Sustainability and Systems Engineering: Reducing the Carbon Footprint of Chemical Plants

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Sustainability Definition

"Sustainability is the path of continuous improvement, wherein the products and services required by society are delivered with progressively less negative impacts upon the Earth."

AIChE Institute for Sustainability

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AIChE Sustainability Index Components

- Strategic Commitment
- Safety Performance
- Environmental Performance
  - Resource use
  - Waste and emissions
  - Environmental liabilities
- Product Stewardship
- Innovation
  - Product and service meeting social needs
  - Process innovation
- Value-Chain Management
  - EHS management
  - Supply chain management
  - Stakeholder engagement

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Sustainability Themes

- Enhancing quality of life
- Efficient use of resources
- Value for customers and stakeholders
- Triple bottom line
- People, planet, profit
- Full cost accounting

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What does this mean for Chemical Process Design?

- Multiple objective optimization?
- Monetization of externalities?
- Renewable energy?
- Biomass feedstocks?

Elements of Sustainability

- Environmental Protection
- Health and Safety
- Energy Efficiency
- Product Stewardship
- Corporate Citizenship

- Renewable Energy
- Water Management
- Biomass Feedstocks
- National Security
- Climate Change

- Industrial Ecology
- Life Cycle Analysis
- Green Chemistry
- Benign by Design
- Waste Minimization
- Watershed Protection
- Pollution Prevention
- Low Energy Separations
- Carbon Trading
- Clean Products
- Systems Analysis

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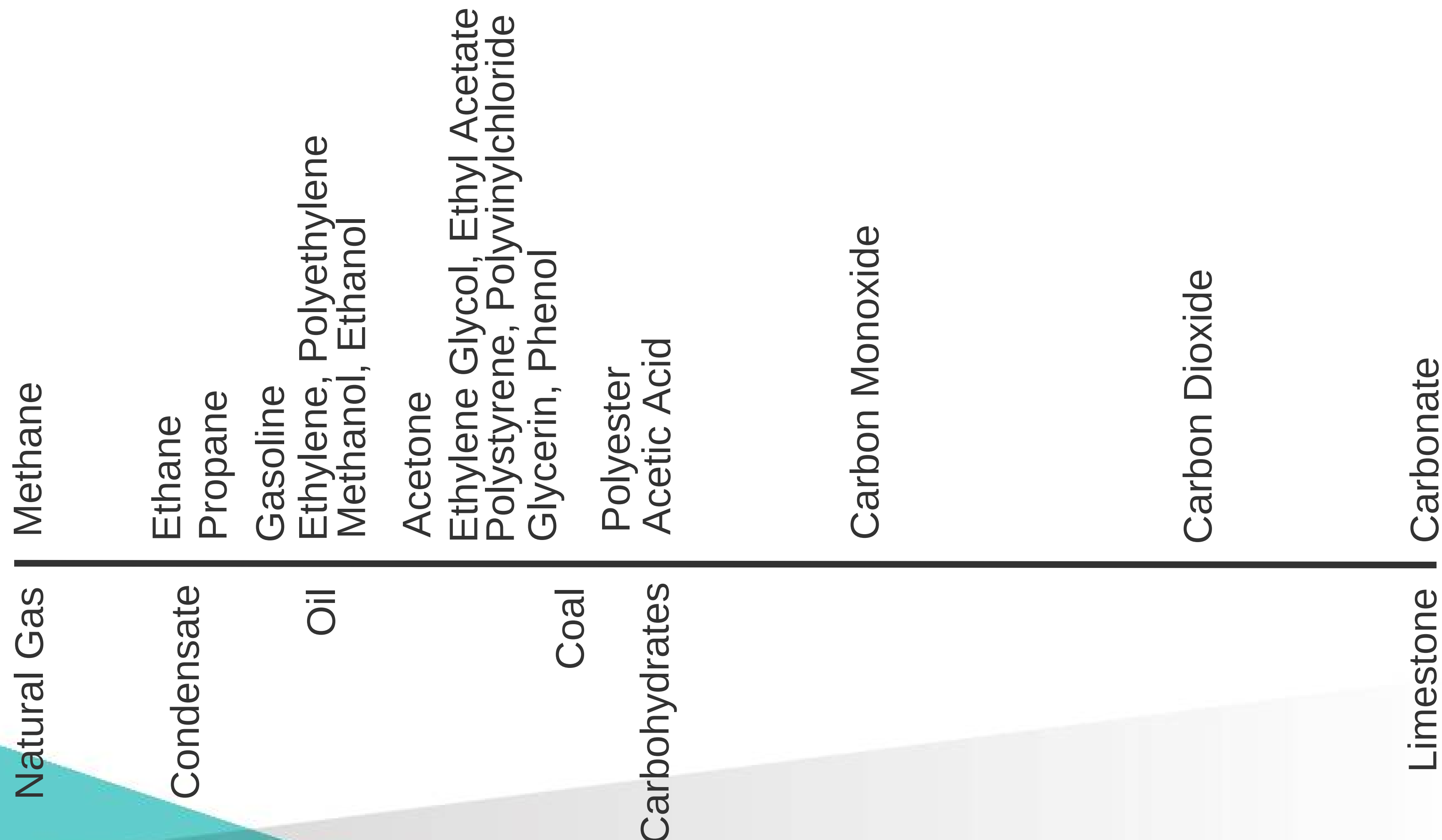
Matching Feedstock and Product Energy



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Which is the sustainable raw material?

- The most abundant (carbonate)?
- The one for which a "natural" process exists for part of the required endothermic oxidation state change (atmospheric carbon dioxide)?
- The one likely to require the least additional energy to process into final product (oil)?
- The one likely to produce energy for export in addition to that required to process into final product (gas)?
- The one likely least contaminated (methane or condensate)?
- The one most similar in structure (perhaps biomass)?
- A compromise: abundant, close oxidation state, easily removed contaminants, generally dry (coal)?

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Feedstock Substitution Challenges
Energy

- As methane, condensate, and light crude become depleted, feedstocks for both transportation fuels and chemicals will become heavier and higher oxidation state
- Hydrogen will be required to reduce these feedstocks
  - If derived as at present from steam reforming, will result in significant additional carbon dioxide production
  - Unless derived from solar or nuclear water-splitting
- Processes will become net endothermic
- Reaction energy and separation/purification energy both to be supplied from utilities

Process industries become much more energy-intensive

Greater role for heat integration, multi-effect operation, low-energy separations, process intensification technologies, etc.

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50-Year Global Energy Demand

- Total energy demand – 1500 Quads
- New electricity capacity – 5000 GW
  - One new world-scale 1000 MW powerplant every three days
  - Or 1000 square miles new solar cells per year
- Clean water for 9 billion people
- Carbon emissions growing from 7 GTC/yr to 26 GTC/yr
  - More, if methane exhausted
  - More, if synthetic fuels are derived from coal or biomass

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Consequences of Continuing Carbon Dioxide Emissions

- At 385ppm, 2.2 GTC/yr more carbon dioxide dissolves in the ocean than did at the preindustrial revolution level of 280ppm
- Currently, about 0.3 GTC/yr is being added to soil carbon and to terrestrial biomass due to changing agricultural and land management practices
- The balance results in ever increasing atmospheric CO_2 concentrations

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Sustainable Energy Challenges

- Even with substantial lifestyle, conservation, and energy efficiency improvements, global energy demand is likely to more than triple within fifty years
- There is an abundance of fossil fuel sources and they will be exploited especially within developing economies
- Atmospheric addition of even a few GTC/yr of carbon dioxide is not sustainable
- In the absence of a sequestration breakthrough, reliance on fossil fuels is not sustainable

Carbon footprint reductions of unprecedented magnitude may be required

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Carbon Management could become the greatest Sustainable Smart Manufacturing challenge facing the processing industries

Carbon Dioxide Sources
Chemical and Refining Industries

- Chemical reactions
  - Hydrogen (steam reforming)
  - Partial oxidations (EO, TPA, MA, etc)
  - Cement (lime)

- Energy from fossil fuel combustion
  - Electricity
  - Steam
  - Fired furnaces

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Two Carbon Reduction Strategies

- Reduce process energy requirement
  - Energy conservation

- Reduce carbon emissions associated with energy production
  - Carbon management

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Reduce Process Energy Requirement
Energy Conservation

- Change product portfolio
  - Choose not to manufacture energy-intensive chemicals
- Process improvement
  - Less energy-intensive chemistry pathways
  - Less energy intensive operations especially separations, compressions, etc
- Process intensification
  - Heat integration and power recovery
  - Process changes enabling greater heat integration
  - Optimizing thermal and mechanical energy

Energy Conservation Challenges

- Energy conservation can adversely impact plant performance and product fitness for use
- Heat and power integration can create interactions and decrease degrees of freedom
- Swapping thermal and electrical energy can affect utility system balance

  - Multi-effect distillation: half the energy, but higher temperatures may require more expensive steam or cause bottoms product thermal degradation
  - Heat integration: alters disturbance rejection path

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Reduce Carbon Associated with Energy Production

Carbon Management

- Reduce Carbon Dioxide Production
- Offset Carbon Dioxide Production
- Carbon Dioxide Capture
- Carbon Dioxide Storage

Reduce Carbon Dioxide Production

- Switch to a more energy-intense fossil source for fuel and feedstock
  - Switch from oil to gas
  - Switch from coal to gas

- Use non-carbonaceous energy sources
  - Nuclear
  - Solar-hydroelectric
  - Solar-wind
  - Solar-photovoltaic
  - Solar-thermal
  - Geothermal
  - Wave
  - Tidal

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Offset Carbon Dioxide Production

- Burn fossil fuel and harvest and bury/sink an equivalent amount of biomass

- Cultivate (crop), recover (residues), or recycle (waste) biomass for fuel and feedstock
  - Burn biomass directly for heat and power
  - Biologically or chemically convert biomass to alternative fuel (e.g., bioethanol, biobutanol, or biodiesel)
  - Pyrolyze/gasify biomass and convert to alternative fuel
  - Convert biomass into chemical feedstock

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Carbon Dioxide Capture

- Capture from low partial pressure point sources – fluegas
  - Alcoholamines
  - Chilled ammonia
  - Caustic or lime
  - Carbonate
  - Zeolite adsorption
  - Active transport membranes
  - Anti-sublimation

- Capture from high partial pressure point sources – gasifiers
  - Rectisol
  - Selexol
  - Metal oxides

- Collect from virtually pure carbon dioxide
  - Oxygen-fired furnaces, kilns, or turbines (oxyfuel)

Energy required to recover CO_2 and regenerate sorbent

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Carbon Dioxide Storage

- Geologic (as pressurized gas, supercritical liquid, or carbonic acid)
  - Porous capped rock (with or without oil recovery)
  - Coal beds (with or without methane displacement)
  - Deep saline aquifer

  Compression and injection energy

- Oceanic
  - Ocean disposal (as carbonic acid)
  - Deep ocean disposal with hydrate formation
  - Ocean disposal with limestone neutralization (as bicarbonate solution)

  Viewed as ocean dumping

- Land disposal as carbonate salt
  - Reaction with silicate

  Geologic time kinetics

Carbon Dioxide Storage
As Biomass

- Ocean sinking of biomass
  - Fertilized ocean (iron or nitrogen)
  - Cultivated terrestrial biomass (crops, grasses, trees, algae)
  - Uncultivated terrestrial biomass

- Land burial of biomass
  - Terrestrial burial of cultivated biomass and residues
  - Terrestrial burial of uncultivated biomass
  - Pyrolysis and separate disposition of liquors and biochar

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Solar Energy Challenges

- Wind
  - Load factor
  - Variable output
  - Distribution
  - Siting

- Solar photovoltaic
  - Diurnal cycle
  - Distribution
  - Manufacturing cost

Massive electrical storage technology needed

Biomass Energy Challenges

- Alternative Energy Mandate only counts biomass from agricultural and currently managed forest lands
  - Already has a competitive food/feed/fiber/lumber uses
  - Limited availability of wastes and byproducts

- Sustainable production from currently unmanaged lands
  - Limited unmanaged productive land available

- What is most appropriate biomass use?
  - Food and feed
  - Structural building material
  - Specialized transportation fuel
  - Heat and power cogeneration
  - Carbon capture system
  - Carbon storage system

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Nuclear Energy Challenges

- Reprocessing
- Transmutation
- Waste storage

- Nuclear Hydrogen

- Nuclear cogeneration
- Nuclear process heat
  - Siting, load following, reliability, back up

- Electrically-dominated chemical processing

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Carbon Footprint Factoids

- Energy optimization and environmental protection have always been process design issues of concern
- The continued atmospheric injection of carbon dioxide from fossil fuel combustion is not sustainable
- Migration to biological and coal-derived feedstocks could increase the energy intensity of chemical processes
- Current estimated costs for fluegas carbon capture and storage are the same order of magnitude as the purchase cost of natural gas and about five times the purchase cost of steam coal

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Carbon Footprint Factoids
Continued

- Not sufficient biomass grows to sustainably meet total projected societal energy demands
- Temporally irregular solar and wind energy cannot contribute more than a few percent of electrical demand before the distribution grid becomes unstable
- Electricity generation is backed up by the grid; there is no grid to back up steam and other process heating utilities
- Clusters of multiple factory-assembled small Generation III+ and IV nuclear reactors could meet process heat reliability requirements
- There could be a shift to electrically-driven chemical processes

Carbon Footprint Factoids

Continued

- Changing product portfolios, alternative chemistries, energy conservation, fuel switching, carbon management, migration to non-fossil energy sources, and a shift to electrically-driven process technologies are all likely components of various strategies to reduce the carbon footprint of chemical plants

- The analysis, evaluation, optimization, and execution of these strategies will depend on the development and use of very large, very complex systems models and other technical contributions from the Chemical Process Systems Engineering Community

Thank You