Process Plants for the Not So Near-Term Future

Workshop on New Frontiers in Sustainable Fuels and Chemicals: What's Beyond the Horizon?
University of California, Santa Barbara
February 6th, 2014

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Outline

- **A Possible Solution for Environmental Sustainability**
  - Coproduction of Electricity & Chemicals
    - Can Vary Electricity / Chemicals Ratio
    - To Complements Intermittency of Renewables (Wind/Solar)
  - Start Phasing in Biomass
- **An Advanced Plant Concept**
  - Thermal Conversion
  - Step Change for Expensive Biomass
    - Hydrogasifier
    - SOFC

No Single Magic Bullet

- **Biomass**
  - Synthesis gas or syngas (H_2, CO, CO_2) by thermal conversion
  - Small carbon footprint on an LCA basis
  - But low energy density, distributed resource & seasonal

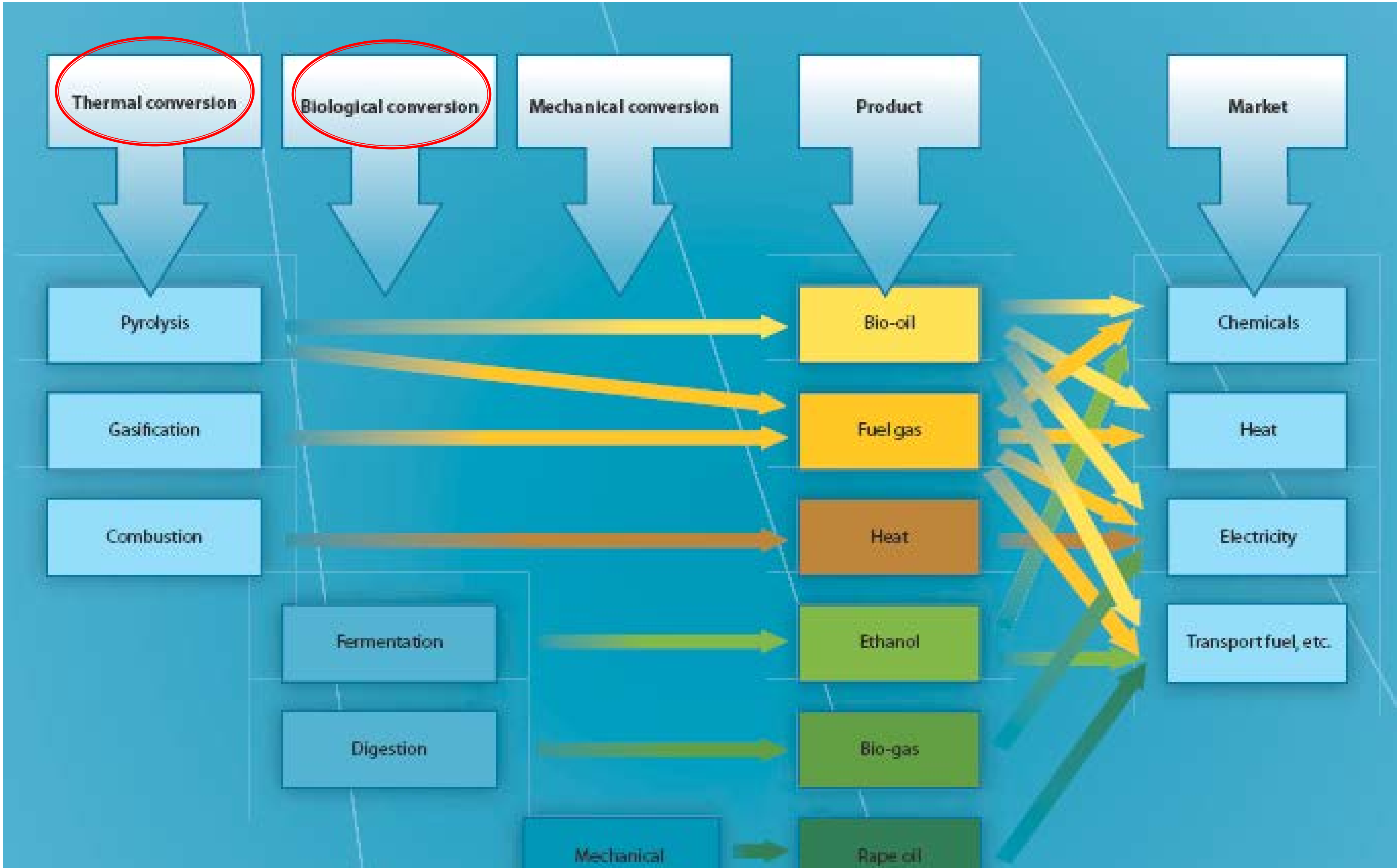
- **Other Options**
  - Wind
  - Direct Solar
  - Nuclear
    - H_2 by electrolysis + CO/CO_2 from other sources*

** Forsberg C., MIT (http://www.ourenergypolicy.org/wp-content/uploads/2011/12/2010_07_AICHE_CEP_Forsberg_NuclearPowerToProduceLiquidFuelsChemicals.pdf)*

Energy Crops

- **Some promising crops but need to further improve yields**
  - Hybrid poplar
  - Hybrid willow
  - Switchgrass
- **Need plants species that do not compete with food production**

Options for Biomass Conversion



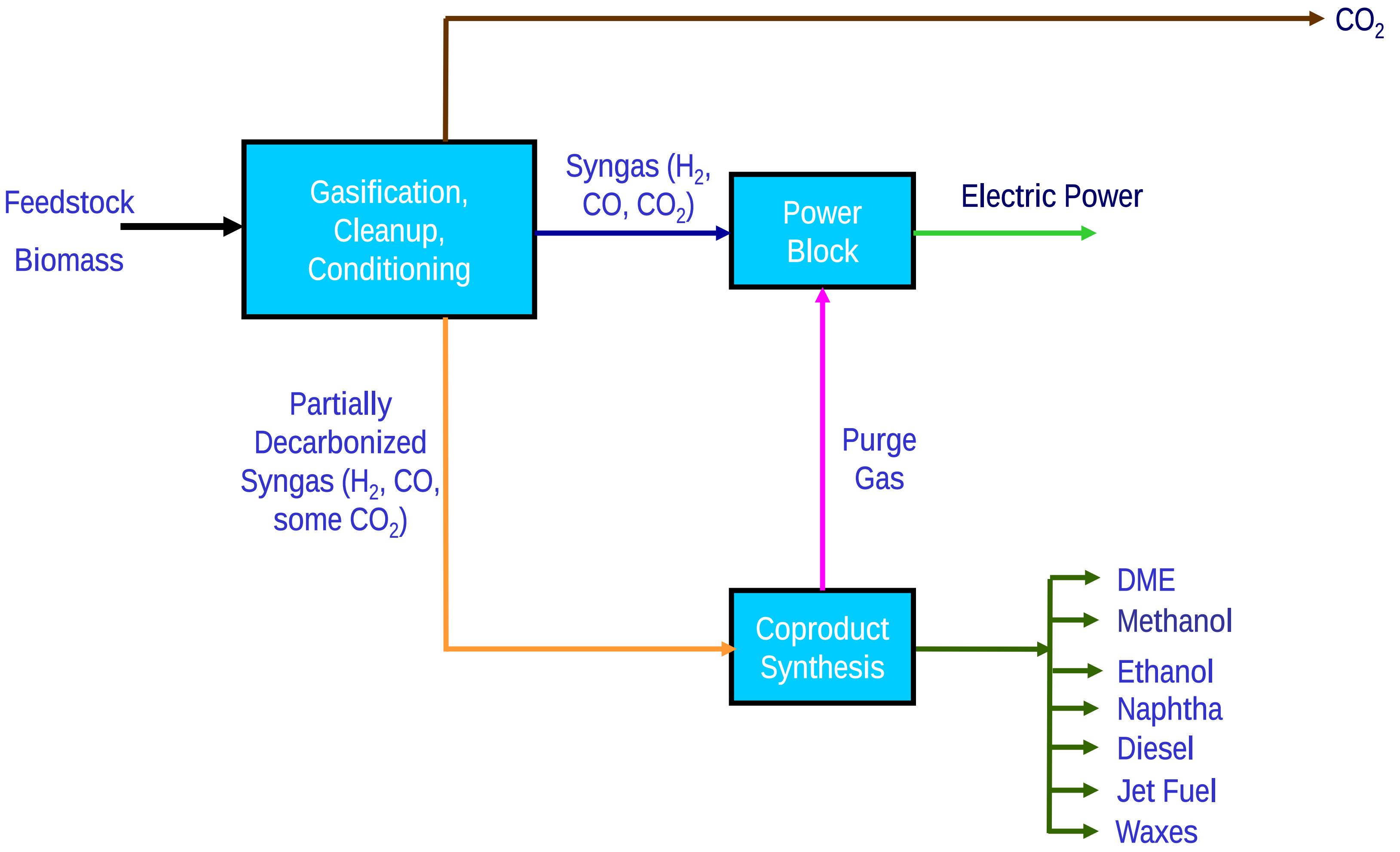
Source: NREL

Thermal vs Biological Conversion

- **Studies have shown they are similar in**
  - Capital cost
  - Operating costs
- **Slight advantage for biological conversion in efficiency**
  - When conventional gasification used for thermal conversion
- **Slight advantage for thermal conversion in water consumption**

Gasification Coproduction Opportunities

H_2 or Alcohols or F-T Liquids or Fertilizers



Synergy in Gasification Coproduction

- **Load following capability**
  - Complements intermittent renewables
  - Change split between syngas to power block versus synthesis unit
- **Economies of Scale of Larger Units**
- **Savings in Synthesis Process**
  - Reduction in synloop recycle
  - Higher reactor through-put (less inerts buildup)
  - Reduced power consumption
- **Integration of Steam Systems & Other Utilities**

Current vs Advanced Coproduction

Current Technology H_2 Coproduction - IGCC

GASIFICATION REACTIONS

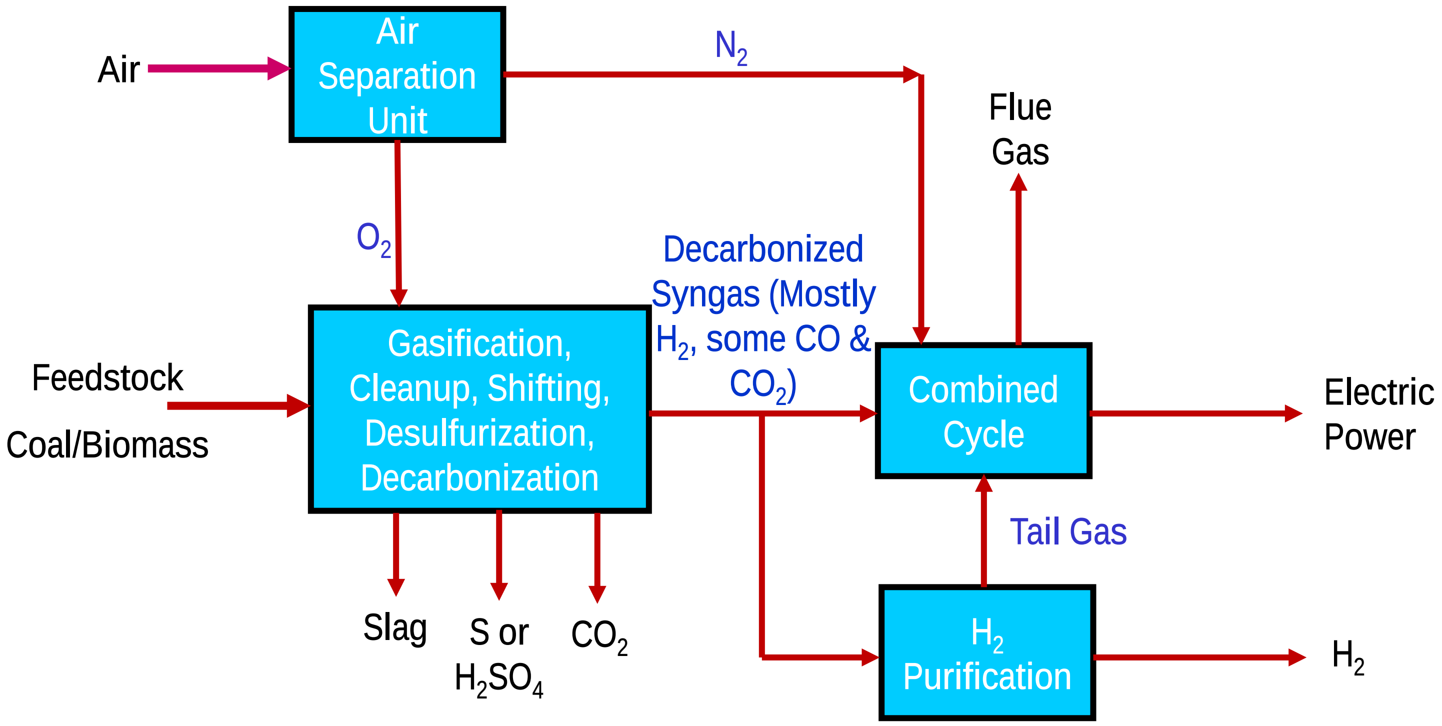
Partial Oxidation: $2C + O_2 = 2CO$ $\Delta H < 0$

Steam Gasification: $C + H_2O = CO + H_2$ $\Delta H > 0$

Shift: $CO + H_2O = CO_2 + H_2$ $\Delta H < 0$

COS Hydrolysis: $H_2O + COS = H_2S + CO_2$ $\Delta H < 0$

Methanation: $3H_2 + CO = CH_4 + H_2O$ $\Delta H < 0$



Future Technology H_2 Coproduction - IGFC

HYDROGASIFICATION REACTIONS

$C + 2H_2 = CH_4 \quad \Delta H < 0$

$CO + H_2O = H_2 + CO_2 \quad \Delta H < 0$

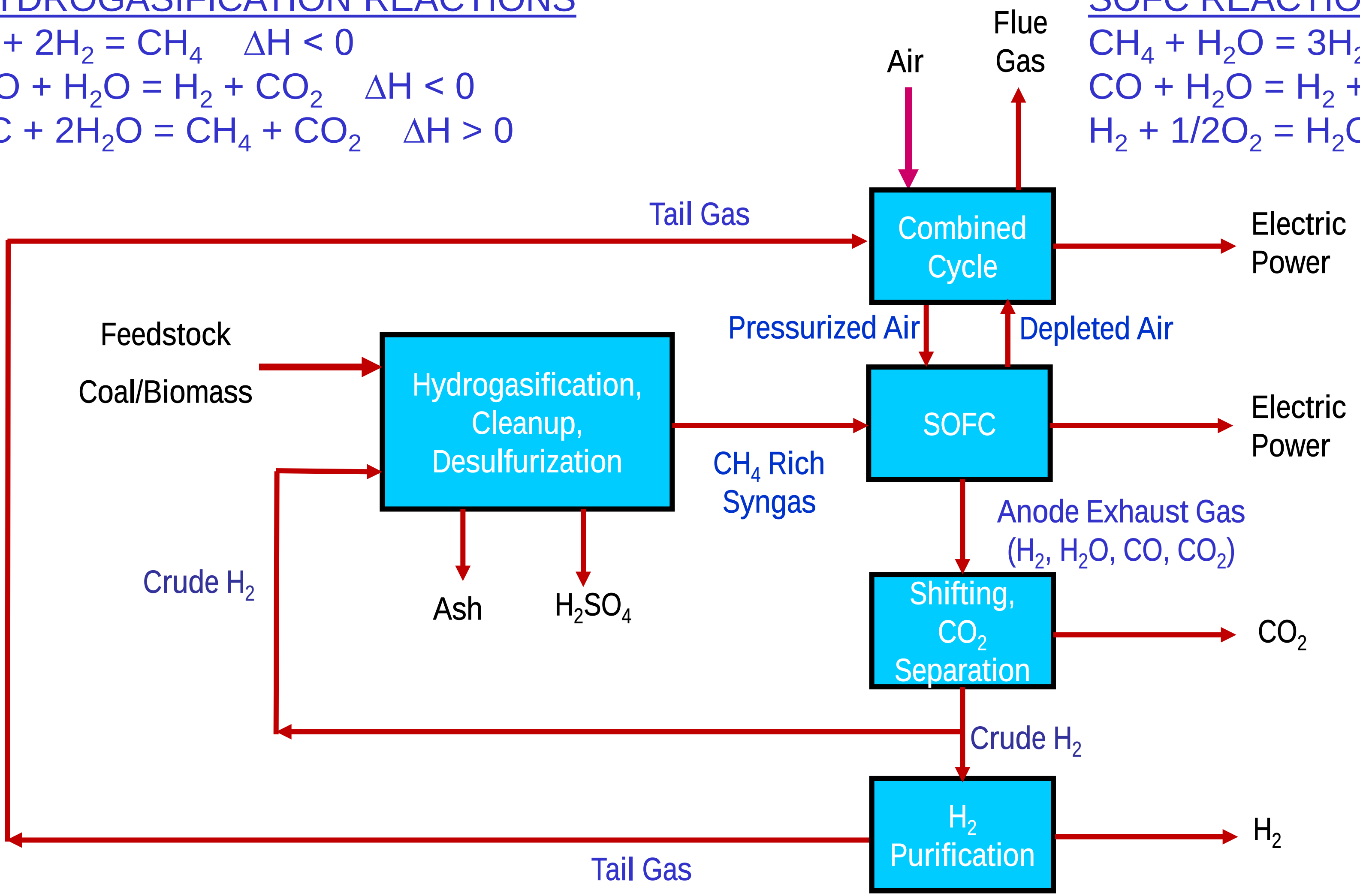
$2C + 2H_2O = CH_4 + CO_2 \quad \Delta H > 0$

SOFC REACTIONS

$CH_4 + H_2O = 3H_2 + CO \quad \Delta H > 0$

$CO + H_2O = H_2 + CO_2 \quad \Delta H < 0$

$H_2 + 1/2O_2 = H_2O \quad \Delta H < 0$



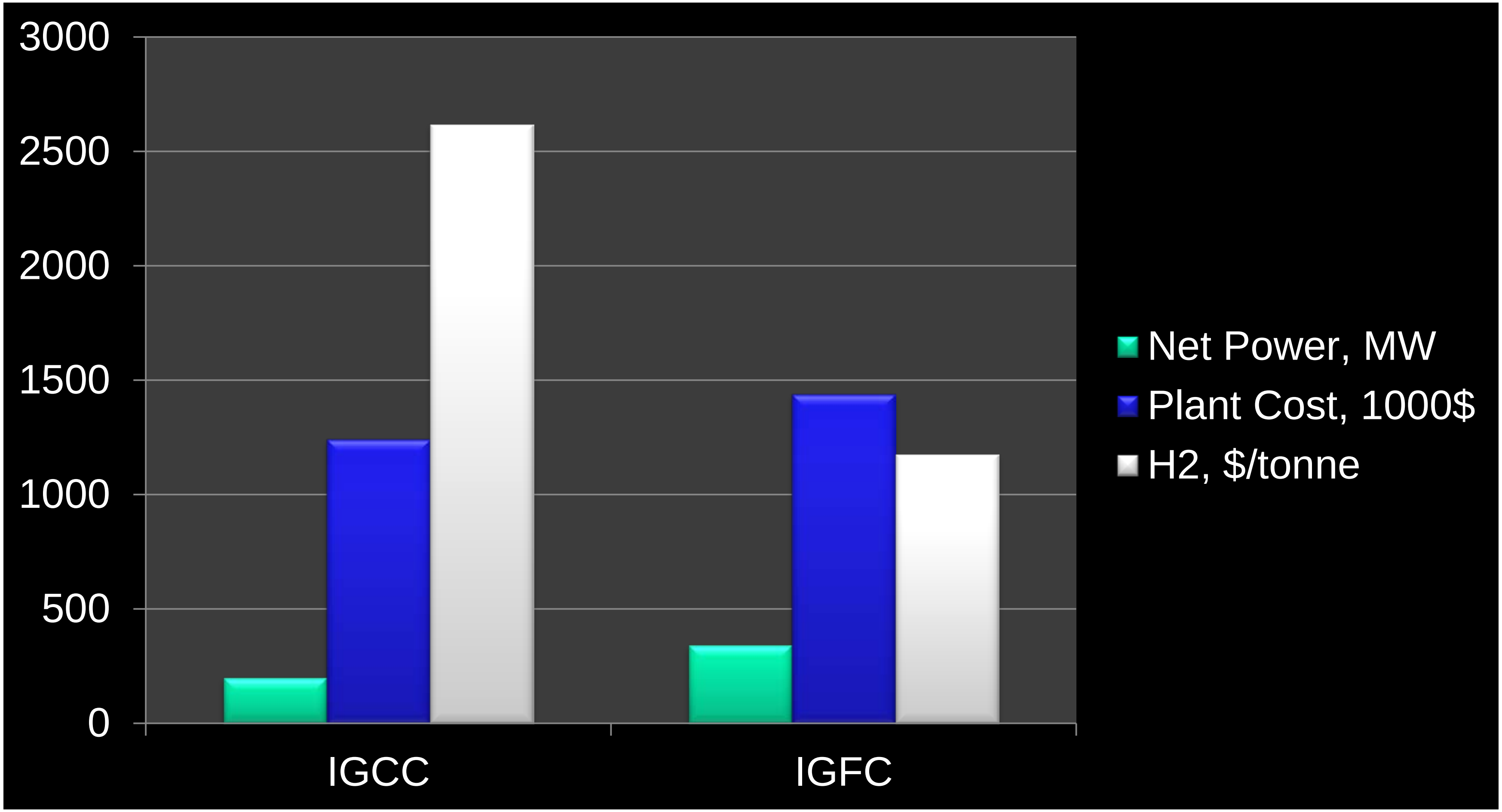
Thermal Performance with H_2 Coproduction & Carbon Capture*

	IGCC	IGFC
Coal feed rate (dry basis, tonne/D)	2511	
Corn stover feed rate (dry basis, tonne/D)	647	
Cereal straw feed rate (dry basis, tonne/D)	647	
Total energy input (HHV, GJ/hr)	3902	
Total gross power (MW)	331	608
Total internal power consumption (MW)	130	265
Net Electric Power(MW)	201	343
H_2 exported (tonne/D)	155	
H_2 exported (% of input fuel HHV)	23.41	
Net power generation efficiency (% HHV)	18.51	31.63
Effective Efficiency (% HHV)	30.4	43.5

** Li M, Rao AD, Samuelsen GS. Performance and Costs of Advanced Sustainable Central Power Plants with CCS and H_2 Co-production. Applied Energy, Vol. 91, pp 43-50, 2012.*

IGCC vs IGFC

Credit of “Green Electricity” = $135/MWh



Hydrogasification

- **Methane can be produced while energy balance can be maintained**

  $C + 2H_2 = CH_4 \quad \Delta H < 0$

  $CO + H_2O = H_2 + CO_2 \quad \Delta H < 0$

  $2C + 2H_2O = CH_4 + CO_2 \quad \Delta H > 0$

- **No need for O_2 except small amount for any left over char conversion**

  Reduction in auxiliary power and plant cost

- **Need H_2 or H_2 + CO instead**

  Gas separation & recycle

- **Potential for high cold gas efficiency**
- **High concentration of CH_4 in syngas: 30 mol% (dry basis)**
- **Operation at 700 to 800°C & 70 bar**

  No tars reported when catalyst used

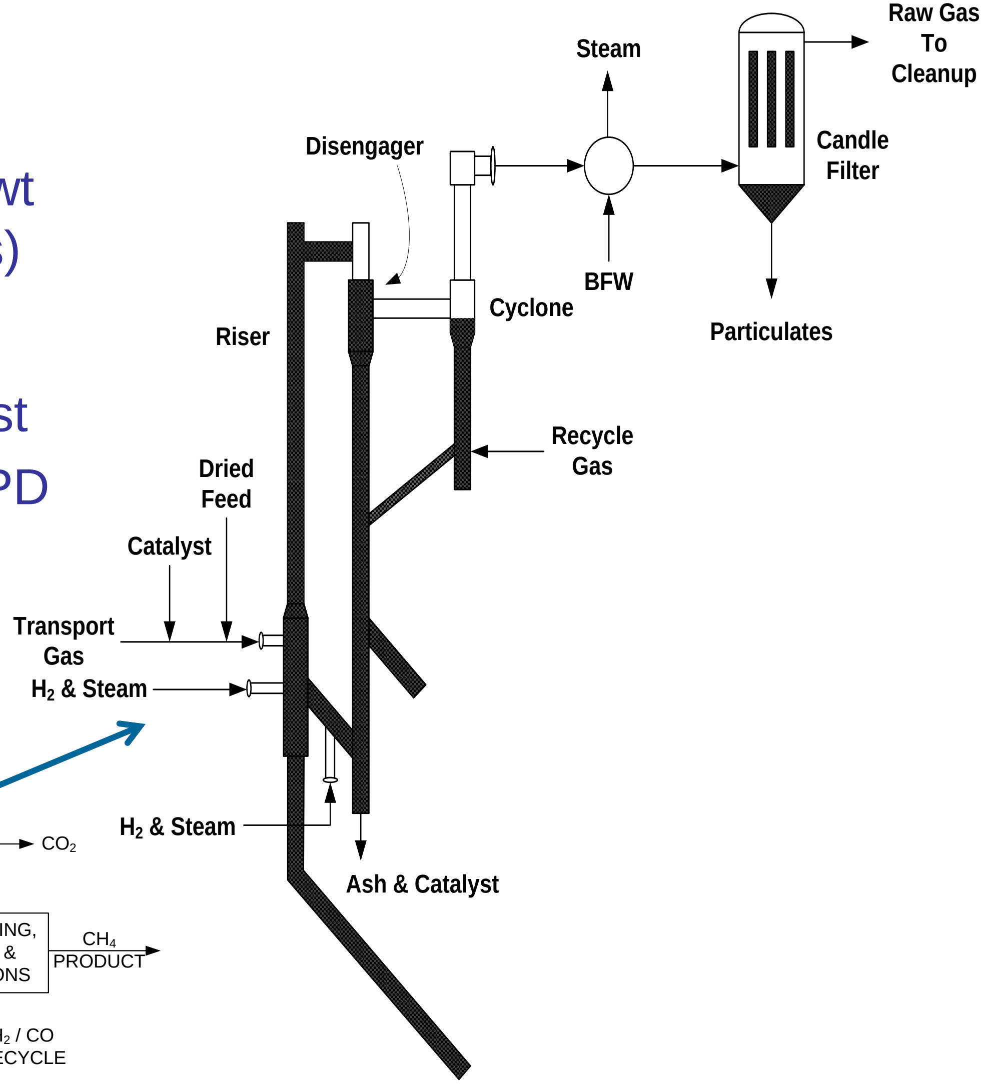
- **Carbon conversion**

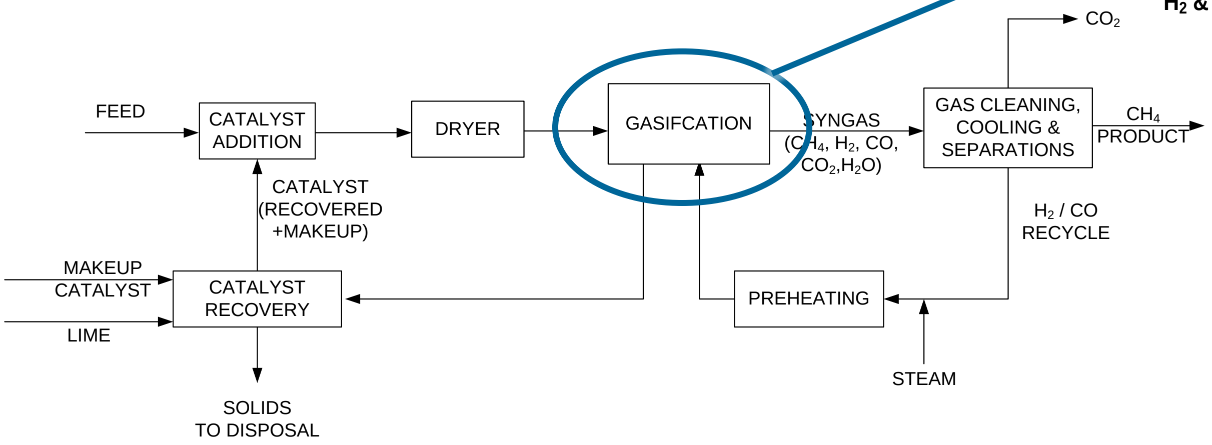
  Approaching 90% for coal (much higher for biomass)

  Feed unconverted char to a 2nd high temperature gasifier

Catalytic Hydrogasification

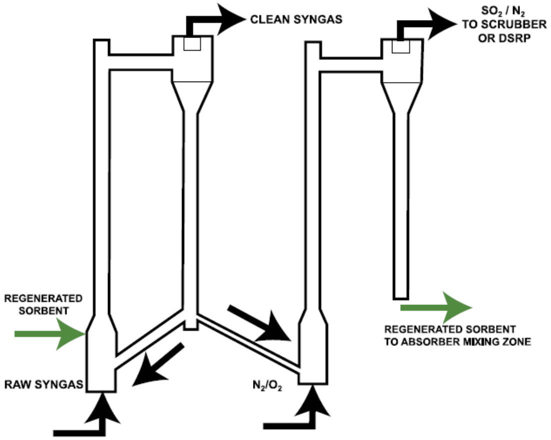
- **Exxon**
  - Investigated in 1970s
  - Using K_2CO_3 or KOH catalyst (15 wt % of dry coal input on K_2CO_3 basis)
- **GreatPoint Energy**
  - bluegas™ using proprietary catalyst
  - Pilot testing in 2006 – 2007 at 1 TPD coal
  - Demo in partnership with China Wanxiang at $30x10^9$ m^3/yr SNG





Gasification – Development Requirements

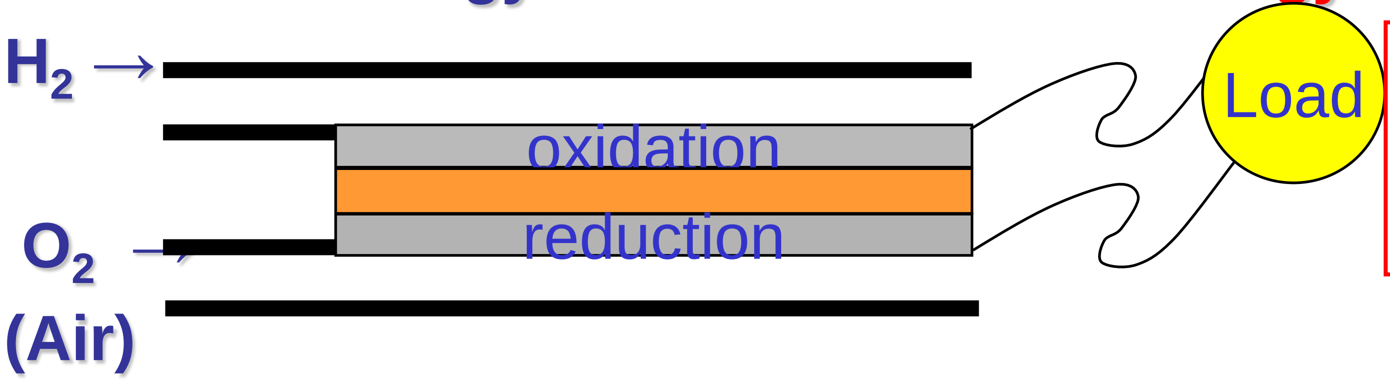
- **Hydrogasifier**
  - Catalyst recovery
- **Biomass Feeding**
  - Friability issue for certain feedstocks
  - Pretreatment to increase friability
- **Warm gas cleanup**
  - Better attrition properties for regenerable beds
  - Reactor design for hot solids transfer
- **Warm gas CO_2 capture**
  - Sorption
  - High temperature membranes



Fuel Cell – Electrochemical Device

Fuel cell energy conversion device:

"chemical energy" → work + thermal energy



Temperature change small
Electrical work

Reduction & oxidation separated in space:

Cathode: $\frac{1}{2} O_2 + 2e^- \rightarrow O^=$

Anode: $H_2 + O^= \rightarrow H_2O + 2e^-$

Ordered electron flow – useful work

CH_4 fuel - Convert thermal energy to chemical energy:

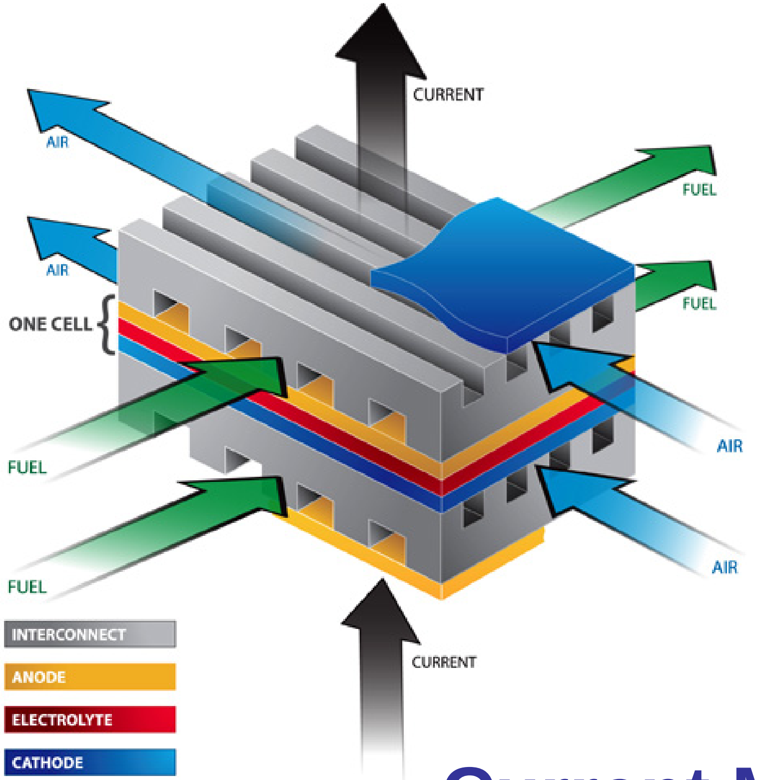
Reformation: $CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \Delta H > 0$

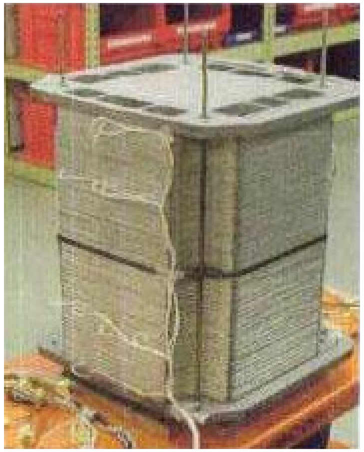
SOFCs Currently Small

- Limited to mostly kW class
- Need 100 MW class

Siemens Energy

Planar SOFC Stack



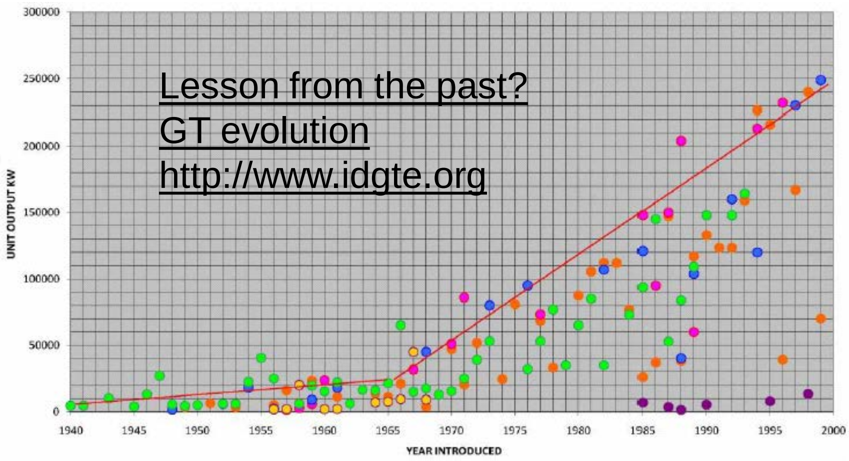


Current Materials - Ceramic

- Electrolyte: Yttria-stabilized zirconia (YSZ)
- Cathode: Lanthanum manganite ($LaMnO_3$) doped with Ca or Sr
- Anode: Nickel-YSZ cermet

Source: http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/primer/cell.html

SOFC – Development Requirements (1)



SCALE

- **Currently limited to mostly kW class**
  - Need 100 MW trains

COSTS

- **Developed for space program in 1960s & 1970s**
  - Extremely expensive ($600,000/kW) then
- **Significant efforts in past 3 decades**
  - Develop more affordable designs for stationary power applications
  - But progress slow
- **Solid State Energy Conversion Alliance (SECA) target**
  - < $700/kW$_e$
- **Cheaper materials operating at lower temperatures**
- **Ionic & not just electronic conductors for electrodes**
- **Improved fabrication techniques**

SOFC - Development Requirements (2)

- **Robust operation**
  - Off-design
  - Dynamic performance
    - Management of internal thermal stresses for fast ramping capability
- **Pressurized fuel cell (~10 bar)**
  - Controllability more complex
    - Sudden depressurization of fuel cell a concern
- **SOFC as reformer**
  - Heat management
- **Some other research areas**
  - Materials less susceptible to fuel & air contaminants
  - Turbo-machinery & BOP controls
  - High efficiency inversion & conversion power electronics
  - Improved interconnects, seals, manifolding

Synthesis Unit - Development Requirements

- **Stability issues of synthesis unit for fast ramping capability**
- **Part-load operation of synthesis unit**
- **Reactor design / separation processes / systems integration**