Challenges for Transformational Processes with Insights from Amine Scrubbing

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September 23, 2014
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Post-combustion capture cannot be transformational

- Second generation amine scrubbing will use only 200-250 kwh/tonne CO_2 removed.
- Separations driven by mechanical compression will not use less energy at less capital cost.
- Separations with thermal swing regeneration will not use less energy.
- Systems with solids and slurries will require more expensive, less feasible equipment.
- Expensive materials will not compete in the dirty coal environment.
- Improved capture processes may come out of reduced capital costs and use of opportunistic energy

W_{min} = 109 kwh/tonne CO_2

Separate CO_2 to 1 bar at 40°C

- $W_{sep} = -\frac{RT}{fx}\left[x\ln x + (1-x)\ln(1-x) - x(1-f)\ln\frac{x(1-f)}{1-fx}\right.$
  - 7.3 kJ/mol CO_2 = 46 kwh/tonne CO_2
  - f=0.9, fraction removal; x=0.12 CO_2 in feed

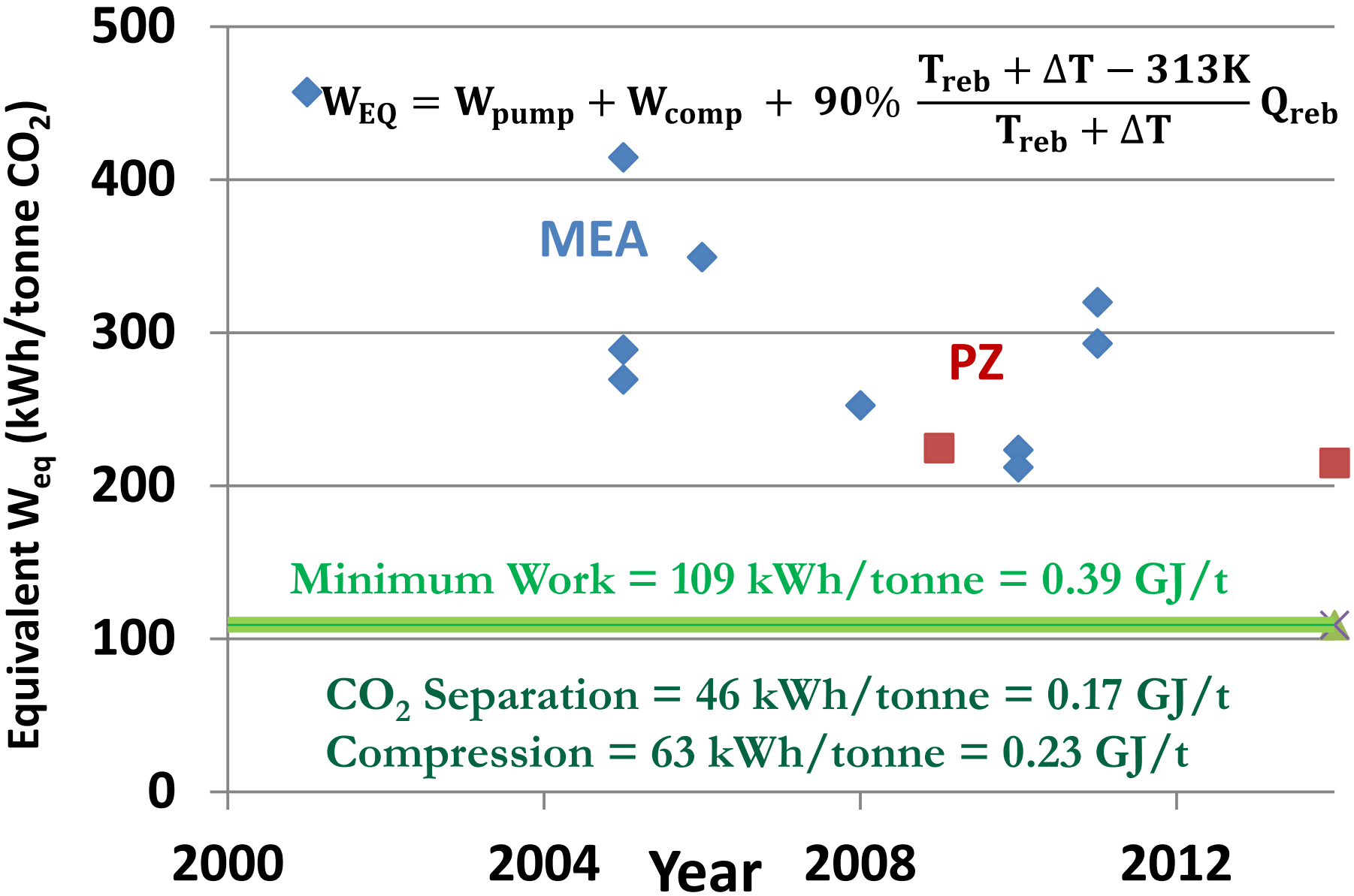
Compress from 1 bar to 150 bar at 40°C

- W_{comp} =ΔH – 313*ΔS (real gas)= 63 kwh/t

1. Second generation amine scrubbing will use only

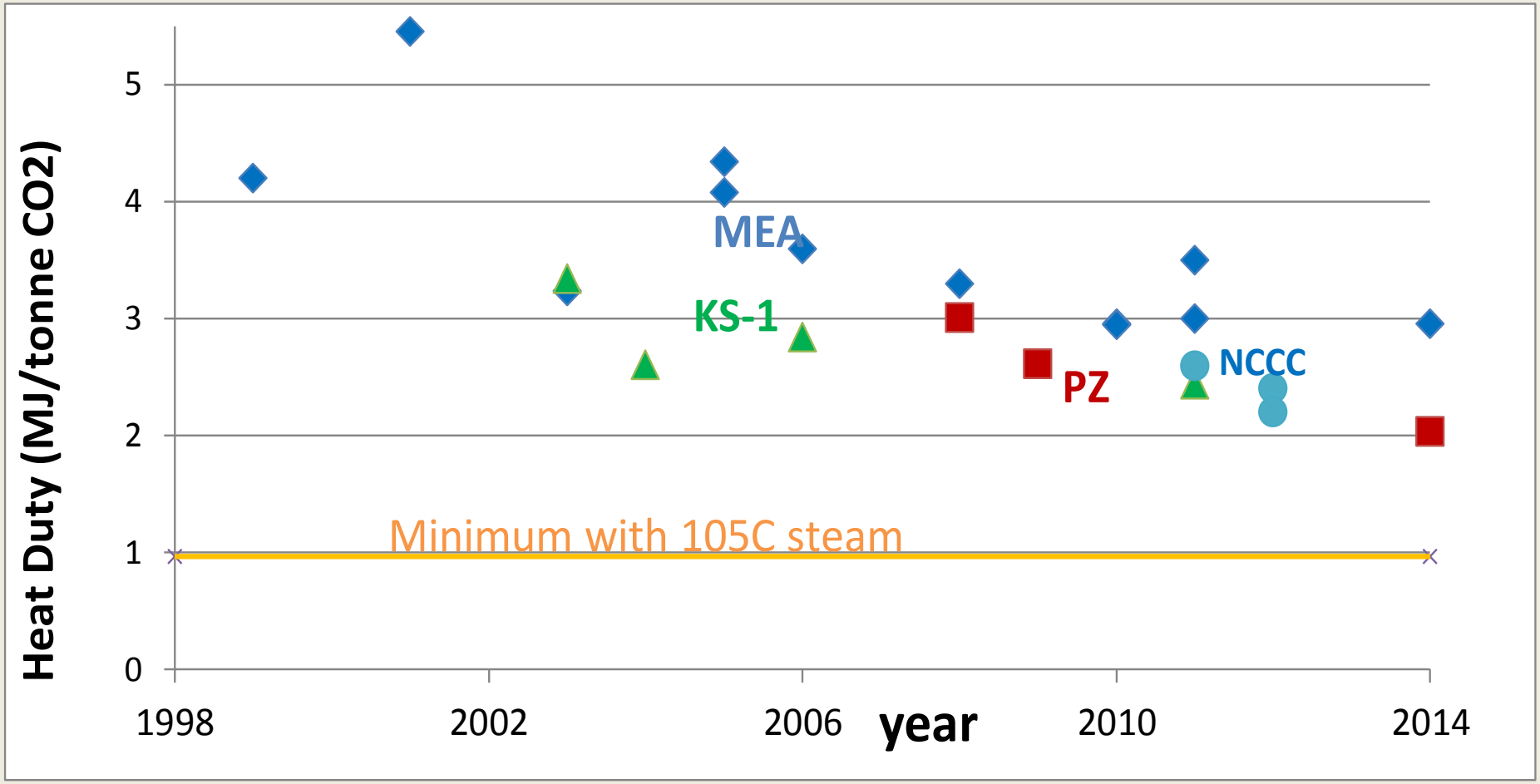
200-250 kwh/tonne CO_2 removed

Giving 44-55% thermodynamic efficiency


$W_{EQ} = W_{pump} + W_{comp} + 90\% \frac{T_{reb} + \Delta T - 313K}{T_{reb} + \Delta T} Q_{reb}$
MEA
PZ
Minimum Work = 109 kWh/tonne = 0.39 GJ/t
CO_2 Separation = 46 kWh/tonne = 0.17 GJ/t
Compression = 63 kWh/tonne = 0.23 GJ/t
Equivalent W_{eq} (kWh/tonne CO_2)
500
400
300
200
100
0
2000
2004
2008
2012
Year

Estimated Heat duty

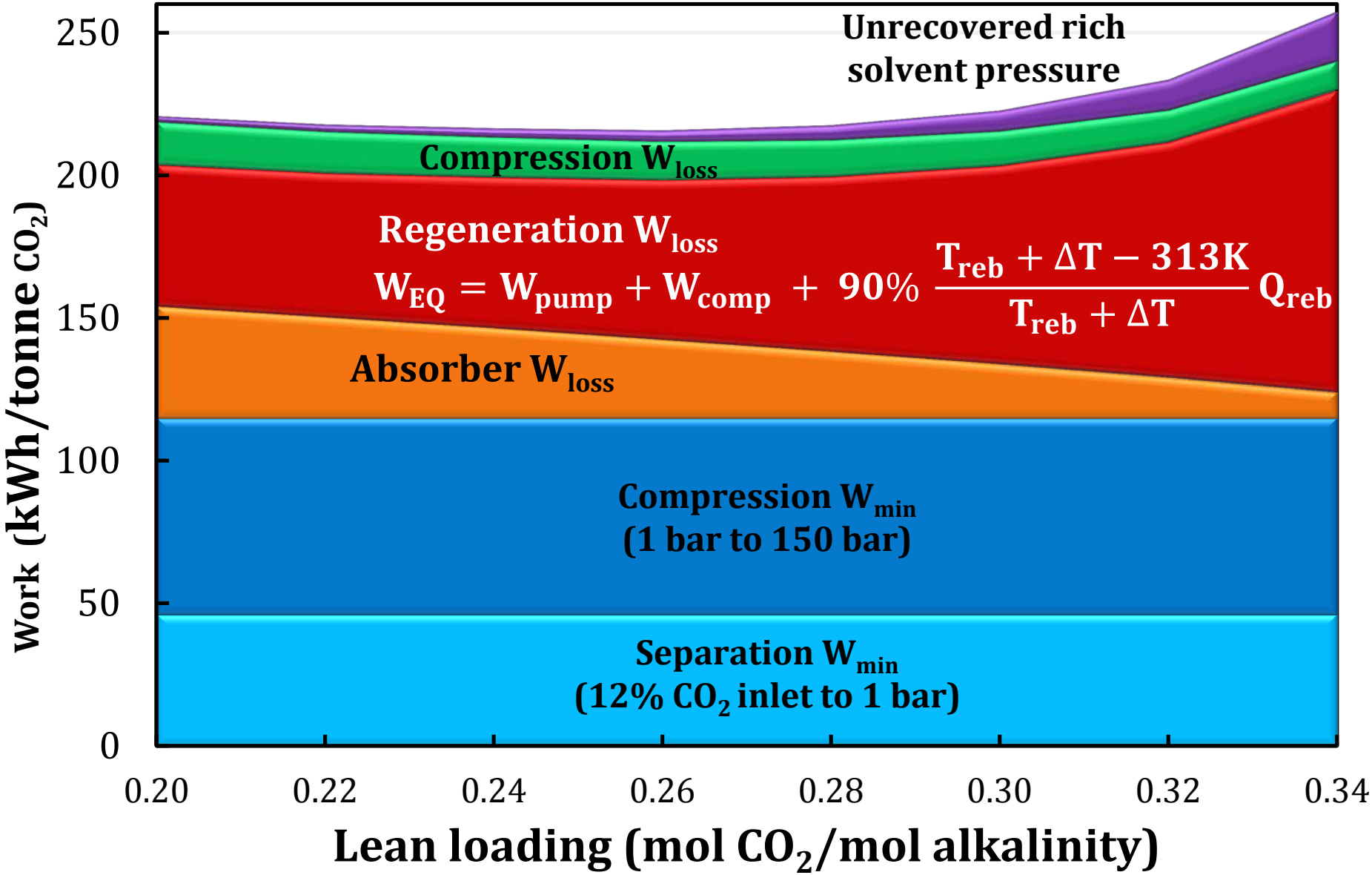
12% CO_2, 90% Removal, 150 bar, 40 °C



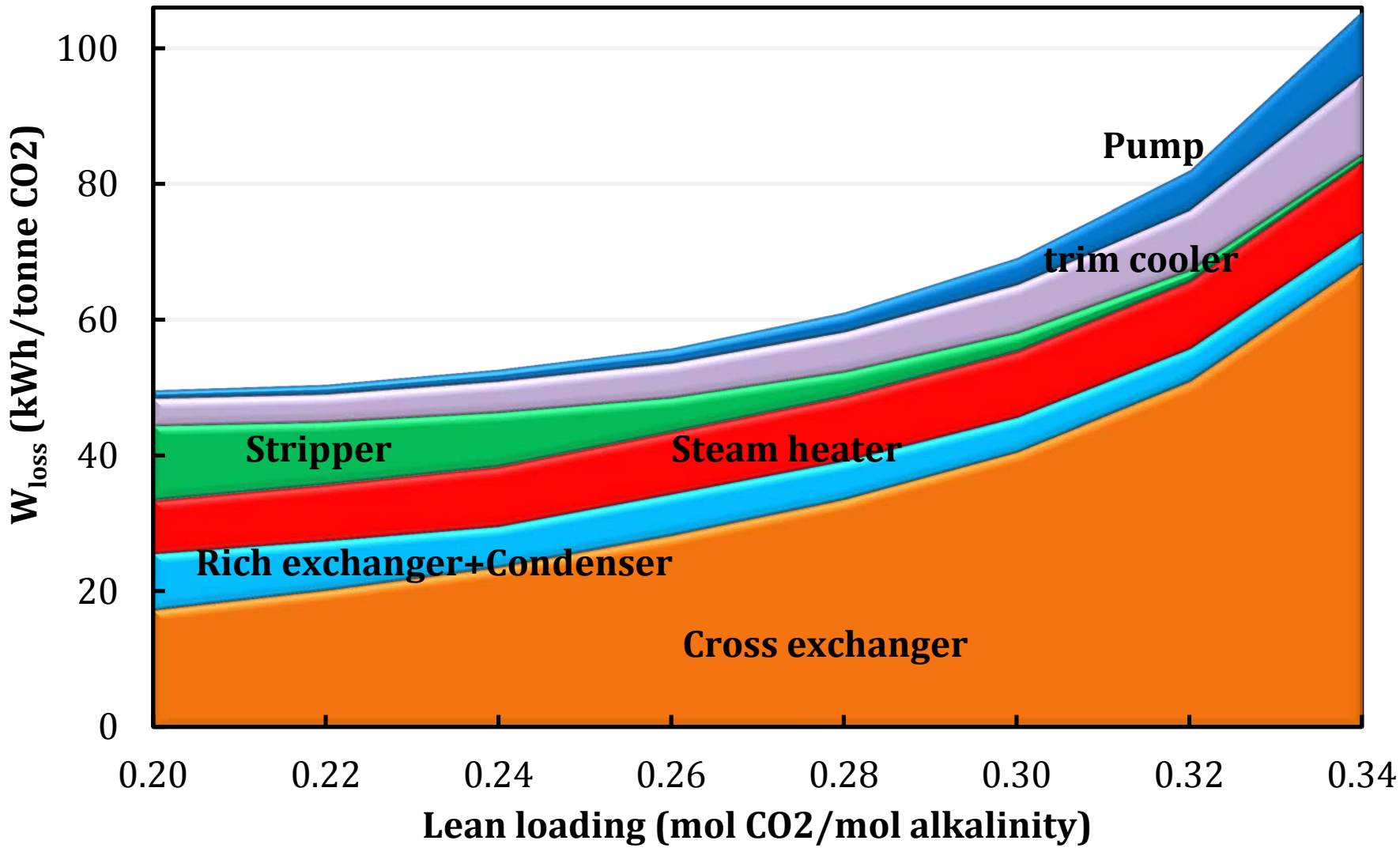
Work Loss in amine scrubbing

- Mass Transfer Driving Force: N_{CO2} RT ln (C_1/C_2)
  - Absorber, stripper
- Heat Exchangers: $W_{loss} = Q\ \Delta T/T$
  - Capital/W_{loss} tradeoff: Cross Exchanger, Reboiler
  - Process loss: Condenser
- Pump/Compressor: $W_{loss} = W_{comp}(eff-1)/eff$
  - $+W_{loss}$ in the intercoolers

Minimum work and irreversibility
5 m PZ, Advanced Flash Stripper, 5°C LMTD, 150°C



W_{loss} in 5 m regeneration by AFS



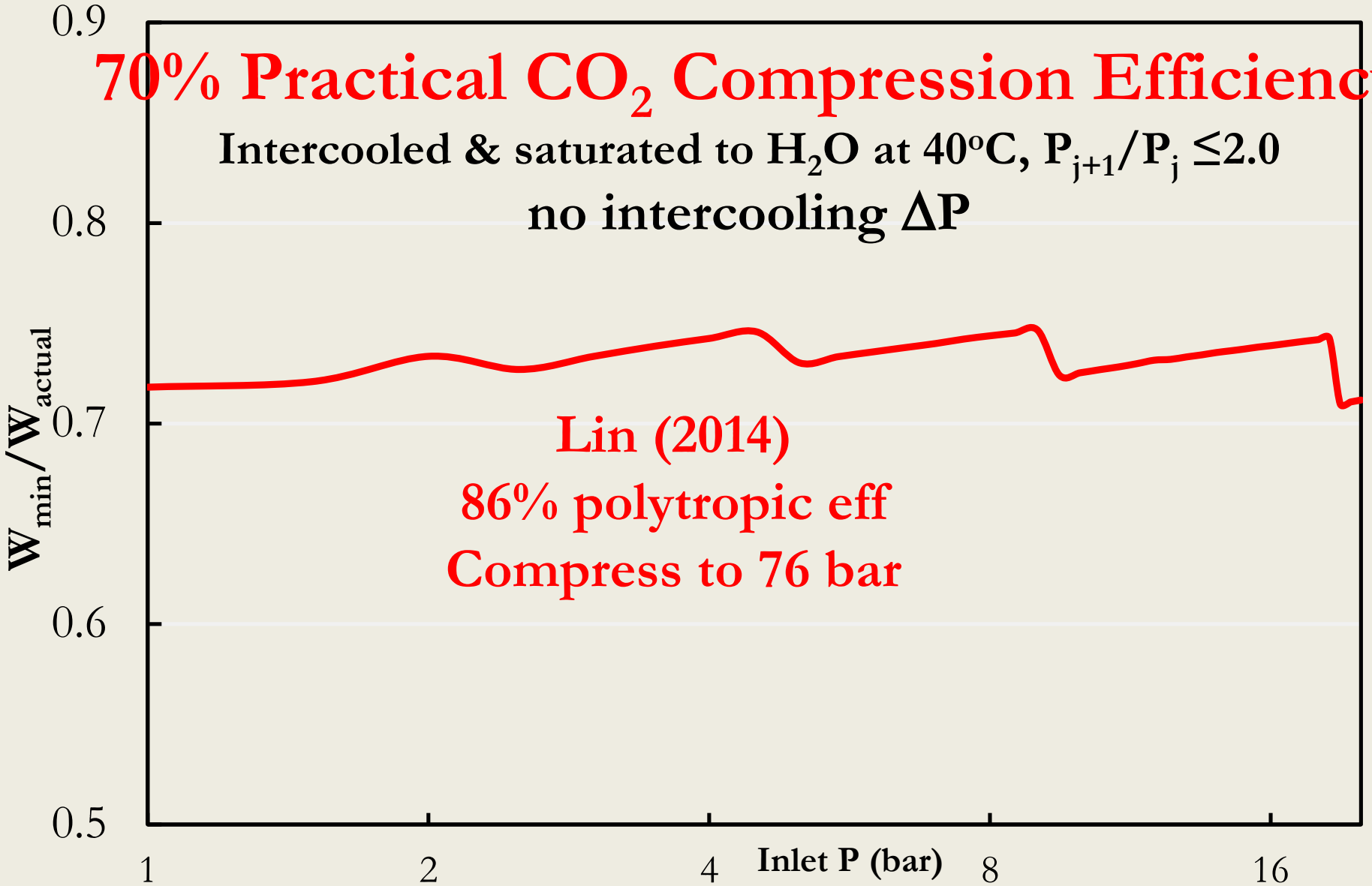
2. Processes that rely on Mechanical Compression to provide W_{min} Cannot be Transformational

- Membranes
- Pressure Swing Adsorption
- Cryogenic Condensation
- Oxycombustion

70% Practical CO_2 Compression Efficiency

Intercooled & saturated to H_2O at 40°C, $P_{j+1}/P_j \leq 2.0$

no intercooling ΔP



Min Annualized Cost w Compressor

$31/tonne CO_2 removed

- W_{min}= 109 kwh/tonne CO_2 removed
  - 12% CO_2, 90% removal, 150 bar, 40°C sink
- If W_{min} provided by mechanical compression
  - W_{comp}= 109/0.7 = 156 kwh/t = $16/t Energy
    - 86% eff, 40C intercooling at $P_1/P_2 \leq 2$, 3% intercooling ΔP
    - $100/MWh
- Capital cost of compressor at W=156 kwh/t
  - Single stage, air compression, $P_2/P_1 = 2$
  - Annualized PEQ = $15/t

ICES supersonic expansion may compete but it is not transformational

- Starts at 156 kwh/t :::: $30.6/t
- Makes Solid CO_2 (more W_{min} than 150 bar CO2)
  - ΔW_{min} = 40 kwh/t
  - ΔW_{comp} =40/0.7 = 57 kwh/t
- If condensation requires a driving force $P_2/P_1 = 2$
  - ΔW_{comp} = 10.4 kwh/t
- If expansion is only 95% efficient
- Total Compressor Work =213/0.95 = 235 kwh/t
  - $46/tonne CO_2 removed (energy and capital)
- Not including dry flue gas, provide ductwork & ΔP, etc.

Thermal Swing Processes with anhydrous sorbents will not be transformational.

- Thermal swing adsorption
- Ionic liquids, designer amines

W_{loss} (kwh/tonne CO_2 removed)

	5 m PZ, advanced flash stripper	Thermal Swing Adsorption
Cross-exchanger	20 (5K ΔT)	40 (10K ΔT)
Intercooled absorber	35 (liquid)	50 (solids)
Regenerator heater	8 (5K ΔT)	16 (10K ΔT)
Compressor	15 (6 bar)	25 (1 bar)
Stripper	9 (countercurrent)	20 (2 stage)
Subtotal	87	151

Solvents w/o H2O will not reduce energy

- Condenser work loss can be a consequence of water
- But advanced stripper configurations eliminate condenser loss
- Furthermore, P_{H2O} generates valuable stripper P
  - Anhydrous solvents/adsorbents generate less P with T swing.
- In the unlikely event that anhydrous solvents have greater capacity (mol CO_2/kg solvent) at <10 cP they may reduce loss of sensible heat.

3. Solids & slurries have poor equipment for heat exchange & contacting

- Packed beds - large ΔP, poor sorbent access, difficult intercooling, costly valving
- Fluidized Bed – large ΔP, in situ intercooling
- Solids heat exchange ???
- Slurries - plugging, scaling, erosion, heat exchange

4. Expensive materials will not compete esp. in the dirty coal environment

- Experience not extensive with adv matls
- Thermal/Hydration: H_2O at 40 to 150°C
- Oxidation: O_2, NO_2, SO_3, Mn^{+2}, Fe^{+2}
- Acidification: SO_2, SO_3, HCl, NO_x
- Particulate: Ash, FeO, MnO
- Impurities: Hg, $CaSO_4$, $CaCO_3$, Se
- Process Upsets with all of the above
- Solids and membranes expensive to replace

5. Opportunities for better processes

- Capital costs (not likely to do better on energy)
  - Mostly poorly defined in beginning stages
- Opportunistic separation energy
  - Combustion
    - Excess ΔG is available from combustion
    - Use combustion air to concentrate CO_2 (MTR)
    - Modify combustion system
  - H_2O evaporation into ambient air or flue gas
    - Consumes water
    - TDA high T adsorption/desorption
  - H_2O condensation from hot flue gas

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Recommendations

- Raise the bar
  - Update amine scrubbing baseline to a second generation technology
- Evaluate against W_{min}
  - Use reversibility analysis to qualify energy claims of advanced processes
- Support amine scrubbing
  - Provide more resources to address the deployment issues of amine scrubbing
- Carefully Consider processes with lower capital cost that use opportunistic energy

GHGT-12

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October 5 - 9, 2014 | AUSTIN, TX - USA