
XS Power MW	20.4	26.9
Power Value (MILS/k Wh)	35.6	53.6
Capital \$MM	367	417
RSP of Hydrogen \$/MMBTU	6.83	8.18

Case 3: Coal to Hydrogen and Power



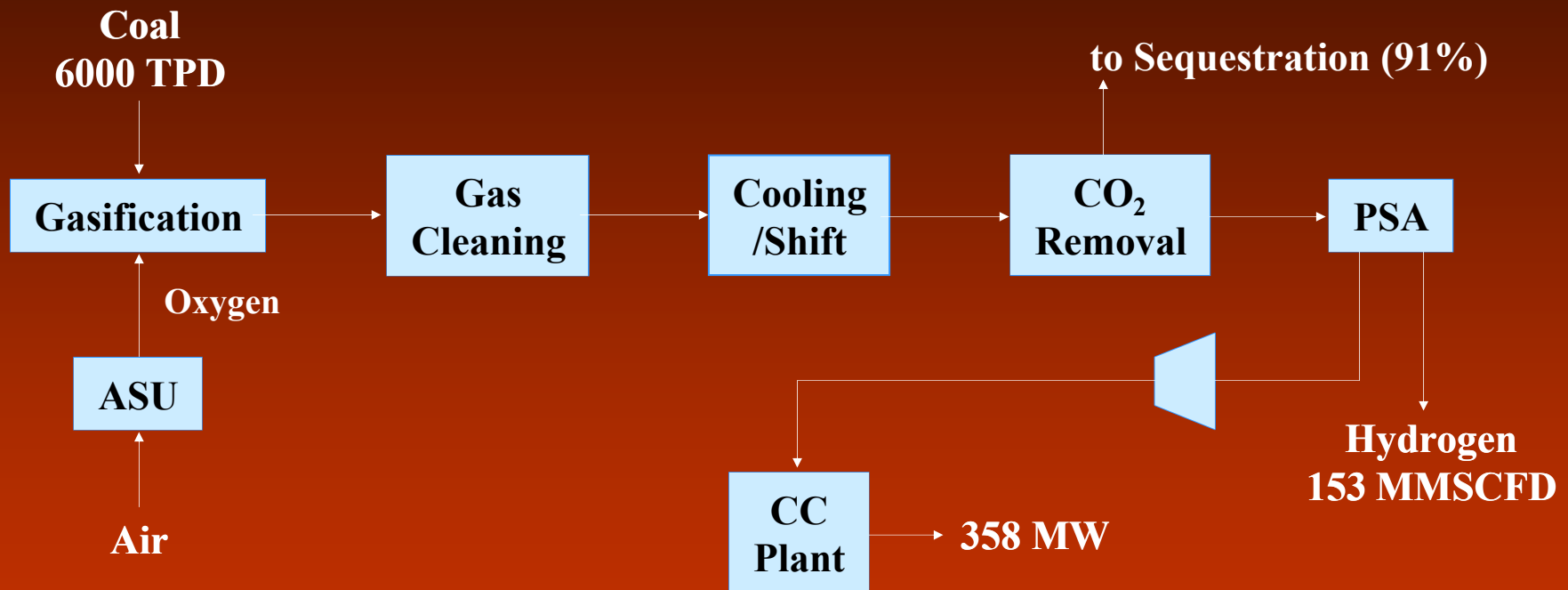
Capital \$910MM

COE 35.6 Mills/kWh

Hydrogen RSP \$5.42/MMBTU

Efficiency 62.4%

Case 4: Coal to Hydrogen and Power (Sequestration)

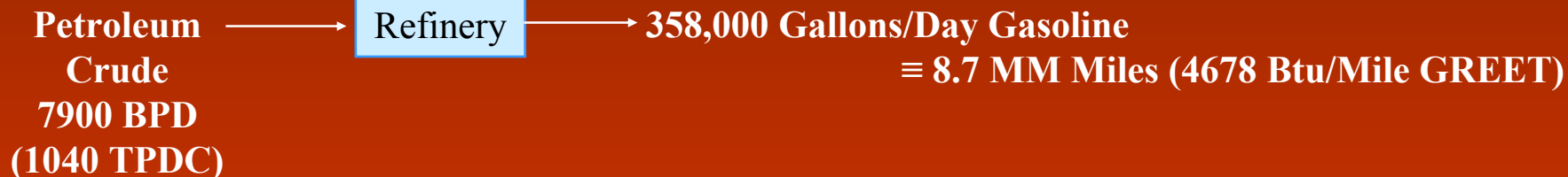


Capital \$950MM	H ₂ RSP \$/MMBTU	COE Mills/kWh	Efficiency 56.5%
	5.64	53.6 (Gas CC, sequestration)	
	6.89	46.3 (Coal IGCC, sequestration)	
	8.73	35.6 (Coal IGCC, no sequestration)	

Summary of Coproduction Cases

	CASE 3	CASE 4
Carbon Sequestration	NO	YES (95%)
Hydrogen MMSCFD	149	153
Coal T/D (AR)	6000	6000
Efficiency (%HHV)	62.4	56.5
XS Power MW	475	358
PowerValue (MILS/kWh)	35.6	53.6
Capital \$MM	910	950
RSP of Hydrogen \$/MMBTU	5.42	5.64

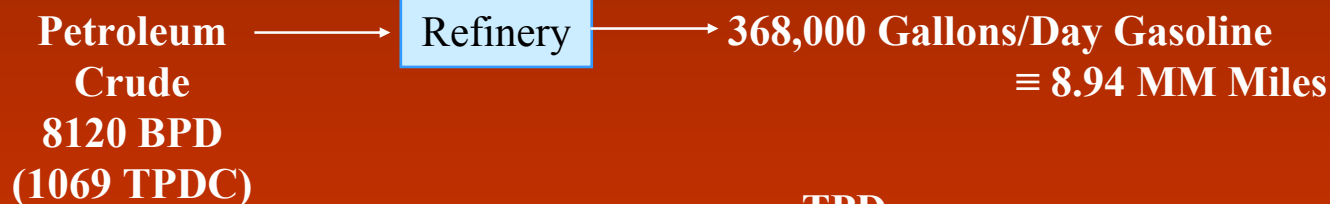
CO₂ Implications of Coal to Hydrogen and Power (Case 3)



Carbon Accounting

TPD
 1176 Power
 1040 x 2.99 = 3108 Fuels (Miles EQ)
4284 Total (-11%)

CO₂ Implications of Coal to Hydrogen and Power (Case 4)

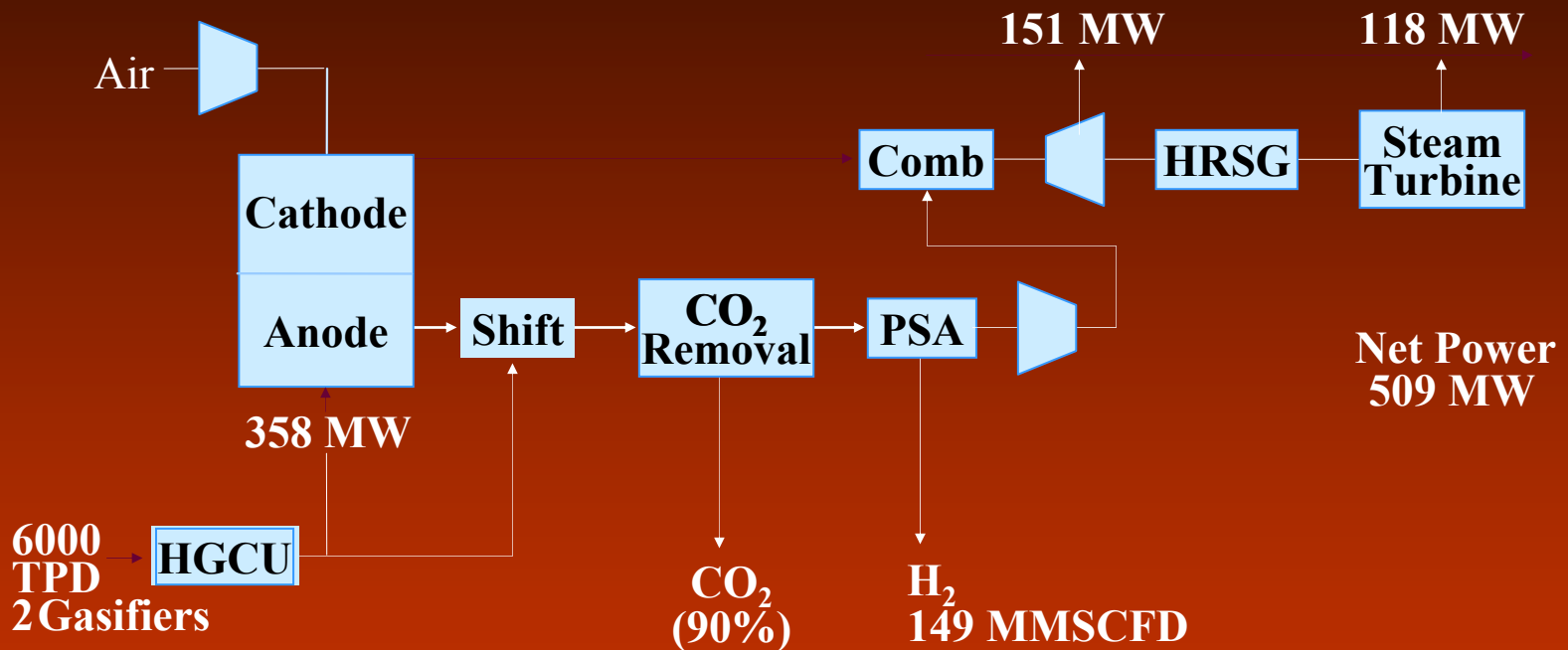


Carbon Accounting

$$1069 \times 2.99 = \frac{\text{TPD}}{4079} \text{ 886 Power Fuels (Miles EQ)}$$

Carbon Avoided = 3,888 (TPD) (4.4 MM Tons CO₂/Yr)

Case 5: SOFC for Power and Hydrogen (Sequestration)



Capital \$1,037 Million

Efficiency 64.5% (HHV)

H₂ \$/MMBTU
 2.79
 4.61
 7.34

COE mills/kWh
 53.6 Gas CC, sequestration)
 41.3 (Coal IGCC, sequestration)
 35.6 (SOFC/sequestration)

The diagram illustrates a coal gasification process for hydrogen production and power generation. The process starts with 6000 TPD Coal entering an HGCU (Hydrogen Gas Cleanup Unit). The output of the HGCU goes to a Membrane separator, which operates at 1100°F. The Membrane separator produces two streams: a top stream (404 MW) that goes to a Cathode/Anode unit, and a bottom stream (8 MW) that goes to an HRSG (Heat Recovery Steam Generator). The Cathode/Anode unit also receives -175 MW Air. The top stream from the Cathode/Anode unit (151 MW) goes to another HRSG, which produces 101 MW of power. The bottom stream from the Cathode/Anode unit (222 MW) goes to a Combustor, which also receives O₂. The Combustor output (222 MW) goes to a third HRSG, which produces 519 MW of Net Power. The third HRSG also receives H₂O and produces CO₂ at 200 Bar. The bottom stream from the Membrane separator (8 MW) is used to produce H₂ at 22 Atm, with a total of 150 MMSCFD H₂ produced.

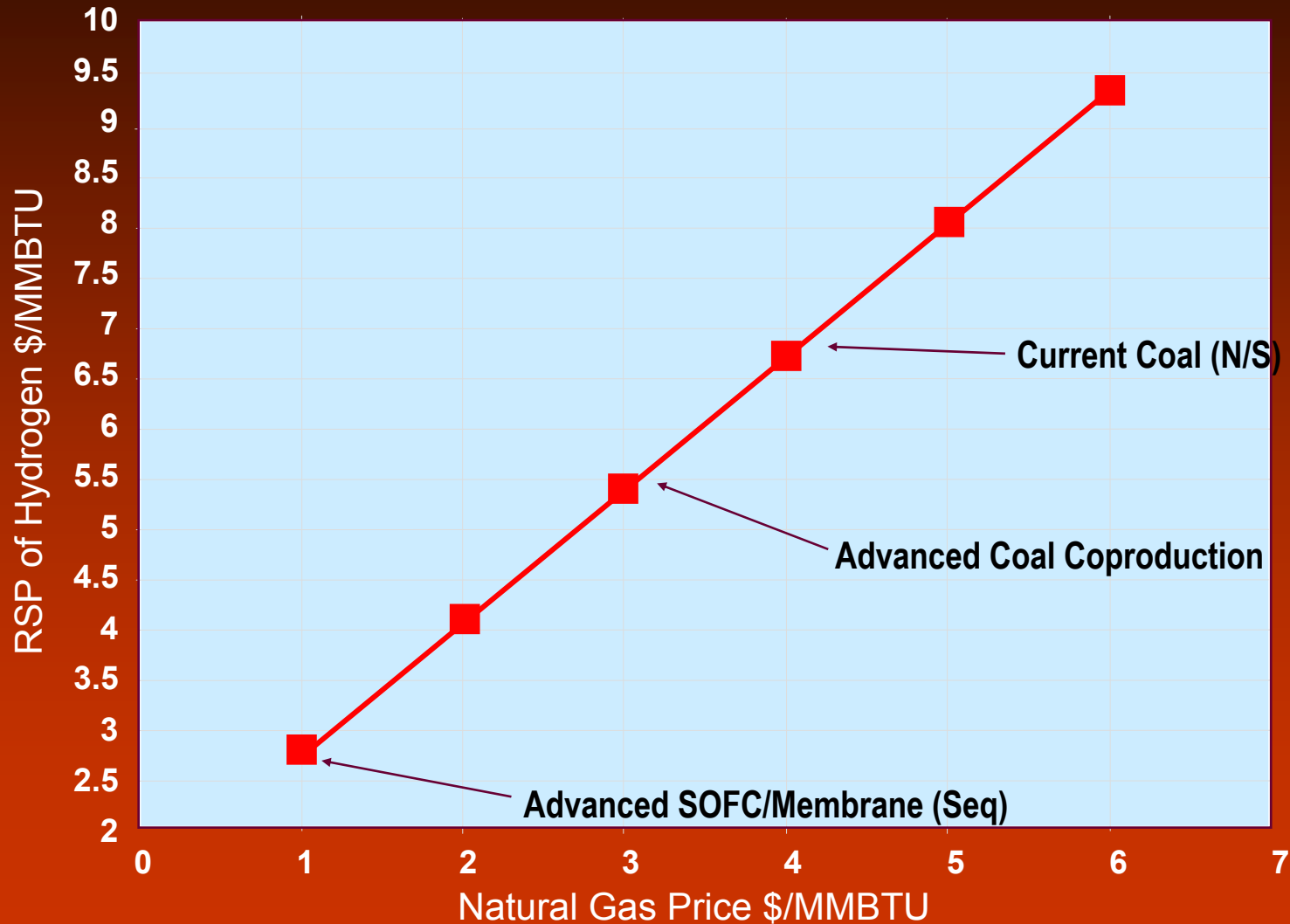
Efficiency 65.2% (HHV)

H₂ \$/MMBTU	COE 53.6 Mills/kWh
2.40	53.6 Gas CC, sequestration)
4.24	46.3 (Coal IGCC, sequestration)
5.58	41.0 (SOFC/sequestration)
6.87	35.6 (Coal IGCC, no sequestration)

Summary of Cases using SOFC Systems

	CASE 5	CASE 6
CARBON SEQUESTRATION	YES (90%)	YES (95%)
HYDROGEN MMSCFD	149	150
COAL T/D (AR)	6000	6000
EFFICIENCY (%HHV)	64.5	65.2
XS POWER MW	509	519
POWER VALUE (MILS)	53.6	53.6
CAPITAL \$MM	1,037	1,019
RSP OF HYDROGEN \$/MMBTU	2.79	2.40

Hydrogen Cost vs Natural Gas Price



Challenges

- **Hydrogen Production:**
 - carbon capture & sequestration
 - improved separations & purification
- **Delivery & Storage:**
 - infrastructure
 - volumetric energy density
- **Hydrogen Utilization:**
 - fuel cell compactness & costs