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Comprehensive Exergy Analysis of Three IGCC Power Plant Configurations with CO_2 Capture

Nicholas S. Siefert, Sarah Narburgh, Yang Chen

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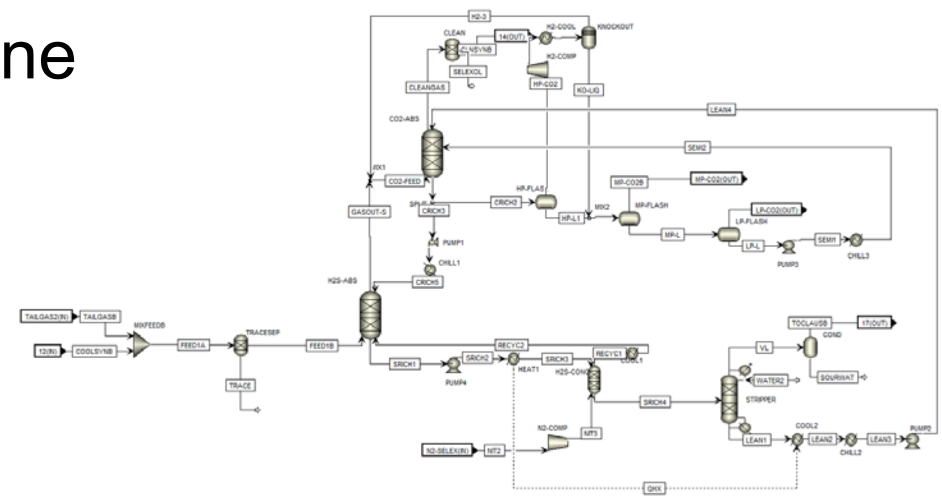
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

Outline

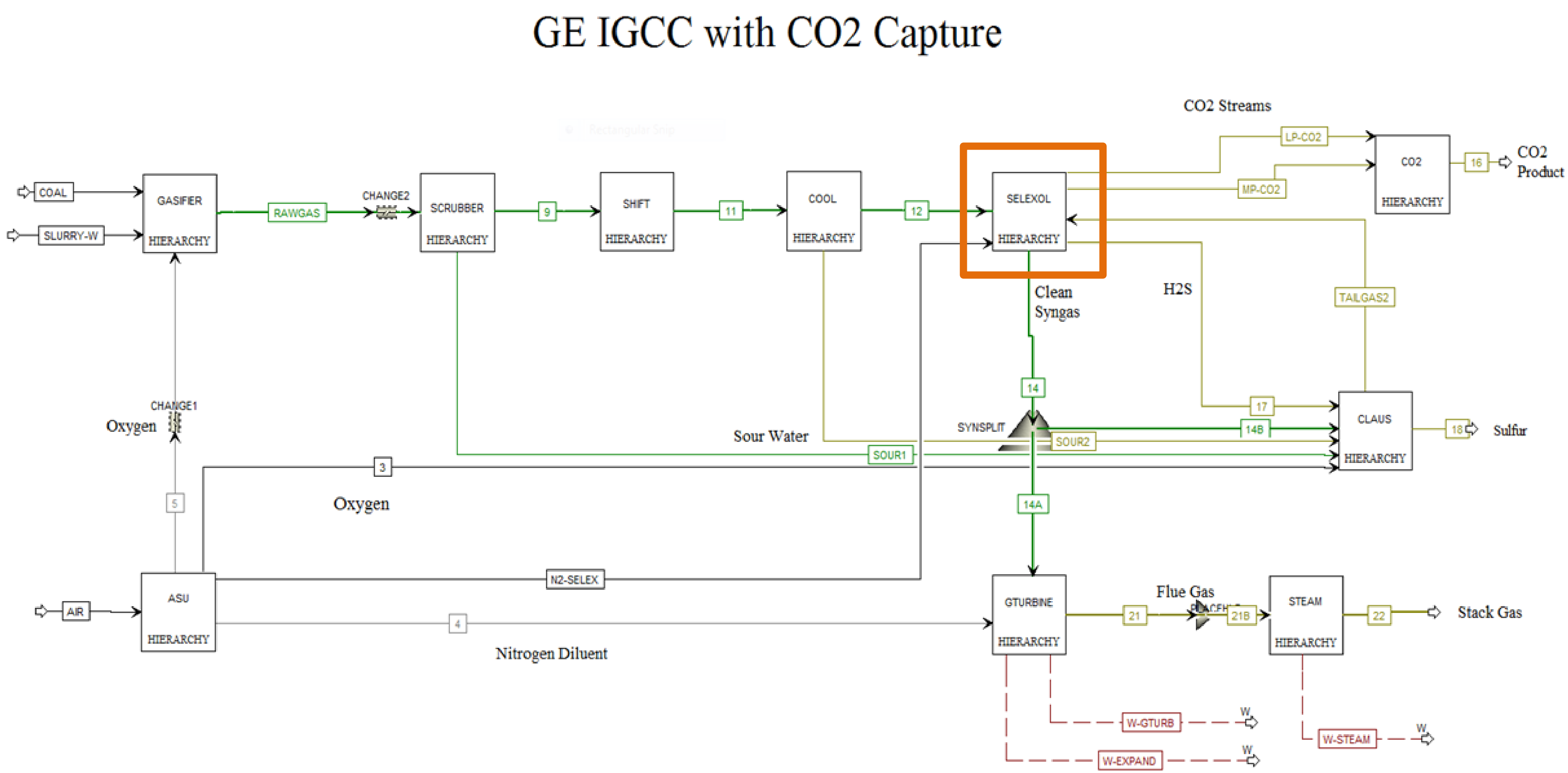
- IGCC-CCS Overview
- Intro to Exergy Analysis for State-Steady Processes
- Overview of All 3 Cases
  - Baseline Selexol™ Model
  - H_2-selective membrane
  - CO_2-selective membrane
- Comparison of Cases
- Conclusions & Future Work

Integrated Gasification Combined Cycle (IGCC)



http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Coal/LR_IGCC_FR_20110511.pdf

Baseline Model includes Ten Subsystems



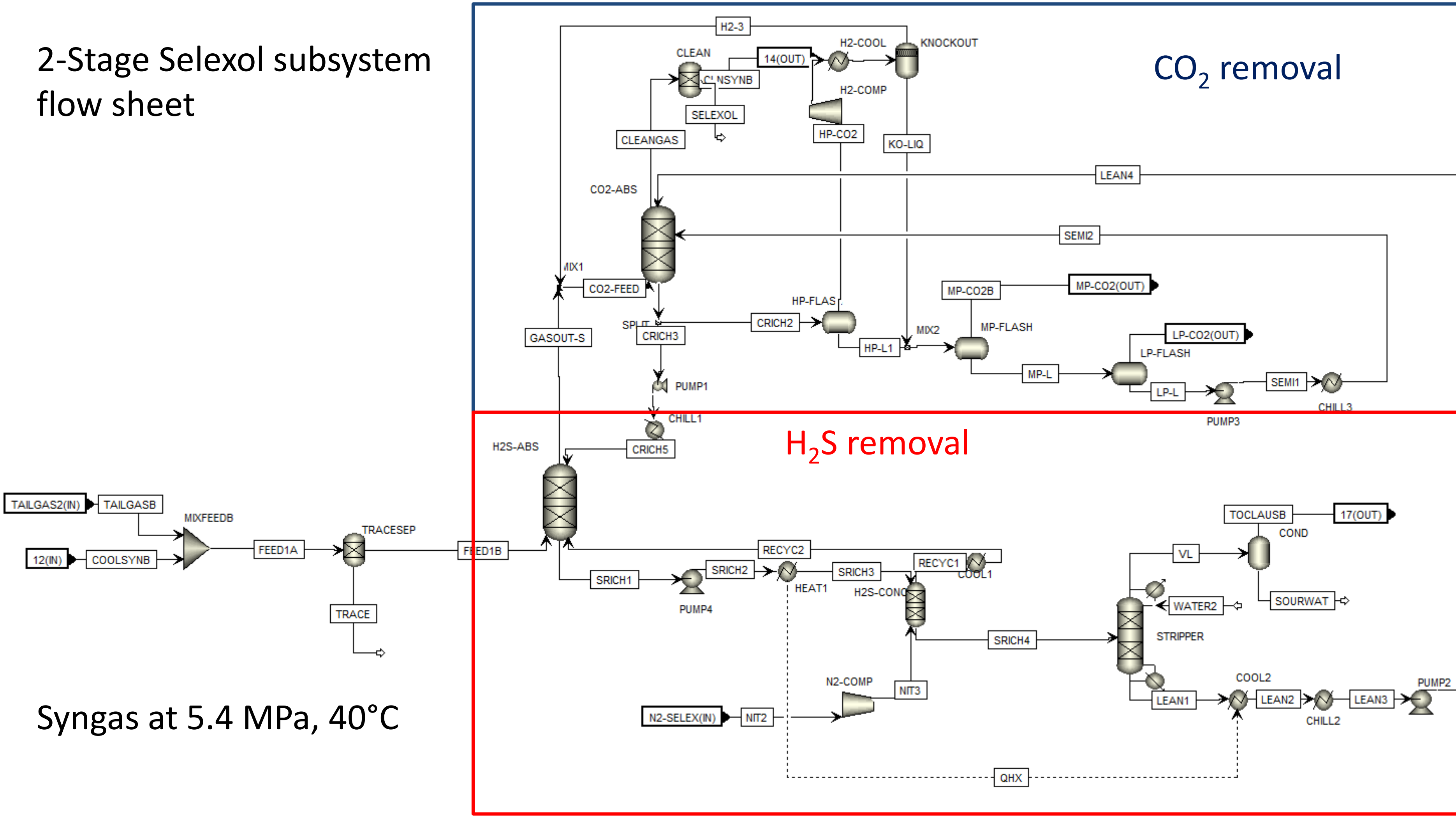
Model #1: Baseline Model from Field and Brasington (2011)

Based off of NETL's Bituminous Baseline Rev 2 (Nov 2010): GEE IGCC-CCS

Field and Brasington, "Baseline Flowsheet Model for IGCC with Carbon Capture," *Ind. Eng. Chem. Res.*, 2011, *50* (19), pp 11306–11312 http://pubs.acs.org/doi/abs/10.1021/ie200288u

Example Subsystem

2-Stage Selexol subsystem flow sheet



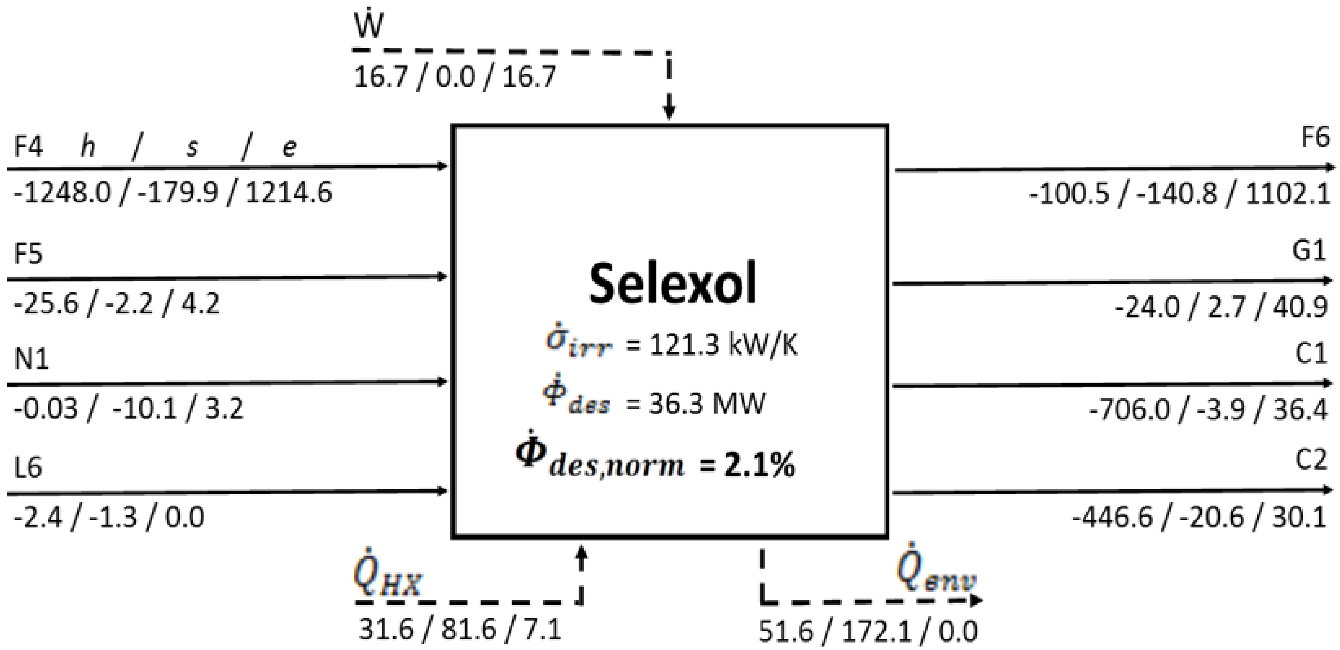
Syngas at 5.4 MPa, 40°C

Subsystem Analysis: Route#1

Guoy-Stodola Theorem $\dot{\Phi}_{des} = T_{env} \cdot \dot{\sigma}_{irr}$

2nd Law
$$\dot{\sigma}_{irr} = \frac{\dot{Q}_{env}}{T_{env}} + \sum_{o=outlet} \dot{n}_o \hat{s}_o - \sum_{i=inlet} \dot{n}_i \hat{s}_i + \sum_j \frac{\dot{Q}_j}{T_{j,o} - T_{j,i}} \ln\left(\frac{T_{j,o}}{T_{j,i}}\right)$$

1st Law
$$\dot{Q}_{env} = \sum_{i=inlet} \dot{n}_i \hat{h}_i - \sum_{o=outlet} \dot{n}_o \hat{h}_o - \dot{W} - \sum \dot{Q}_j$$



Siefert, Narburgh, and Chen, "Comprehensive Exergy Analysis of Three IGCC Power Plant Configurations with CO_2 Capture," Energies, *under review*.

Subsystem Analysis: Route#2

Exergy Analysis

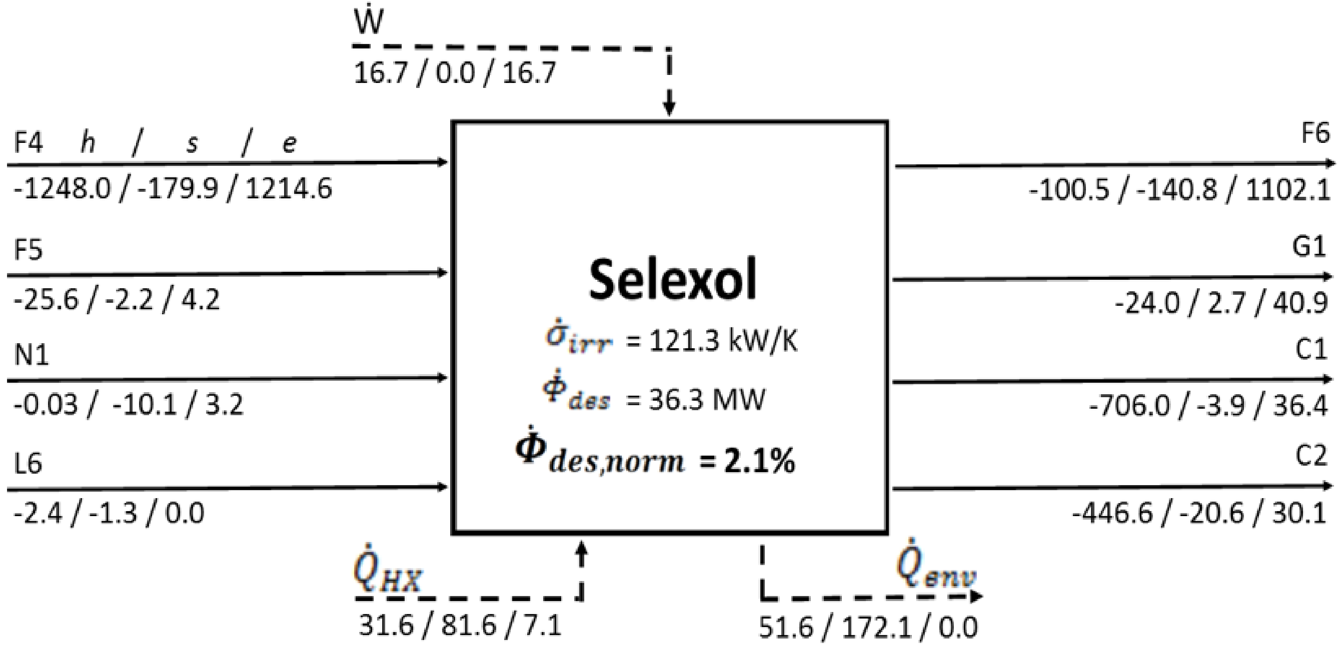
$$\dot{\Phi}_{des} = \sum_{i=inlet} \dot{n}_i \hat{e}_i - \sum_{o=outlet} \dot{n}_o \hat{e}_o - \dot{W} - \sum_j \dot{E}_j$$

Exergy of a stream

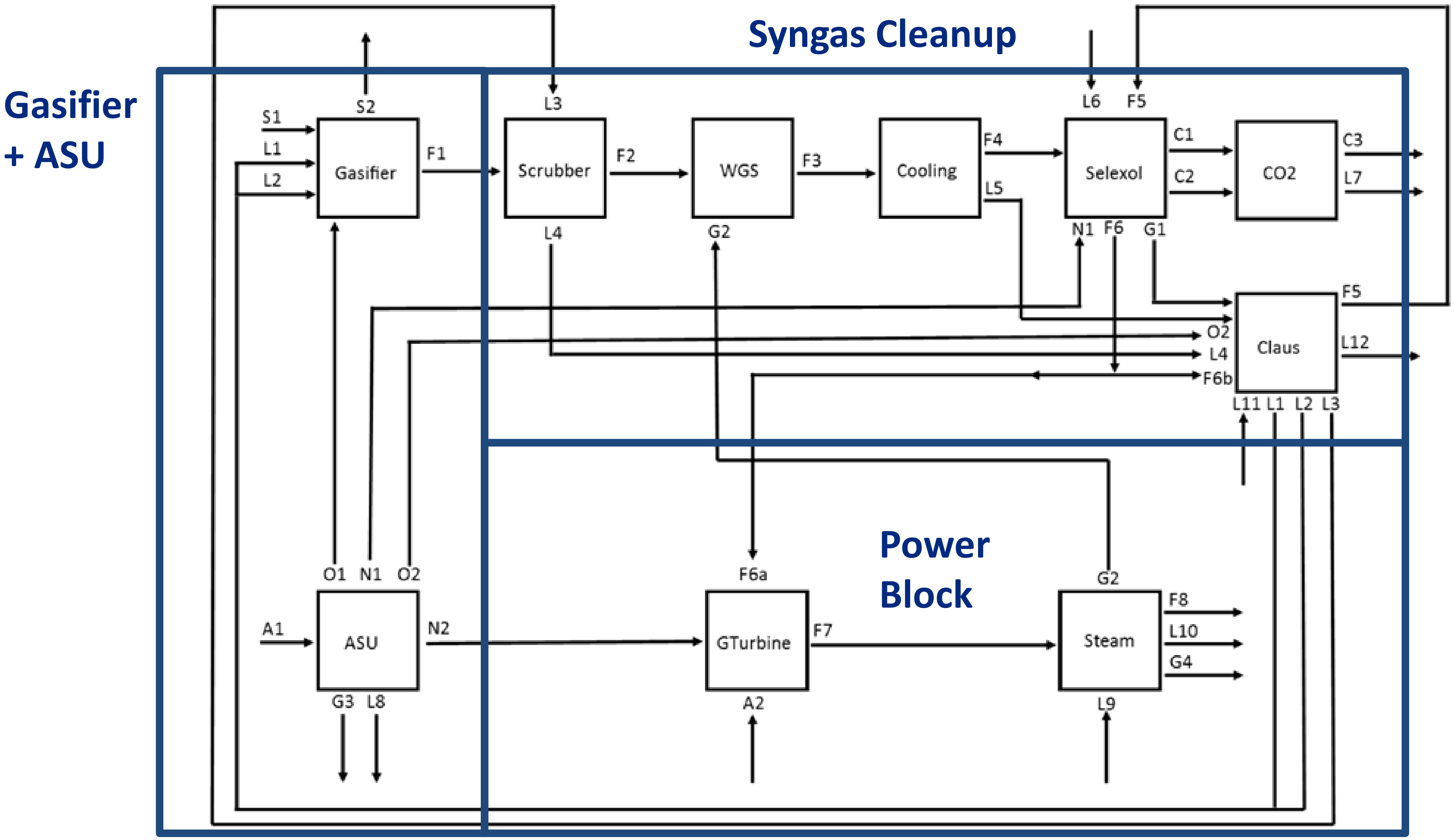
$$\hat{e} = \left[\left(\hat{h} - \hat{h}_{stp}\right) - T_{env}\left(\hat{s} - \hat{s}_{stp}\right)\right] + \hat{e}_{chem}$$

Exergy of Heat

$$\dot{E}_j = \dot{Q}_j \cdot \left[1 - \frac{T_{env}}{T_{j,o} - T_{j,i}} \ln\left(\frac{T_{j,o}}{T_{j,i}}\right)\right]$$



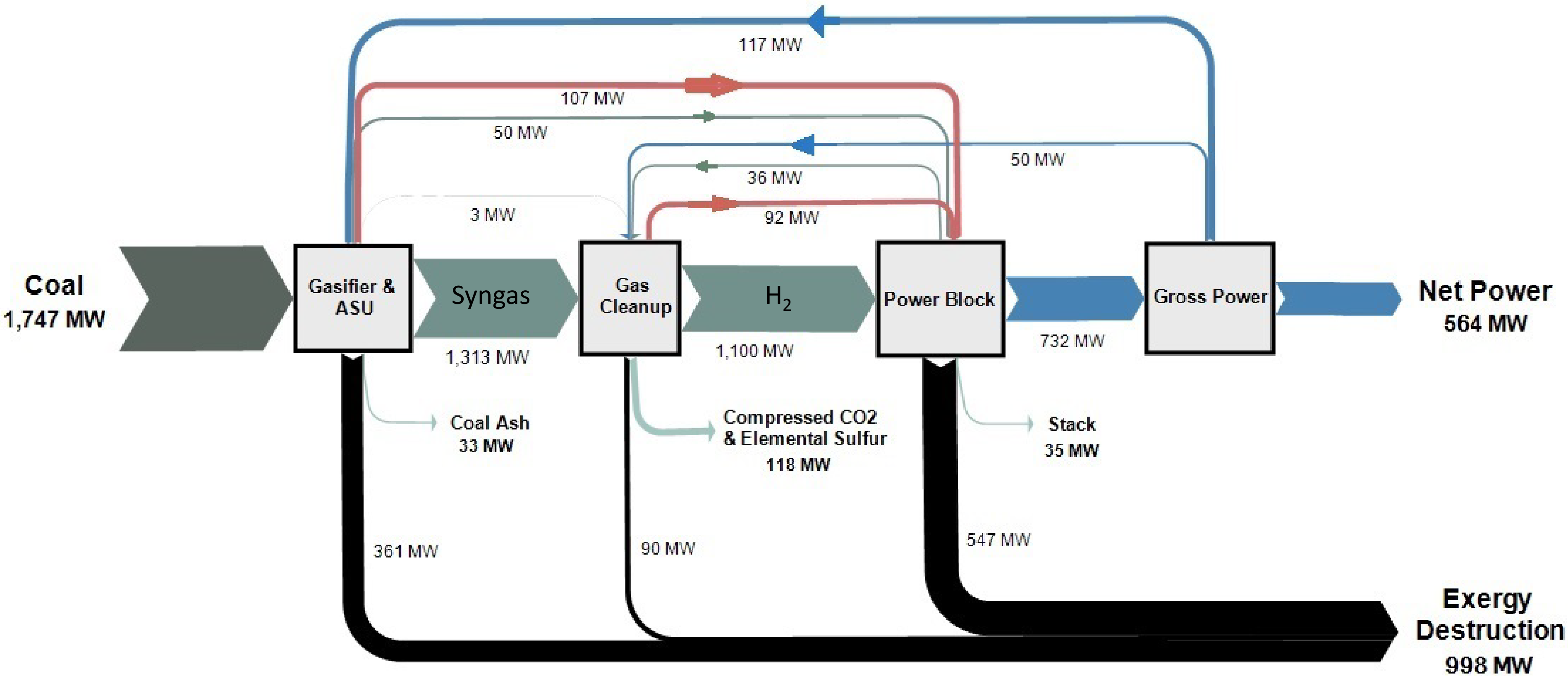
Baseline Model: Revisited



Model #1: Baseline Model from Field and Brasington (2011)

Based off of NETL's Bituminous Baseline Rev 2 (Nov 2010): GEE IGCC-CCS

Exergy Sankey Diagram: Baseline



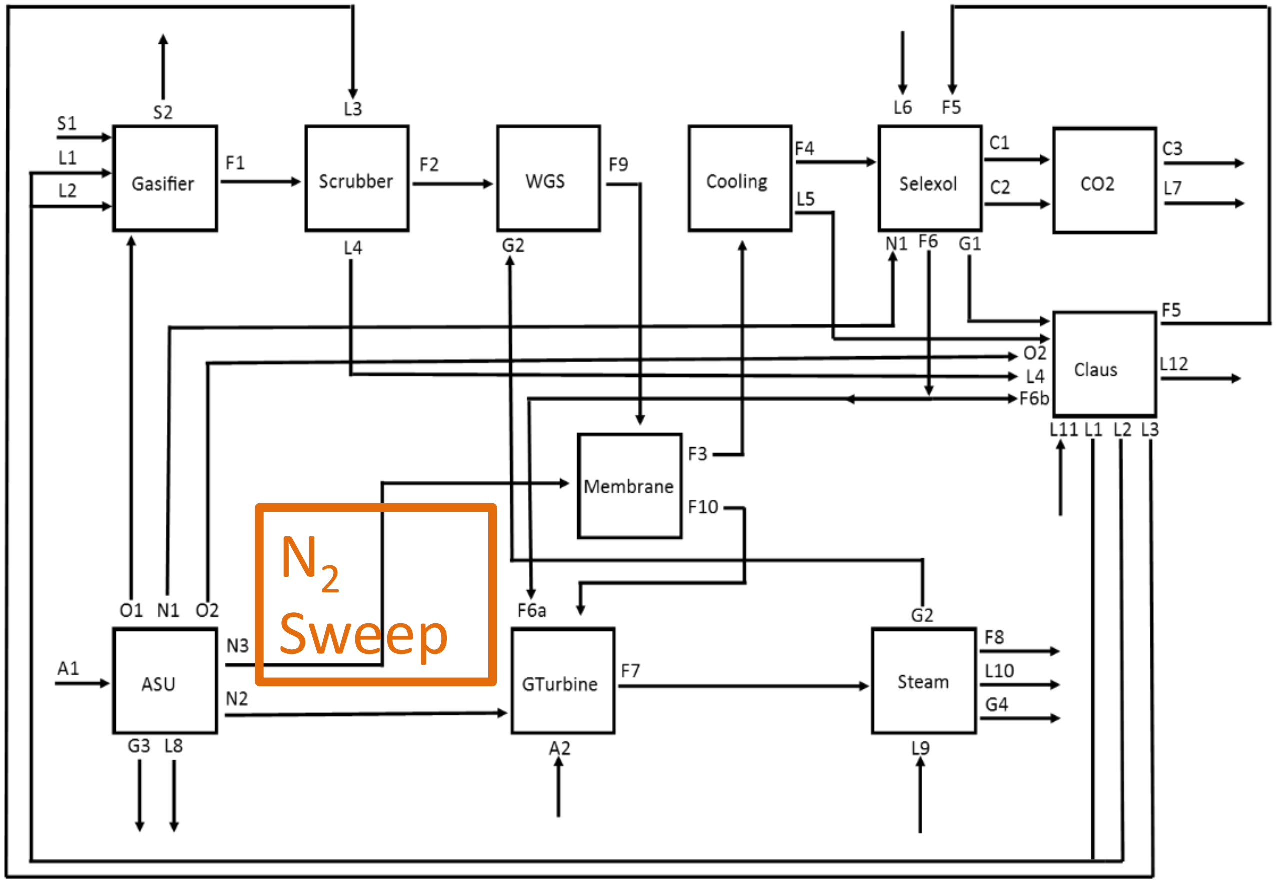
Red = Flow of Thermal exergy between sub-systems

Blue = Flow of Electricity

Teal = Flow of Materials streams with exergy

Black = Exergy Destruction

H_2-Selective Membrane Model



Model #2: Hydrogen Membrane Model process flow diagram

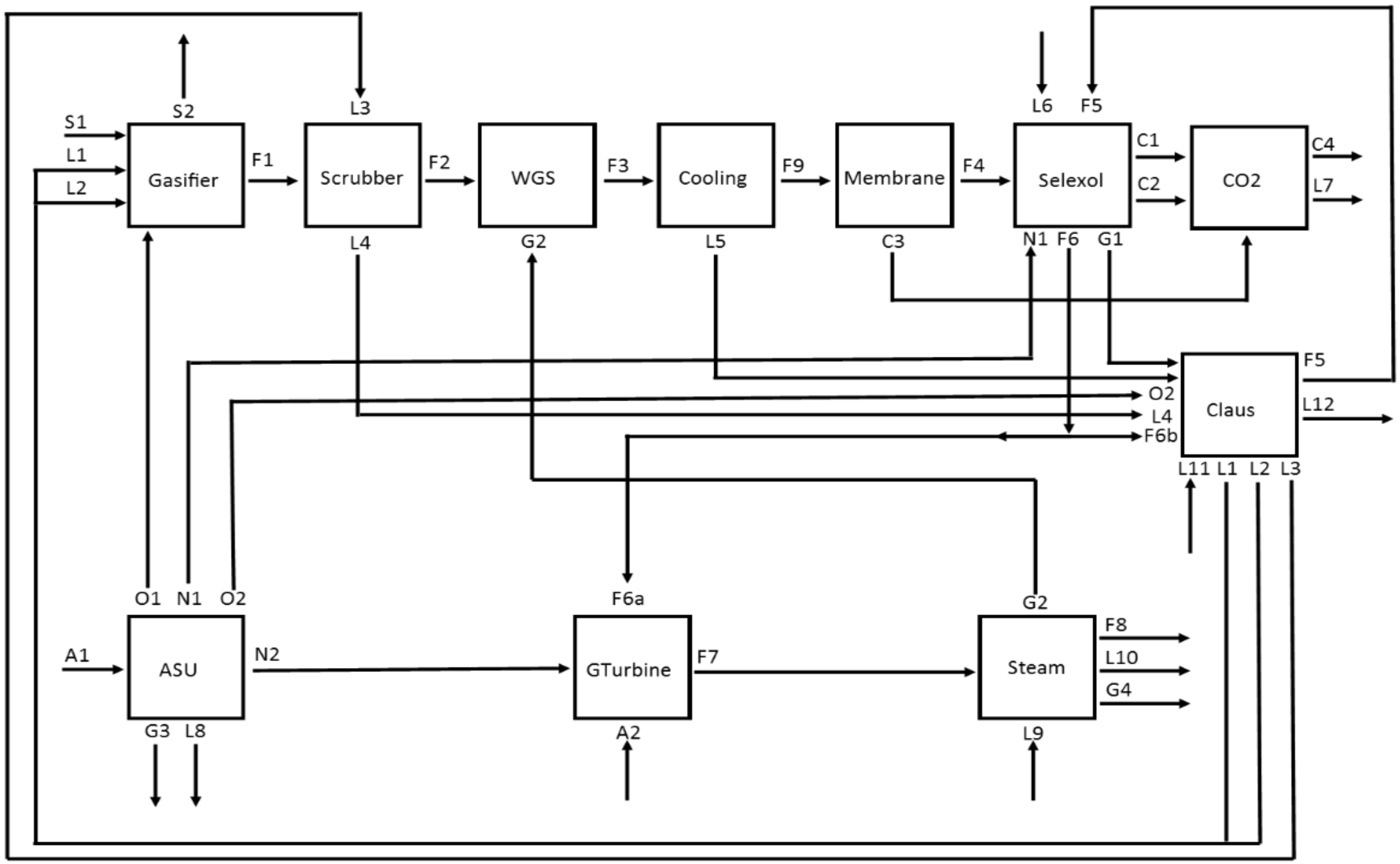
Aspen Custom Modeler (ACM) used to model the H_2-Selective Membrane

Membrane operates at 250°C. Modeled after the PBI membrane process developed by Berchtold *et. al* at LANL

$H_2/CO_2 = 48$, $H_2/CO = 100$, $H_2/CH_4 = 234$, $H_2/H_2S = 1289$, $H_2/N_2 = 233$, $H_2/H_2O = 0.33$

Kathryn A. Berchtold, Rajinder P. Singh., Kevin W. Dudeck, Ganpat J. Dahe, and Cynthia F. Welch In *High temperature polymer-based membrane systems for pre-combustion carbon dioxide capture*, NETL CO2 Capture Technology Meeting, Pittsburgh, PA, 31 July 2014, 2014; Pittsburgh, PA, 2014.

CO_2-Selective Membrane Model



Model #3: Carbon Dioxide Membrane Model process flow diagram

Aspen Custom Modeler (ACM) used to model the CO_2-Selective Membrane

Membrane operates at 40°C. Optimistic values of CO_2/H_2 and CO_2/other gases were assumed because, even at optimistic values, the process could not compete against the baseline model. CO_2 Selectivity was assumed to be 50 for all gases, except H_2O.

Comparison Between Cases

	Baseline Model			Hydrogen Membrane Model			CO_2 Membrane Model		
Subsystem or *Exiting Stream*	**Norm. Power [%]**	**Norm. Exergy Destruction [%]**	**Norm. Exergy Remaining [%]**	**Norm. Power [%]**	**Norm. Exergy Destruction [%]**	**Norm. Exergy Remaining [%]**	**Norm. Power [%]**	**Norm. Exergy Destruction [%]**	**Norm. Exergy Remaining [%]**
Gasifier	0.00	17.4	-	0.0	17.4	-	0.0	17.4	-
Scrub	0.00	0.2	-	0.0	0.2	-	0.0	0.2	-
WGS	0.00	1.3	-	0.0	1.3	-	0.0	0.2	-
Mem	-	-	-	0.0	0.7	-	0.0	0.2	-
Cool	0.00	0.0	-	0.0	0.0	-	0.0	1.1	-
Selexol	-1.0	2.1	-	-0.8	1.5	-	-0.4	1.0	-
CO_2	-1.6	0.4	-	-1.1	0.3	-	-1.5	0.5	-
ASU	-6.7	3.2	-	-5.8	3.4	-	-6.2	2.7	-
GT	27.0	22.6	-	26.9	21.8	-	25.2	21.5	-
Steam	14.8	8.8	-	14.4	8.0	-	14.7	9.3	-
Claus	-0.3	1.1	-	-0.2	0.8	-	-0.3	1.2	-
Slag		-	1.9	-	-	1.9	-	-	1.9
CO_2 Prod		-	5.0	-	-	4.9	-	-	7.8
S-out		-	1.7	-	-	1.6	-	-	1.6
Stack Gas		-	2.0	-	-	2.3	-	-	1.8
Knock Out		-	0.04	-	-	0.2	-	-	0.2
Total	**32.3**	**57.1**	**10.6**	**33.4**	**55.4**	**11.2**	**31.5**	**55.1**	**13.4**

Summary of Results

	Baseline Model	H_2-Selective Membrane Model	CO_2-Selective Membrane Model
Work Produced [MW]	732.1	721.5	697.3
Work Consumed [MW]	167.8	137.2	147.4
Net Work [MW]	564.3	584.3	549.9
Total Heat Transferred to the Environment [MW_{th}]	799.3	686.3	759.4
CO_2 Captured / (CO_2 Capture + CO_2 Emitted) [%]	90.0	90.0	90.0
Hydrogen Recovered [%]	99.86	99.94	95.5
Total CO_2 Captured [kg/s]	128	128	128
Normalized CO_2 emissions [kg/MWh]	90.7	87.6	93.1

Conclusions & Future Work

- H_2 membrane case increased the net efficiency compared with the baseline, whereas the CO_2 membrane case decreased the net efficiency
- In all cases, there was large exergy destruction in the entrained flow, quenched gasifier
  - 17.4% exergy destruction in gasifier
  - 2.4% exergy destruction in heat transfer to Rankine cycle
  - 1.9% exergy remaining in the carbon-rich slag
- From an exergy point of view, there is major room for improvement in both the gasifier and GTurbine subsystems
- Future Work: Techno-economic analyses of these 3 cases, along with a few other cases, is currently in preparation

  Chen, Y., Fisher, J.C. II, Turner, M. J., Woods, M., Miller, D.C. "Techno-economic Analysis for H_2- and CO_2-selective Membranes in the Integrated Gasification Combined Cycle (IGCC) Process," in preparation.

Questions?

Thank you for your attention.

Back Up Slides

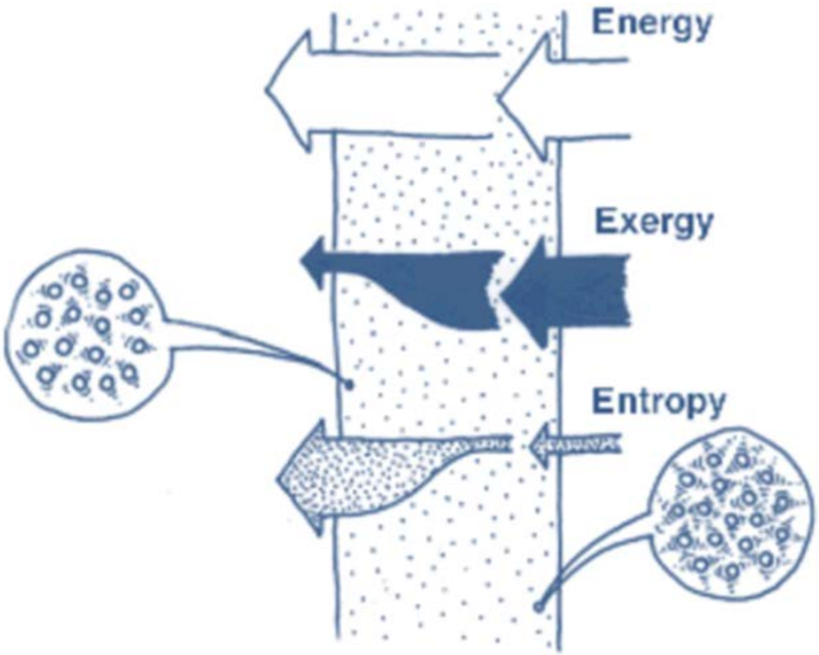
Definition of Exergy & Exergy Destruction

- Exergy = Maximum amount of useful work that can be obtained from a reversible process by bringing material into full mechanical, thermal, and chemical equilibrium with the environment
- Environment is usually assumed to be Earth's atmosphere at standard temperature and pressure
- Exergy cannot be negative
- Exergy can be destroyed, but not created
- All real-world processes destroy some exergy; the goal is to find the balance between low exergy destruction and low cost

$$\hat{e} = \left[\left(\hat{h} - \hat{h}_{stp}\right) - T_{env}\left(\hat{s} - \hat{s}_{stp}\right)\right] + \hat{e}_{chem}$$

$$\dot{E}_j = \dot{Q}_j \cdot \left[1 - \frac{T_{env}}{T_{j,o} - T_{j,i}} \ln\left(\frac{T_{j,o}}{T_{j,i}}\right)\right]$$

$$\dot{\Phi}_{des} = T_{env} \cdot \dot{\sigma}_{irr}$$



Chemical exergy of species at STP

Gas Species	Molar chemical exergy at STP [kJ/mol]	Solid Species	Molar chemical exergy at STP [kJ/mol]
N_2(g)	0.69	FeO(s)	125.4
O_2(g)	3.97	Fe (s)	367.6
H_2O(g)	8.55	C(s)	409.8
Ar(g)	11.7	S(s) / S_8(s)	75.3 / 602.7
CO_2(g)	19.4	CaO/MgO	0*
H_2(g)	235.2	Na_2O/K_2O	0*
CO(g)	274.6	Fe_2O_3/SiO_2/Al_2O_3	0*
NH_3(g)	336.7		
H_2S(g)	804.6	**Liquid Species**	
CH_4(g)	829.6	H_2O(l)	0*
COS(g)	848.8	* = approximation for simplicity	

Chemical exergies derived from Gibbs Free Energy of Formation along with assumptions listed in the next slide for the composition of the environment

Composition of reference environment at 298 K and 1 atm

Gas Species	mol%	Liquid	Activity	Solid	Activity
N_2	75.67	$H_2O(l)$	1	$CaCO_3$	1
O_2	20.35	NaCl(aq)	Not Appl.	$CaSO_4 \cdot 2H_2O$	1
$H_2O(g)$	3.03			SiO_2	1
Ar	0.91			Al_2O_3	1
CO_2	0.04			Fe_2O_3	1

Assumption in All Three Cases

Gas Turbine	
Turbine Inlet	1185°C
Turbine Outlet	0.105 MPa
Comp. Outlet	1.62 MPa
T_{fuel}	180°C
P_{fuel}	3.17 MPa
$\eta_{comp,isen}$	86.5%
$\eta_{comp,mech}$	98.5%
$\eta_{turb,isen}$	89.8%
$\eta_{turb,mech}$	98.8%

Steam	
HP Inlet	12.5 MPa
MP Inlet	6.00 MPa
IP Inlet	2.90 MPa
NP Inlet	1.73 MPa
LP Inlet	0.45 MPa
η_{isen}	87.5%
η_{mech}	98.3%
η_{pump}	82.0%
Condenser	0.007 MPa

Additional Information	
η_{pump}	75.0-100%
η_{comp}	73.5-85%
EOS	PR-BM
EOS- Selexol	PC-Saft
Steam Table	STEAMNBS
CO_2 pipeline pressure	15.3 MPa
Gasifier	
Pressure	5.6 MPa
Outlet T	1370°C

Baseline Model: Results

Subsystem	Gasifier	Scrub	WGS	Cool	Selexol	CO_2	ASU	GT	Steam	Claus	Total
Power [MW]	0.0	0.0	0.0	0.0	-16.7	-28.3	-117.4	472.6	259.5	-5.4	564.3
Thermal Energy Transferred to Env [MW_{th}]	16.9	0.0	0.3	7.7	51.6	51.3	140.3	15.5	454.3	61.4	799.3
Exergy Destroyed [MW]	304.6	4.1	22.2	0.7	36.3	7.5	56.2	394.2	153.2	19.5	998.5
Exergy in Heat To/From Steam Subsystem [MW]	122.2	0.0	80.4	14.1	-7.1	0.0	-15.4	-8.1	-190.3	4.3	0.0
Normalized Power [%]	0.0	0.0	0.0	0.0	-1.0	-1.6	-6.7	27.0	14.8	-0.3	**32.3**
Normalized Exergy Destruction [%]	17.4	0.2	1.3	0.04	2.1	0.4	3.2	22.5	8.8	1.1	**57.1**
Outlet Stream	*Slag*	–	–	–	–	*CO_2 Prod*	*Knock Out*	–	*Stack Gas*	*S-out*	
Exergy Remaining [MW]	33.0					87.4	0.7		34.2	30.2	185.6
Normalized Exergy Remaining [%]	1.9					5.0	0.0		2.0	1.7	**10.6**
Total											**100.0**

Siefert, Narburgh, and Chen, "Comprehensive Exergy Analysis of Three IGCC Power Plant Configurations with CO_2 Capture," Energies, *under review*.

H_2-Selective Membrane: Results

Subsystem	Gasifier	Scrub	WGS	Mem	Cool	Selexol	CO_2	ASU	GT	Steam	Claus	Total
Power [MW]	0.0	0.0	0.0	0.0	0.0	-13.2	-19.5	-101.5	470.1	251.4	-3.0	584.3
Thermal Energy Transferred to Env [MW_{th}]	16.9	0.0	0.0	0.0	5.6	38.4	41.9	127.7	15.6	405.9	34.3	686.3
Exergy Destroyed [MW]	304.6	4.1	22.8	12.4	0.8	26.2	5.3	59.4	381.0	140.6	14.7	972.0
Exergy in Heat To/From Steam Subsystem [MW]	122.2	0.0	42.8	3.9	6.8	-5.5	0.0	0.0	-3.8	-160.8	5.5	0.0
Normalized Power [%]	0.0	0.0	0.0	0.0	0.0	-0.8	-1.1	-5.8	26.9	14.4	-0.2	**33.4**
Normalized Exergy Destruction [%]	17.4	0.2	1.3	0.7	0.0	1.5	0.3	3.4	21.8	8.0	0.8	**55.6**
Outlet Stream	***Slag***	–	–	–	–	–	***CO_2 Prod***	***Knock Out***	–	***Stack Gas***	***S-out***	
Exergy Remaining [MW]	33.0						86.3	3.6		40.5	28.5	192.0
Normalized Exergy Remaining [%]	1.9						4.9	0.2		2.3	1.6	**11.0**
Total												**100.0**

Siefert, Narburgh, and Chen, "Comprehensive Exergy Analysis of Three IGCC Power Plant Configurations with CO_2 Capture," Energies, *under review*.

H_2-Selective Membrane: Results

Subsystem	Gasifier	Scrub	WGS	Mem	Cool	Selexol	CO_2	ASU	GT	Steam	Claus	Total
Power [MW]	0.0	0.0	0.0	0.0	0.0	-7.4	-26.7	-107.7	440.9	256.4	-5.7	549.9
ThermalEnergy Transferred to Env [MW_{th}]	16.9	0.0	0.0	0.0	7.6	28.3	39.3	99.7	15.2	490.8	61.6	759.4
Exergy Destroyed [MW]	304.6	4.1	4.2	3.9	18.6	17.3	8.3	47.0	375.9	162.4	20.7	967.2
Exergy in Heat To/From Steam Subsyst. [MW]	122.2	0.0	80.4	0.0	14.1	-4.2	0.0	-3.3	-7.5	-205.5	3.9	0.0
Normalized Power [%]	0.0	0.0	0.0	0.0	0.0	-0.4	-1.5	-6.2	25.2	14.7	-0.3	**31.5**
Normalized Exergy Destruct. [%]	17.4	0.2	0.2	0.2	1.1	1.0	0.5	2.7	21.5	9.3	1.2	**55.2**
Outlet Stream	***Slag***	–	–	–	–	–	***CO_2 Prod***	***Knock Out***	–	***Stack Gas***	***S-out***	
Exergy Remaining [MW]	33.0						136.0	2.9		31.3	28.1	231.3
Normalized Exergy Remaining [%]	1.9						7.8	0.2		1.8	1.6	**13.3**
Total												**100.0**

Siefert, Narburgh, and Chen, "Comprehensive Exergy Analysis of Three IGCC Power Plant Configurations with CO_2 Capture," Energies, *under review*.