TEES | GFRC
GAS & FUELS
RESEARCH CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

Sustainability in the Context of Process Engineering

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Environmental Engineering Symposium, AIChE Dallas Section
October 27th, 2017

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Past Positions:

Post Doctoral Research Associate at the Artie McFerrin Department of Chemical Engineering, Texas A&M University, College Station, TX (May 2014 ‑ December 2015)

ORISE Post Doctoral Fellow at the National Risk Management Research Laboratory, **US Environmental Protection Agency, Cincinnati, OH** (November 2010 ‑ April 2014)

Doctorate (Chemical Engineering) : Louisiana State University (2005-2010)

Bachelor (Chemical Engineering) : Jadavpur University, India (1999-2003)

American Institute of Chemical Engineers

2nd Vice Chair, Environmental Division, AIChE 2017

Programming Chair, Environmental Division, AIChE 2015-2017

Director, Environmental Division, AIChE 2011-2014

Director, Fuels and Petrochemical Division, AIChE 2016-2019

The GFRC is a Texas A&M Engineering Experiment Station (TEES) center that has been created to provide **research, educational, and outreach services** in the area of **gas and fuels**.

These activities and services support the **substantial growth of shale and natural gas exploration, production, processing, and monetization**, especially in the **United States and in Qatar**.

There is a **critical need** to support this growing industry and to offer novel approaches to its **sustainable development**. The GFRC aims to serve as a global leader in this area.

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TEXAS A&M UNIVERSITY at QATAR

Sustainability

Rainwater Harvesting?

Riding a bike?

Wind?

Solar?

Renewable Fuels?

Recycling?

Electric/Hybrid Cars?

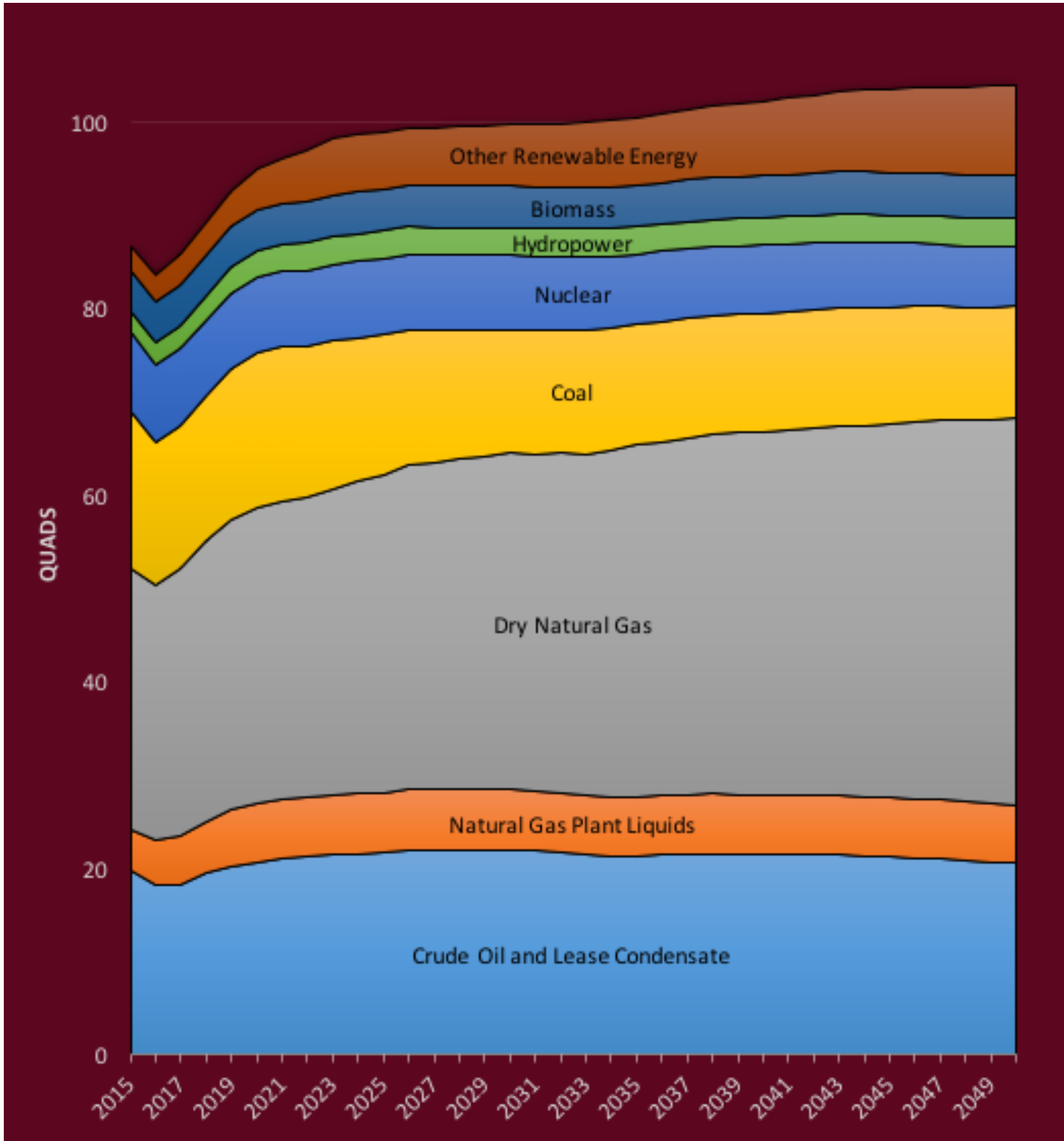
Reality

Natural Gas, Coal and Crude are going to continue as primary energy sources.

Natural Gas is the ”new” resource that the United States has, but not enough use other than LNG and electricity.

Natural gas liquids responsible for new boom in industrial development in the Gulf Coast.

Total Energy Production, EIA, AEO 2017



Sustainability

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” – Brundtland Report, United Nations World Commission on Environment and Development (WCED), 1987

There are numerous approaches to apply sustainable development by world organizations, countries and industries.

MONSANTO

institute for sustainability
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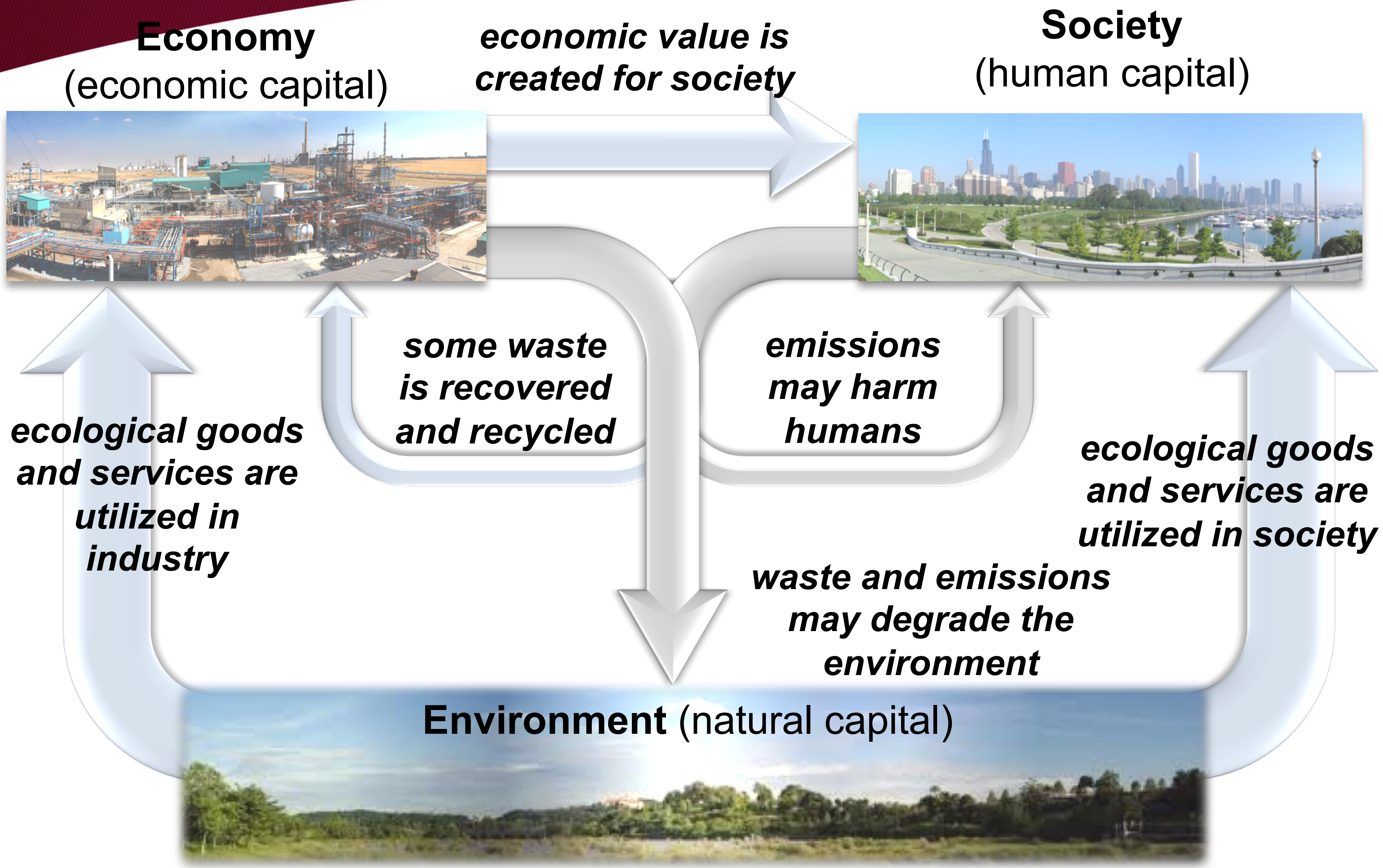
Systems View of Sustainability



Economy
(economic capital)

economic value is created for society

Society
(human capital)

some waste is recovered and recycled

emissions may harm humans

ecological goods and services are utilized in industry

ecological goods and services are utilized in society

waste and emissions may degrade the environment

Environment (natural capital)

Scale of Systems

Type I: Global Systems (e.g. global CO_2 budgeting)

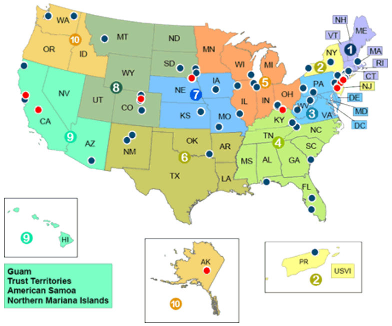
Type II: Systems bounded by geographical boundaries, such as National Systems (energy system, material flow) and Regional Systems (e.g. watersheds, Brownfields)

Type III: Business Systems (e.g. business networks, waste exchange networks)

Type IV: Sustainable technologies (e.g. green materials, sustainable products)

I: Global Scale
(e.g. global CO_2 budgeting)

II. National Scale (e.g. energy) and Regional Scale (e.g. watersheds, epa regions)



III: Business or Institutional Scale (e.g. eco-industrial park)

IV: Sustainable Technologies Scale (e.g. sustainable products)

Sikdar, Subhas K. "Sustainable development and sustainability metrics."AIChE journal 49.8 ***(2003)****: 1928-1932.*

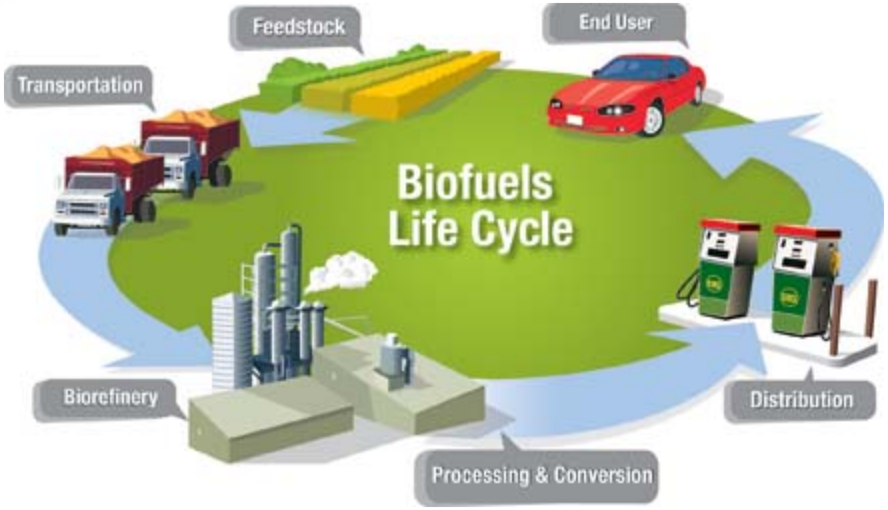
Quantifying Sustainability

- How does the vision for the world organizations translate into what we do as process engineers?
- How do we link the information needs at the global scales to what is in our control?
- What methods exist in the academic community, and how does it differ from business perspectives?

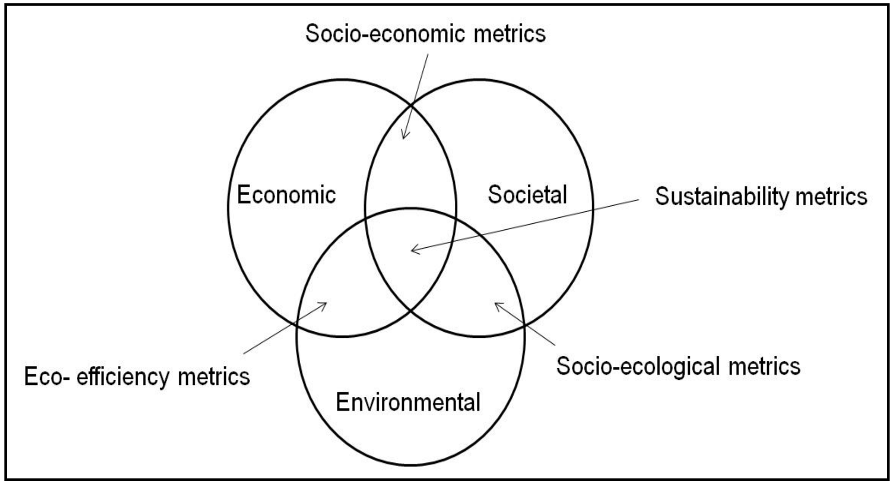
Axioms for Sustainability Considerations

- Sustainability is about **systems**
- Sustainability is always **relative**, never absolute
- Sustainability functions (economic, environmental, and societal) of systems are described by a **parsimonious set of indicators**
- **Scale of the system** determines the **nature of the set of indicators** and the sustainability analysis
- Indicators are **not pure** (in Brundtland sense); they are often two or three dimensional

Life Cycle Assessment (LCA)

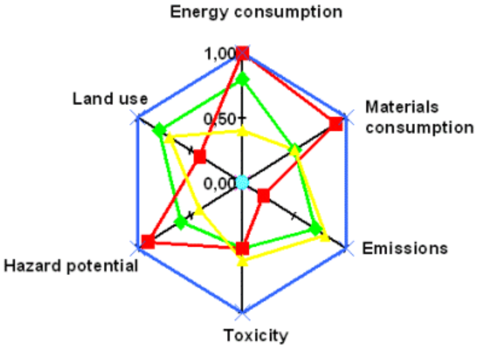


Sustainability Indicators: Metrics and Indices



Footprints (ecological, water, nitrogen, phosphorus etc.)

Eco-Efficiency Analysis



Industrial Ecology, Eco-Industrial Parks

Carbon Dioxide Sequestration (geological sequestration, bio-sequestration, chemical sequestration)

Total Cost Assessment Methodology (TCA) (Economic Costs, Environmental Costs, Societal Costs)

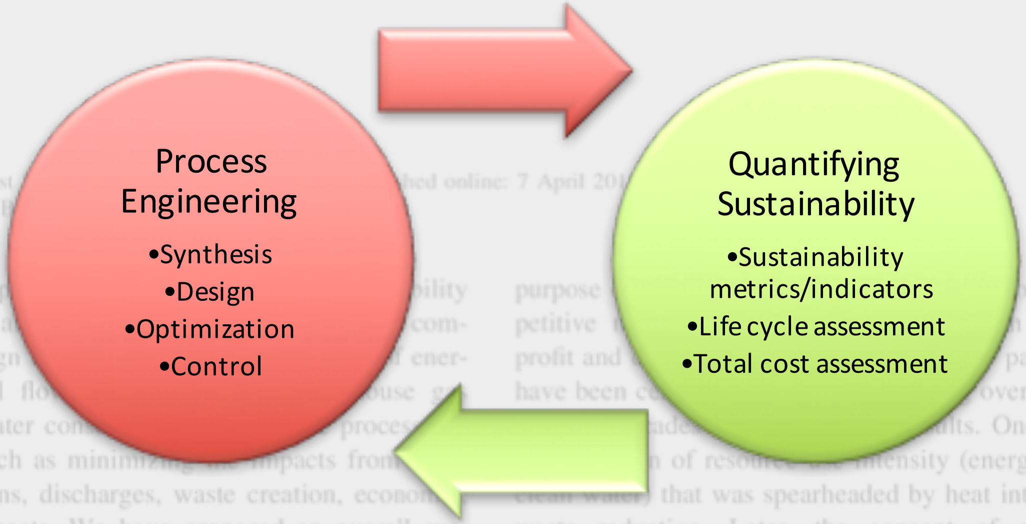
Sustainable Supply Chains

Motivation

Clean Techn Environ Policy (2015) 17:833–840
DOI 10.1007/s10098-015-0952-7

Sustainability in the context of process engineering

Rajib Mukherjee[1] · Debalina Sengupta[2] · Subhas K. Sikdar[3]



Process Engineering
- Synthesis
- Design
- Optimization
- Control

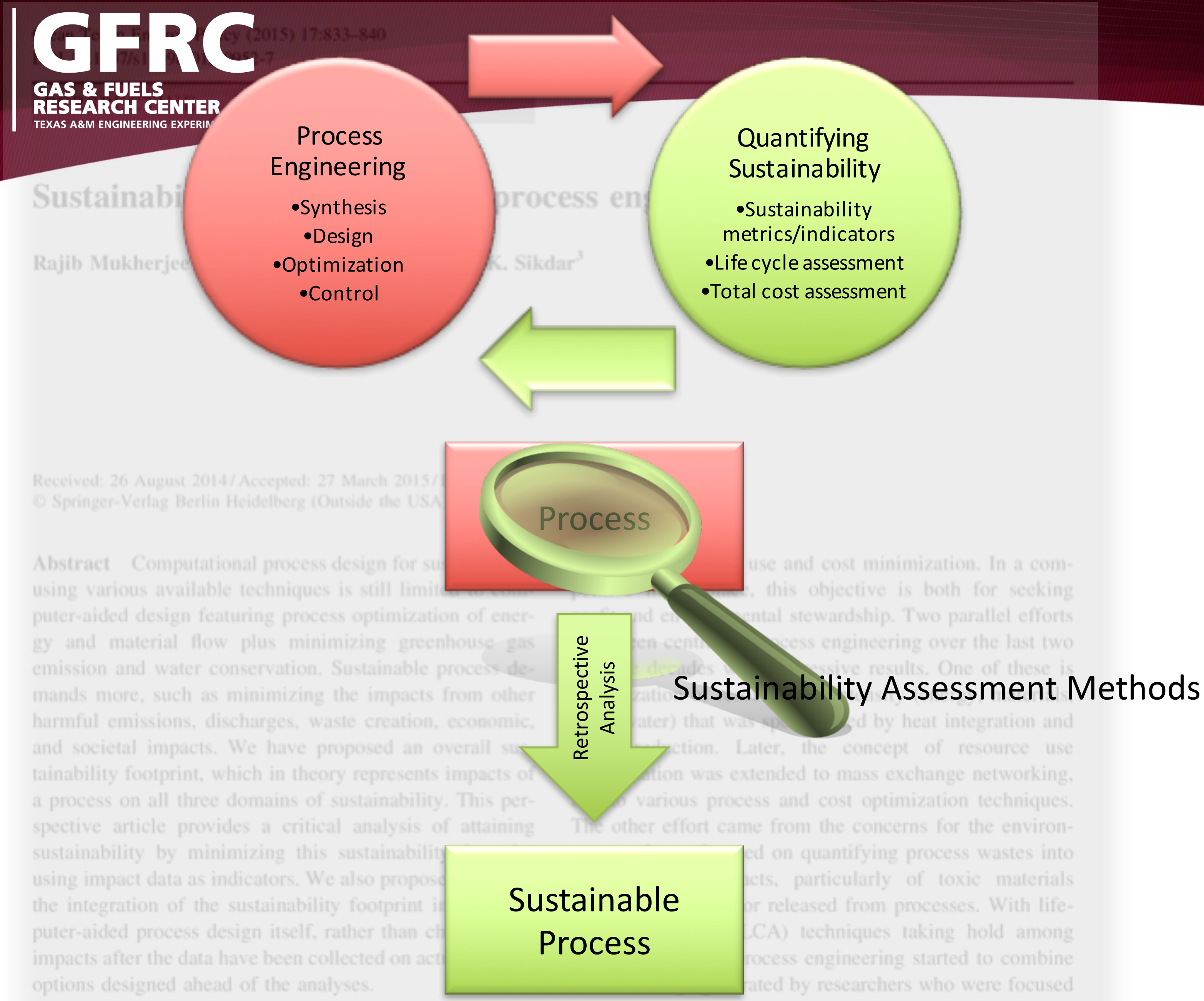
Quantifying Sustainability
- Sustainability metrics/indicators
- Life cycle assessment
- Total cost assessment

and societal impacts. We have proposed an overall sustainability footprint, which in theory represents impacts of a process on all three domains of sustainability. This perspective article provides a critical analysis of attaining sustainability by minimizing this sustainability footprint using impact data as indicators. We also propose the use of the integration of the sustainability footprint in the computer-aided process design itself, rather than checking the impacts after the data have been collected on actual process options designed ahead of the analyses.

waste reduction. Later, the concept of resource use minimization was extended to mass exchange networking, and to various process and cost optimization techniques. The other effort came from the concerns for the environment and was focused on quantifying process wastes into environmental impacts, particularly of toxic materials generated, emitted, or released from processes. With life-cycle assessment (LCA) techniques taking hold among process designers, process engineering started to combine the knowledge generated by researchers who were focused on devising measures for exposures of toxic compounds to

Mukherjee, R., Sengupta, D., & Sikdar, S. K. (2015). Sustainability in the context of process engineering. Clean Technologies and Environmental Policy, 17(4), 833-840.

Motivation



Process Engineering

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Quantifying Sustainability

- Sustainability metrics/indicators
- Life cycle assessment
- Total cost assessment

Process

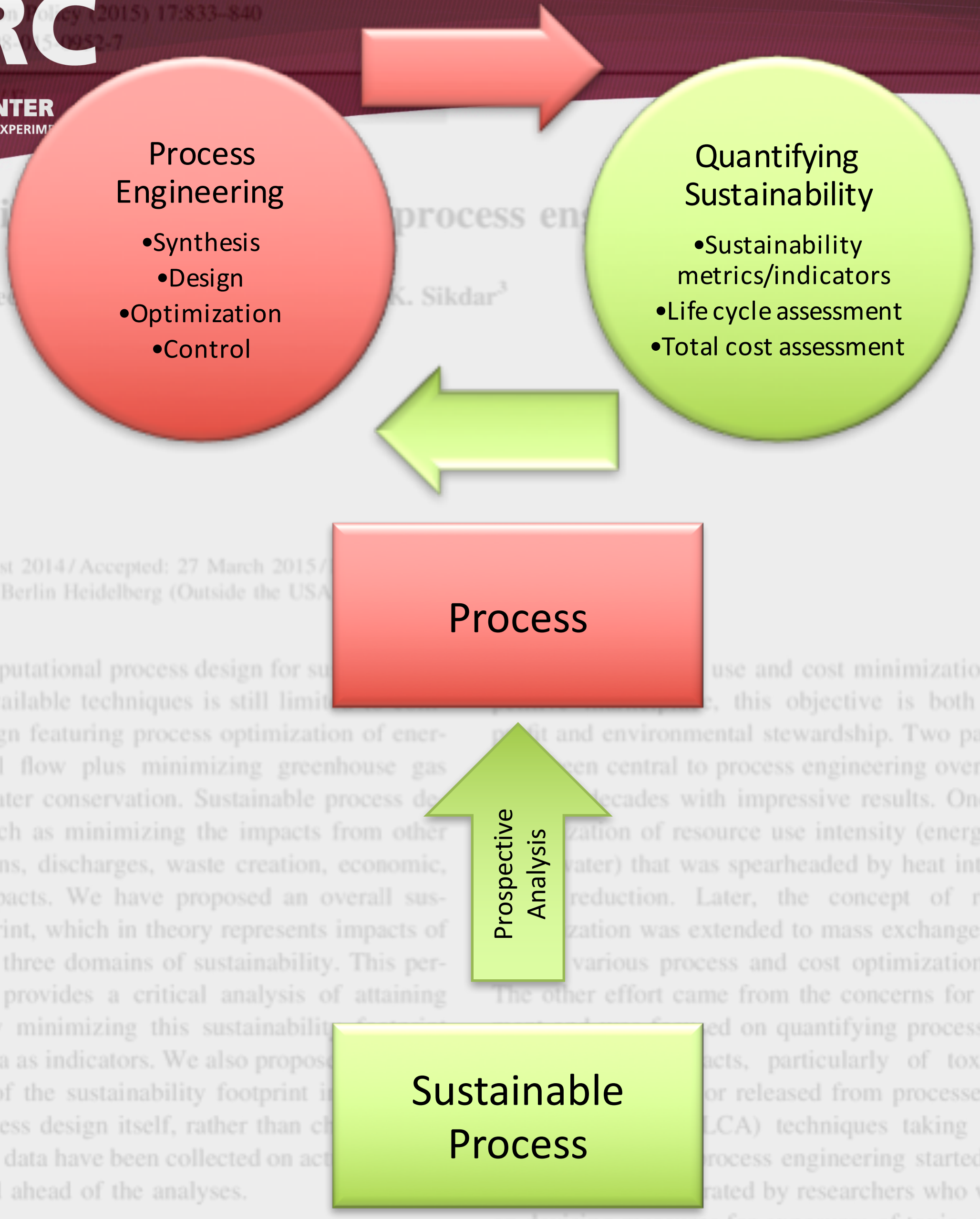
Retrospective Analysis

Sustainability Assessment Methods

Sustainable Process

Mukherjee, R., Sengupta, D., & Sikdar, S. K. (2015). Sustainability in the context of process engineering. Clean Technologies and Environmental Policy, 17(4), 833-840.

Motivation



Process Engineering
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Quantifying Sustainability
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Process

Prospective Analysis

Sustainable Process

Mukherjee, R., Sengupta, D., & Sikdar, S. K. (2015). Sustainability in the context of process engineering. Clean Technologies and Environmental Policy, 17(4), 833-840.

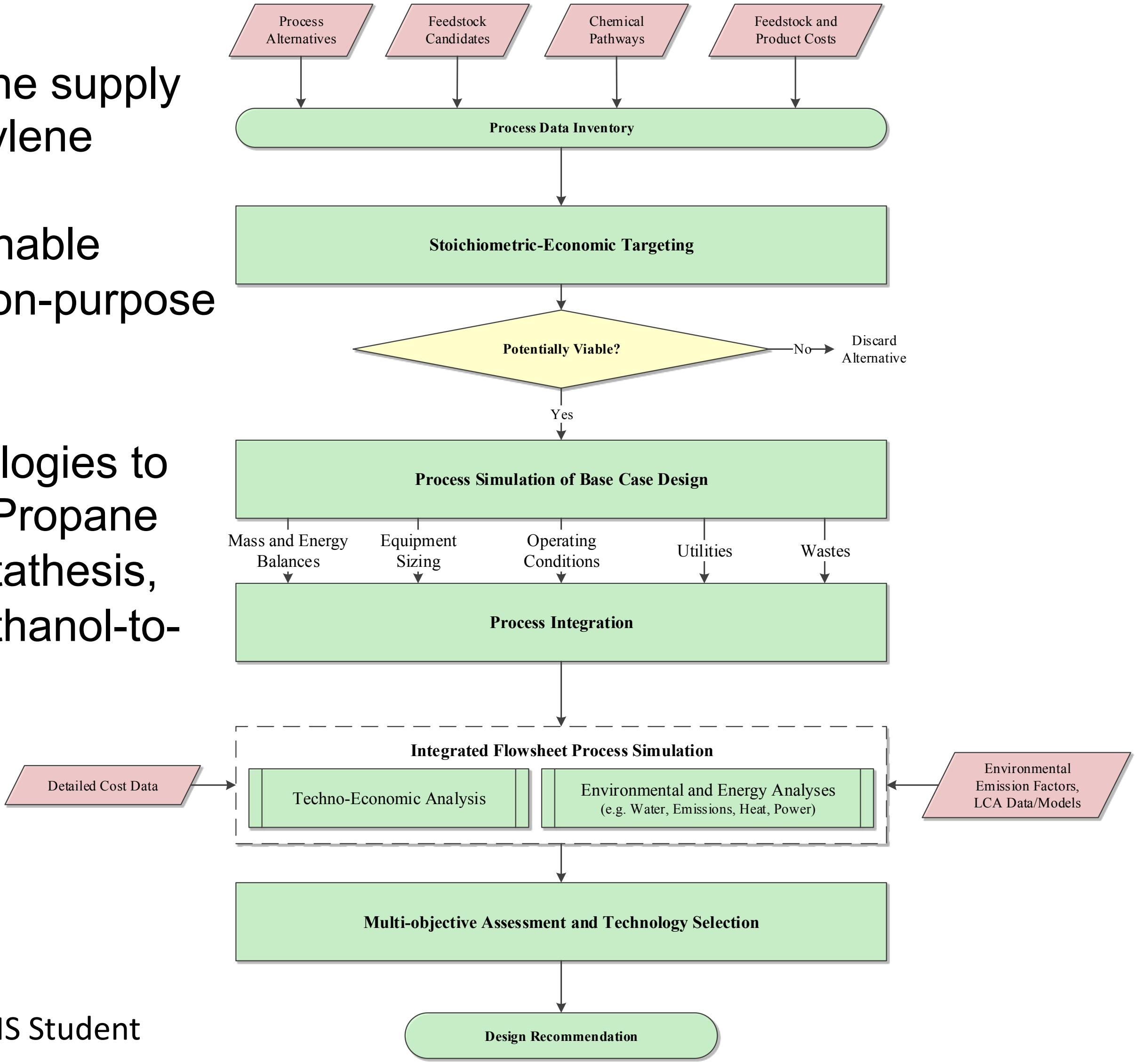
Overview of Projects

- Process Integration
  - **Single Process - PDH Process**
  - **Multiple Processes - Eco-Industrial Park**
- Life Cycle Assessment – Inventory Analysis
  - Sustainable Supply Chain Design of Biofuels
  - Sustainable Supply Chain Design of Consumer Products
  - Sustainability Metrics
  - Development of the Sustainability Footprint method

REMEMBER! SCALE OF PROCESS IMPORTANT FOR SUSTAINABILITY ANALYSIS!

On-purpose Propylene Production

- Increasing spread between the supply and demand curves for propylene
- Aim is to investigate a sustainable process design approach to on-purpose propylene production
- Following established technologies to directly produce propylene : Propane Dehydrogenation (PDH), Metathesis, Methanol-to-Olefins and Methanol-to-Propylene (MTO/MTP)



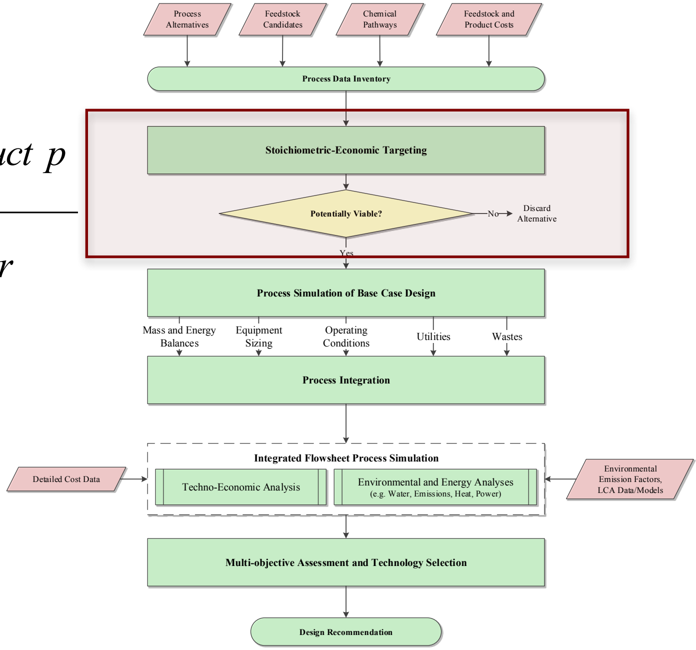
Acknowledgement: **Mr. Ashwin Agarwal**, MS Student

Manuscript in review at ACS Green Chemistry and Engineering Journal

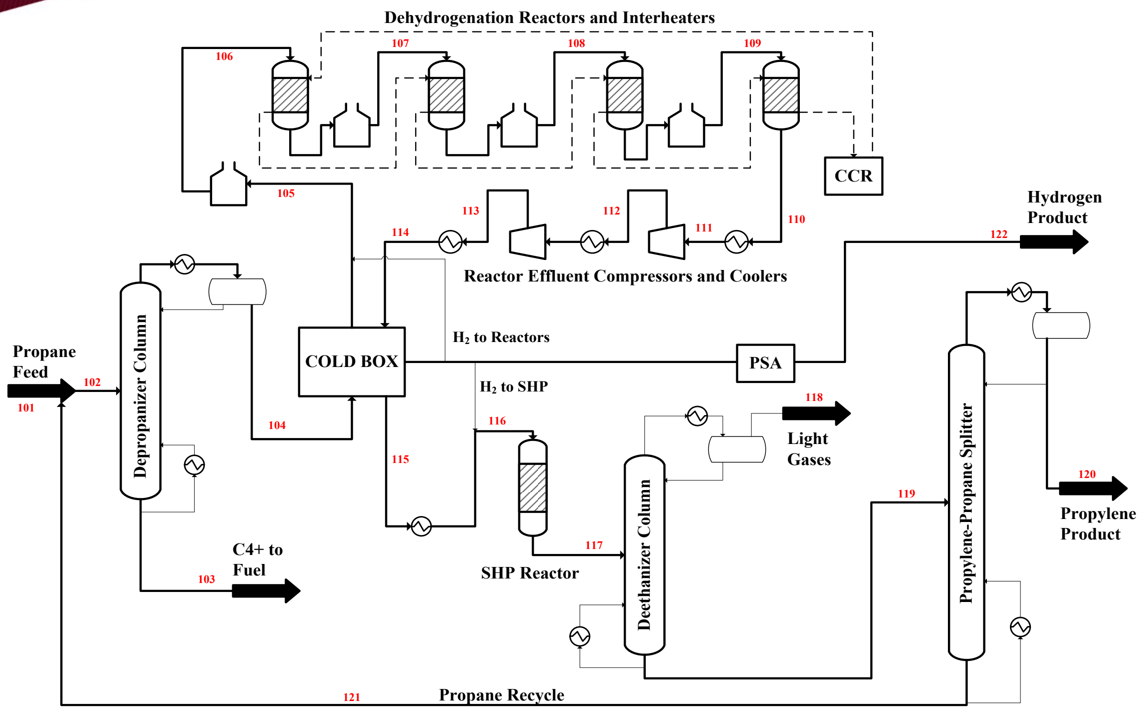
On-purpose Propylene Production

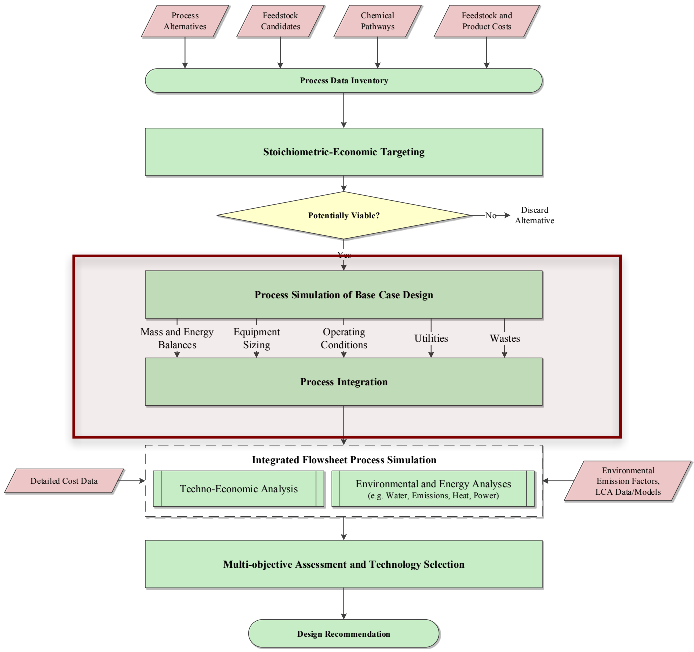
$$MISR = \frac{\sum_{p=1}^{N_{products}} Annual\ production\ rate\ of\ product\ p \times Purchase\ price\ of\ product\ p}{\sum_{r=1}^{N_{reactants}} Annual\ feed\ rate\ of\ reactant\ r \times Purchase\ price\ of\ reactant\ r}$$

On-Purpose Propylene Process	MISR
Propane Dehydrogenation	2.07
Olefin Metathesis	0.95
Methanol to Olefins	0.98



On-purpose Propylene Production





Process Alternatives
Feedstock Candidates
Chemical Pathways
Feedstock and Product Costs

Process Data Inventory

Stoichiometric-Economic Targeting

Potentially Viable?
No
Discard Alternative
Yes

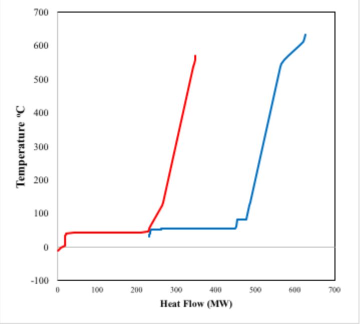
Process Simulation of Base Case Design
Mass and Energy Balances
Equipment Sizing
Operating Conditions
Utilities
Wastes
Process Integration

Integrated Flowsheet Process Simulation
Detailed Cost Data
Techno-Economic Analysis
Environmental and Energy Analyses
(e.g. Water, Emissions, Heat, Power)
Environmental Emission Factors, LCA Data/Models

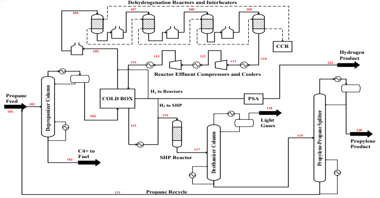
Multi-objective Assessment and Technology Selection

Design Recommendation

Utility Type	Unit Cost	Duty (MW)	Cost (MM$/yr)	% of Total Utility	Major Consumer in Process
Cooling Water	\$0.023/m^3	358	8.4	10.7%	PP Splitter Condenser and Reactor Effluent Coolers (83%)
LP Steam	$10.7/kg	237.4	35.5	45%	PP Splitter Reboiler (80%)
Natural Gas	$10.1/MW-hr	159.3	15.7	19.9%	Fired Heaters (100%)
Electricity	$0.065/KW-hr	35.6	19.2	24.4%	Reactor Effluent Compressors (95%)
Total Utility		790.3	78.8	100%	

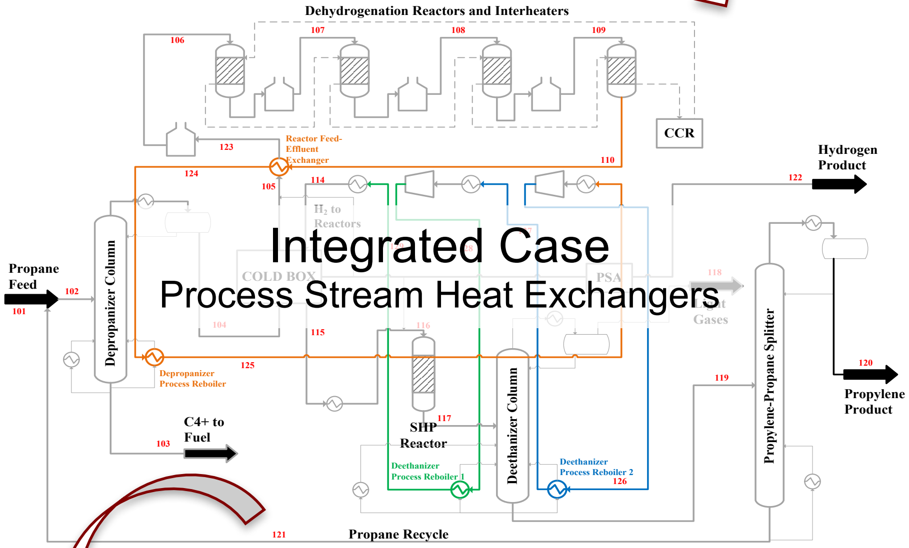


On-purpose Propylene Production



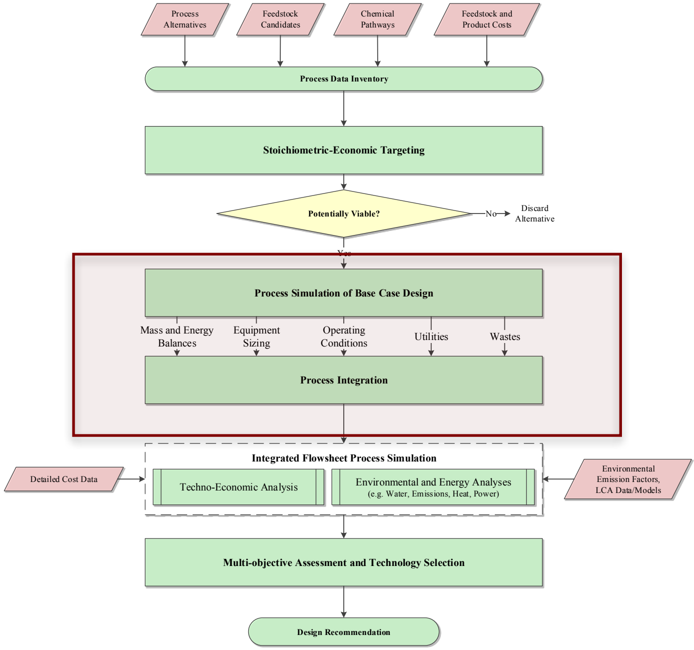
Base Case

Completely unintegrated design
(no information available, other than stoichiometry)



Integrated Case

Process Stream Heat Exchangers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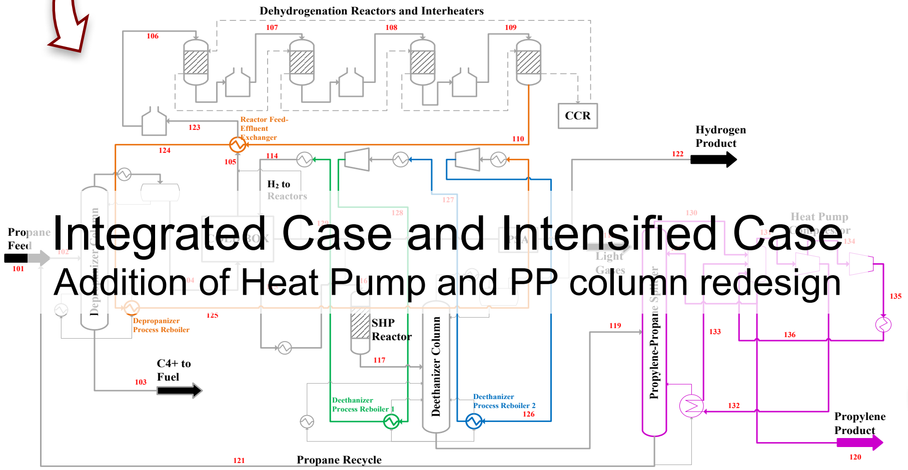


Integrated Case and Intensified Case

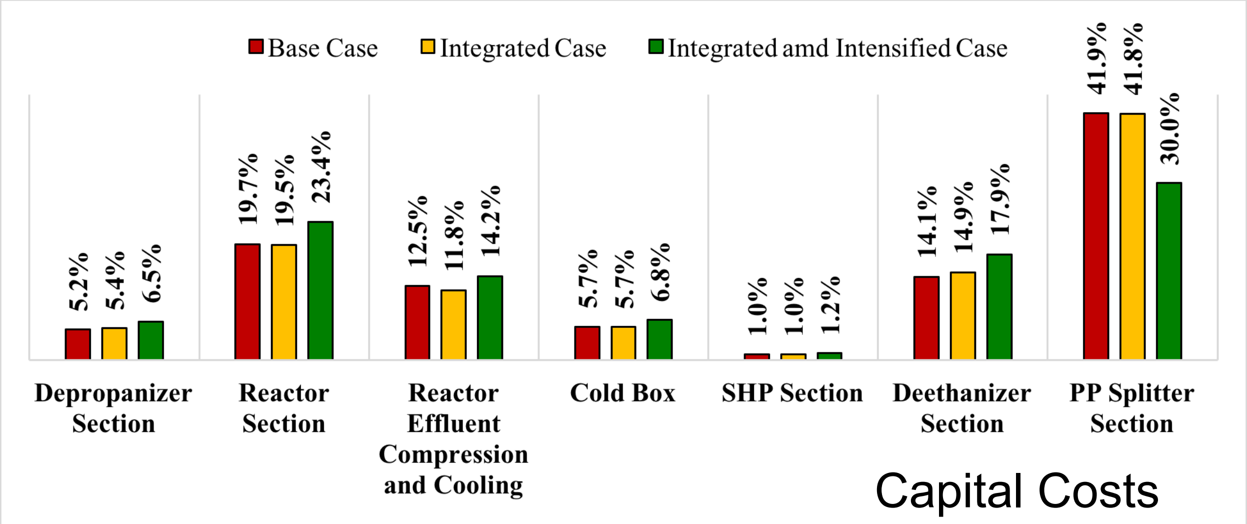
Addition of Heat Pump and PP column redesign

Integrated Case and Intensified Case + WHR + OGR

Waste heat recovery from fired heaters
Off gas recovery as fuel

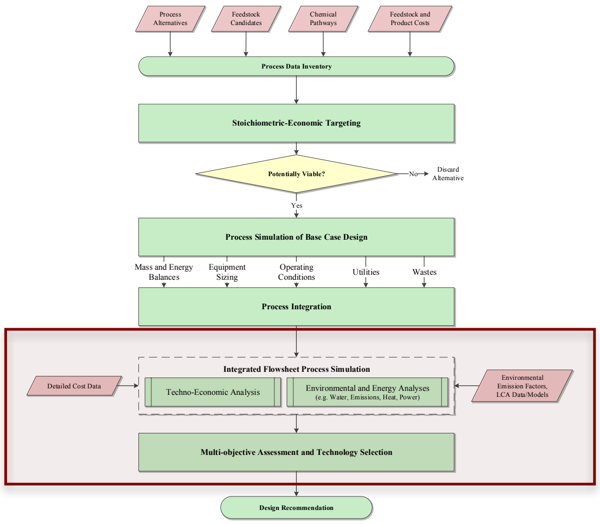
On-purpose Propylene Production

Economic Criteria	Base Case	Integrated Case	Integrated and Intensified Case
Simple Pay-back (yrs)	5.82	5.34	4.06
Return on Investment (15yrs)	15%	17%	25%
NPV (15 yrs) [$MM]	240.7	314.6	489.5
IRR (15 yrs)	14%	16%	22%



Capital Costs

By section



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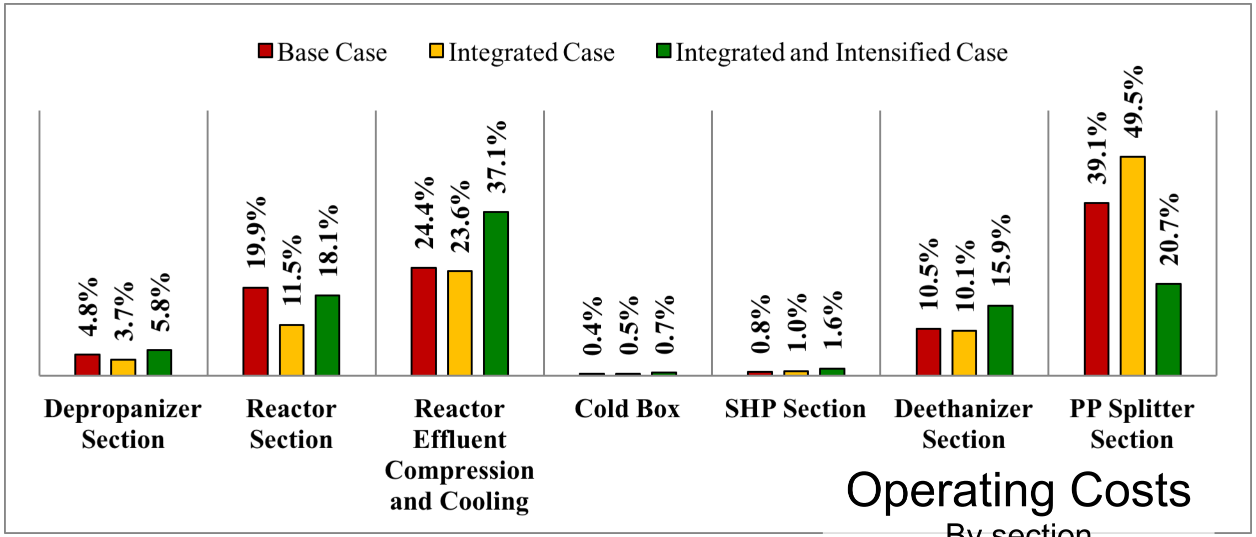
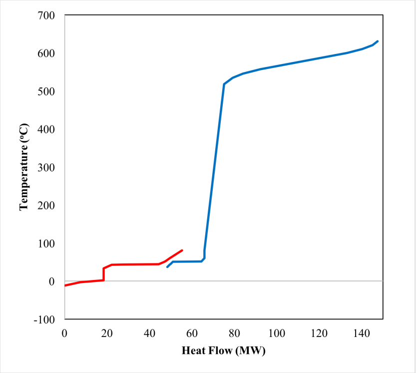


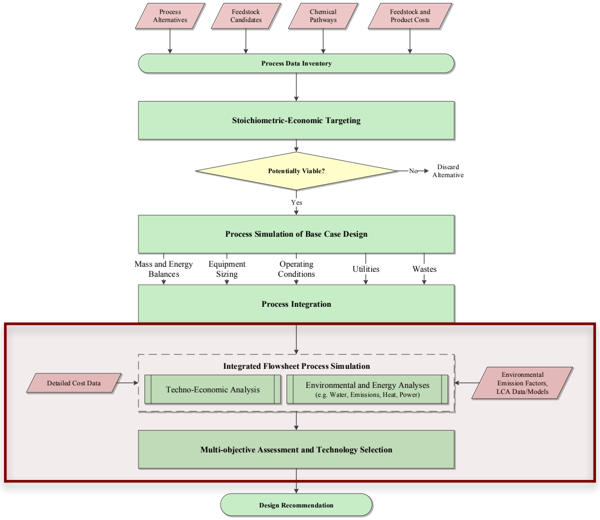
Operating Costs

By section



On-purpose Propylene Production

Pollutant	Emission Factor (lb/10^6scf)	Emission Factor Rating
CO_2	120,000	A
N_2O (Low NOx Burner)	0.64	E
SO_2	0.6	A
TOC	11	B
Methane	2.3	B
VOC	5.5	C

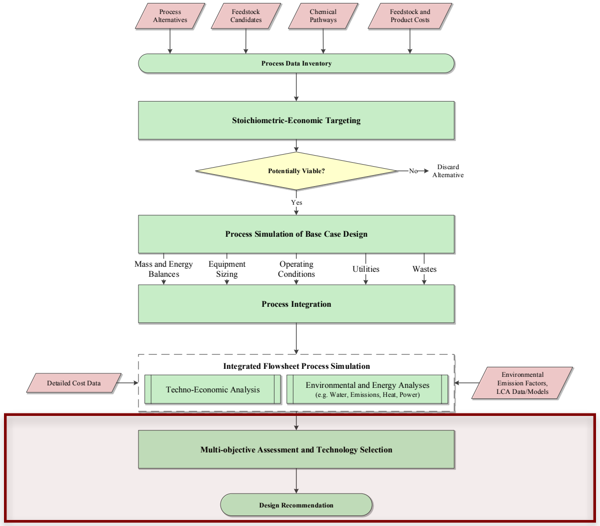


Electricity Source	CO_2 (lb/MWhr)	Methane (lb/GWhr)	N_2O (lb/GWhr)
ERCOT (Texas) Grid	1142.8	81.8	11.6
US Avg.	1122.9	110.9	16.0
SRMW (SERC Midwest)	1772.0	208.8	30.4

	Base Case			**Integrated Case**			**Integrated + Intensified Case**		
Pollutant	Base Case	Base Case + WHR	Base Case + WHR + OGR	Integrated Case	Integrated Case with WHR	Integrated case +WHR + OGR	Integrated + Intensified Case	Integrated + Intensified Case with WHR	Integrated + Intensified case with WHR+ OGR
	tons/yr			tons/yr			tons/yr		
CO_2	1,013,054	911,646	748,282	820,723	776,074	612,710	531,606	480,676	317,312
Methane	21.94	20.00	20.00	18.25	17.40	17.40	15.99	15.01	15.01
SO_2	3.57	3.07	3.07	2.61	2.39	2.39	0.85	0.60	0.60
TOC	65.50	56.20	56.20	47.87	43.77	43.77	15.63	10.96	10.96
VOC	32.75	28.10	28.10	23.93	21.89	21.89	7.81	5.48	5.48
N_2O	4.98	4.44	4.44	3.95	3.72	3.72	2.71	2.44	2.44
Total Emissions	***1,013,182***	***911,758***	***748,394***	***820,819***	***776,164***	***612,800***	***531,649***	***480,711***	***317,347***
Cost of CO_2 Emissions @$25/ton $MM/yr	**25.33**	22.79	18.71	20.52	19.40	15.32	13.29	12.02	**7.93**

OGR – Off Gas Recovery
WHR – Waste Heat Recovery

Sustainability Analysis



Sustainability Weighted Return on Investment (SWROI) metric which is an extension of the Return on Investment concept with the augmented sustainability metrics and process integration targeting approaches.

Considering a set a process alternatives: p = 1, 2, 3, $N_{projects}$. For the p^{th} project,

a new term called the Annual Sustainability Profit (ASP) is given by:

$$\mathrm{ASP_P} = \mathrm{AEP_P}\left[1 + \sum_{i=1}^{N_{indicators}} w_i \left(\frac{Indicator_{p,i}}{Indicator_i^{\mathrm{Target}}}\right)\right]$$

$\mathrm{AEP_p}$ is the Annual Economic Profit
w_i :ratio representing the relative importance of the i^{th} sustainability indicator compared to the annual net economic profit
$Indicator_{p,i}$:represents the value of the i^{th} sustainability indicator associated with the $p^{th\ project}$
$Indicator_i^{Target}$: target of the i^{th} sustainability indicator (benchmarking or taken as the largest value from all project)

$$\mathrm{SWROI_P} = \frac{\mathrm{ASP_P}}{\mathrm{TCI_P}}$$

Mahmoud M. El-Halwagi, Chapter 3 - Benchmarking Process Performance Through Overall Mass Targeting. In *Sustainable Design Through Process Integration (Second Edition)*, Butterworth-Heinemann: 2017; pp 73-125.

Sustainability Analysis

$$ASP_P = AEP_P\left[1 + \sum_{i=1}^{N_{indicators}} w_i\left(\frac{Indicator_{p,i}}{Indicator_i^{Target}}\right)\right] \qquad SWROI_P = \frac{ASP_P}{TCI_P}$$

AEP_p is the Annual Economic Profit

***w_i* :weight factor** ratio representing the relative importance of the i^{th} sustainability indicator compared to the annual net economic profit

***$Indicator_{p,i}$* :** represents the value of the i^{th} sustainability indicator associated with the p^{th} *project*

***$Indicator_i^{Target}$*:** target of the i^{th} sustainability indicator (benchmarking or taken as the largest value from all project)

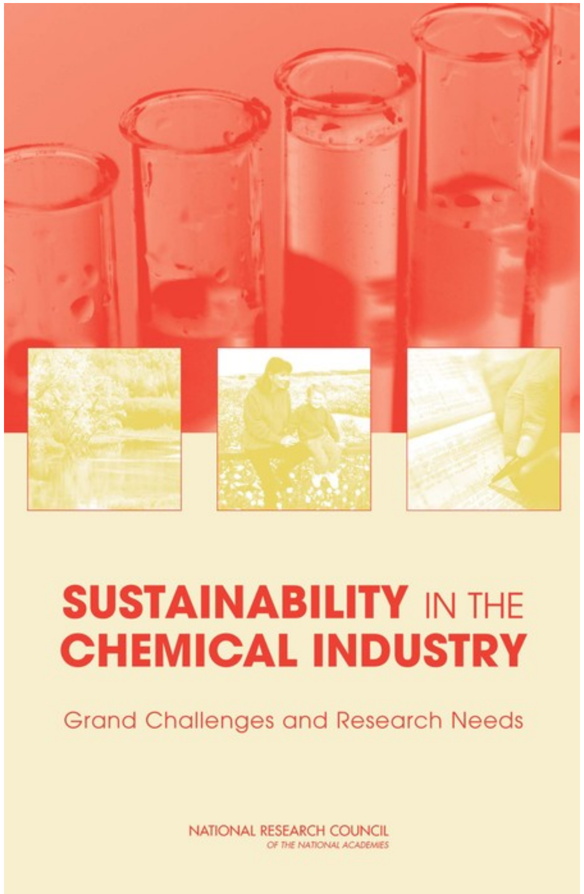
Description	10 yr. Avg. Taxable Income	Total Capital Investment	Water Reduction (Steam + CW)	Electrical Energy Savings (Power)	Fuel Savings (NG Firing in Fired Heaters)	CO_2 emission Reductions	VOC Reduction	ROI (10 yrs)	SWROI
	MM$/yr	MM$	10^6 kg/hr	MW	MW	10^3 tons/yr	tons/yr		
Weight Factors			0.1	0.1	0.07	0.25	0.05		
Targets			45.08	36	159	1013	32.7		
Base Case + WHR	67	643	0	0	0	101.4	4.6	10.38%	10.71%
Base Case + WHR + OGR	67	643	0	0	0	264.8	4.6	10.38%	11.13%
Integrated Case	79	645	25.6	0	87	192.3	8.8	12.29%	14.21%
Integrated Case + WHR	79	645	25.6	0	87	237	10.9	12.29%	14.38%
Integrated Case + WHR + OGR	79	645	25.6	0	87	400.3	10.9	12.29%	14.88%
Integrated + Intensified Case	104	536	38.7	-14.5	87	481.4	24.9	19.45%	24.12%
Integrated + Intensified Case + WHR	104	536	38.7	-14.5	87	532.4	27.3	19.45%	24.43%
Integrated + Intensified Case + WHR + OGR	104	536	38.7	-14.5	87	695.7	27.3	19.45%	**25.21%**

On-purpose Propylene Production

Recap:

- Calculate your common economic metrics for your projects.
- Calculate your environmental (and possible social metrics) metrics.
- Use the ASP (Annual Sustainability Profit) and SWROI (Sustainability Weighted ROI) to make a decision about a project.
- If your ROI is reasonable, but you can show a much higher SWROI, project justification can be made.
- SWROI provides a reflection of how sustainable your project is from different competing choices.

Eco-Industrial Park

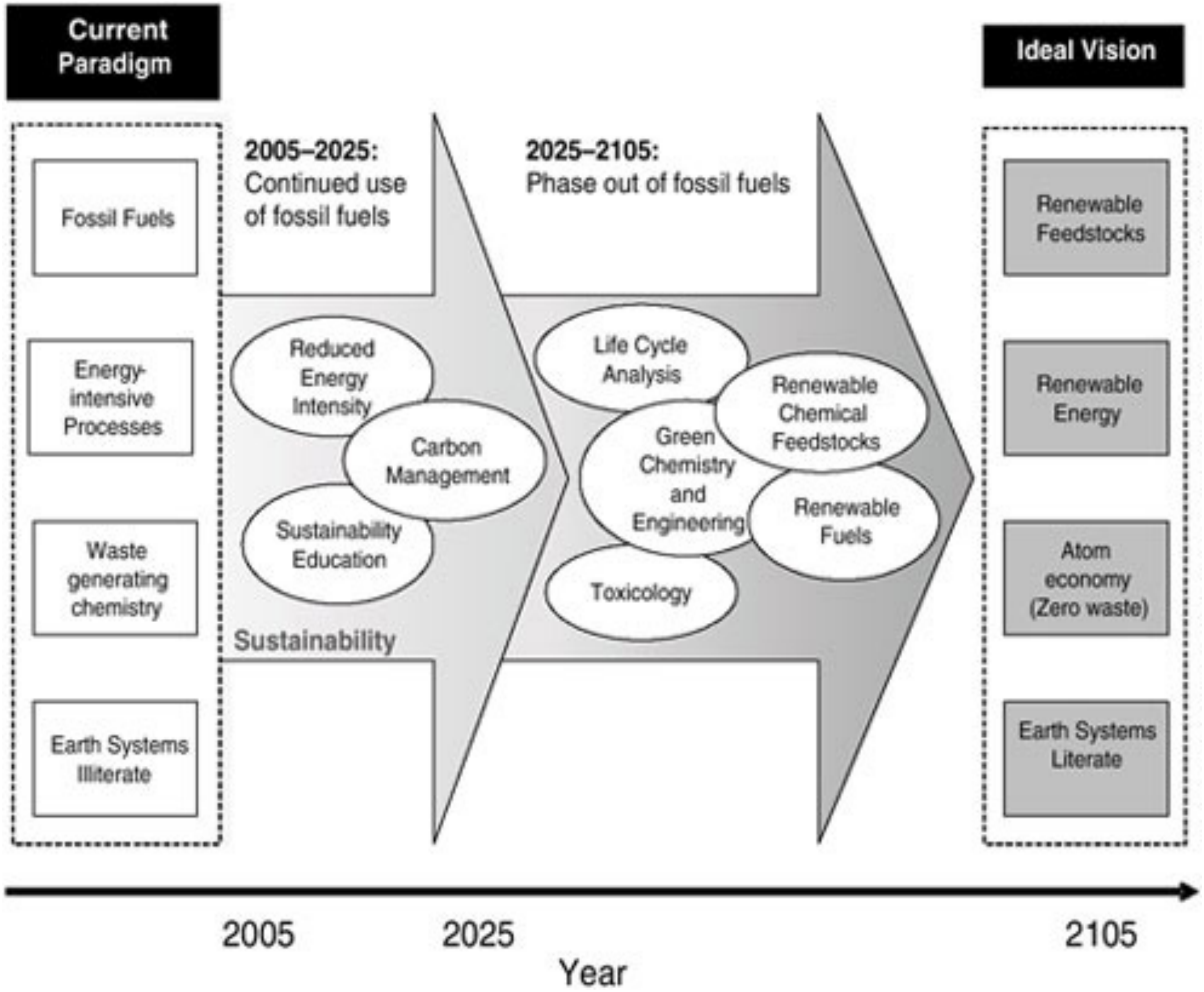


SUSTAINABILITY IN THE CHEMICAL INDUSTRY

Grand Challenges and Research Needs

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

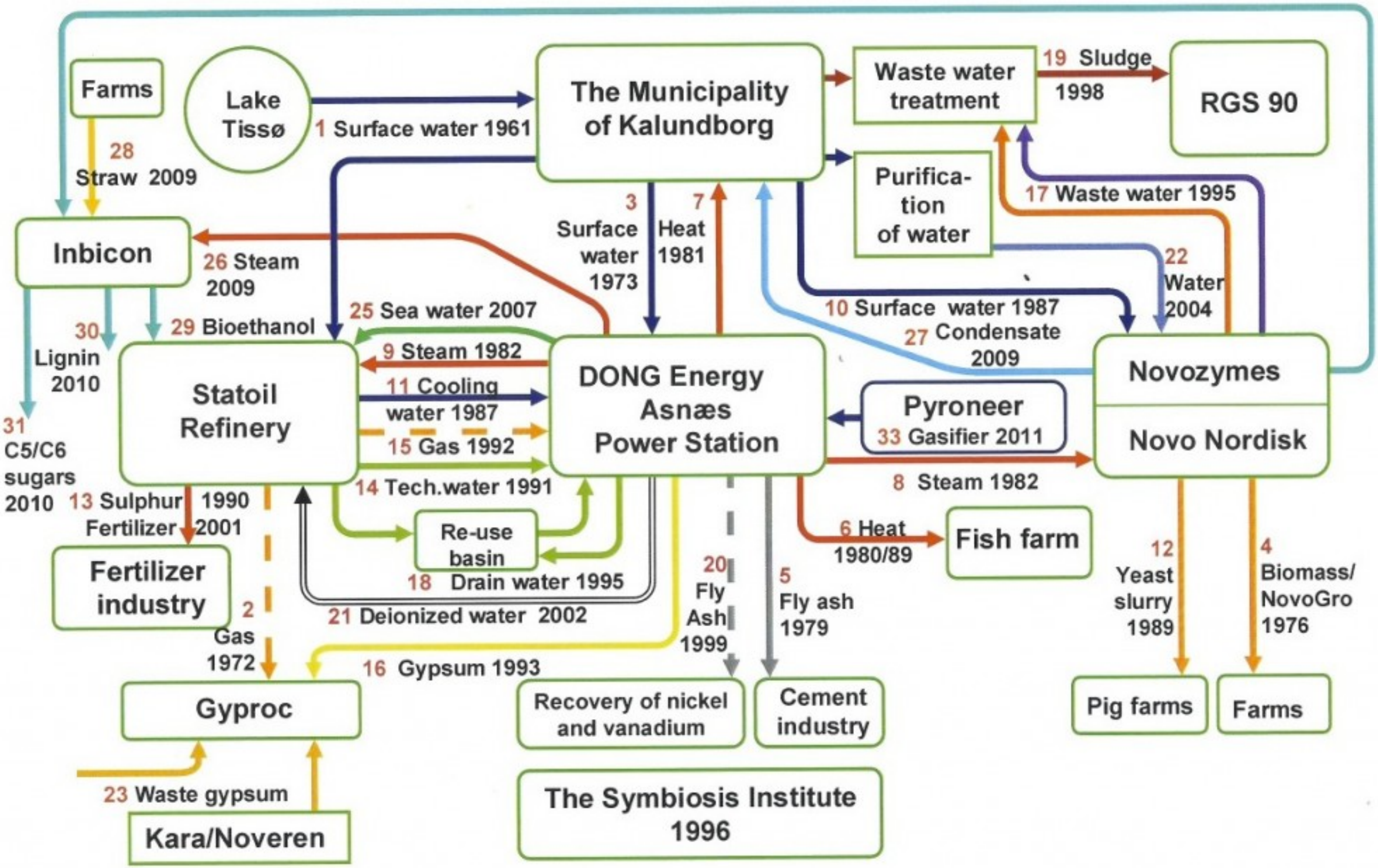
Status: Final Book
Downloads: 1,890



National Research Council. *Sustainability in the Chemical Industry: Grand Challenges and Research Needs - A Workshop Report*. Washington, DC: The National Academies Press, **2005**. doi:10.17226/11437

Eco-Industrial Park

Kalundborg, Denmark



Farms
Lake Tissø
1 Surface water 1961
The Municipality of Kalundborg
Waste water treatment
19 Sludge 1998
RGS 90
28 Straw 2009
Purification of water
17 Waste water 1995
Inbicon
26 Steam 2009
3 Surface water 1973
7 Heat 1981
22 Water 2004
10 Surface water 1987
27 Condensate 2009
30 Lignin 2010
29 Bioethanol
25 Sea water 2007
31 C5/C6 sugars 2010
Statoil Refinery
9 Steam 1982
11 Cooling water 1987
15 Gas 1992
14 Tech.water 1991
DONG Energy Asnæs Power Station
Novozymes
Novo Nordisk
Pyroneer
33 Gasifier 2011
8 Steam 1982
13 Sulphur 1990
Fertilizer 2001
Fertilizer industry
Re-use basin
18 Drain water 1995
21 Deionized water 2002
6 Heat 1980/89
Fish farm
2 Gas 1972
20 Fly Ash 1999
5 Fly ash 1979
12 Yeast slurry 1989
4 Biomass/ NovoGro 1976
16 Gypsum 1993
Gyproc
Recovery of nickel and vanadium
Cement industry
Pig farms
Farms
23 Waste gypsum
Kara/Noveren
The Symbiosis Institute 1996

Eco-Industrial Park

Petrochemical complex in the lower Mississippi River Corridor

- Dow
- DuPont
- BASF
- Shell
- Exxon
- Monsanto
- Mosaic

…. and others

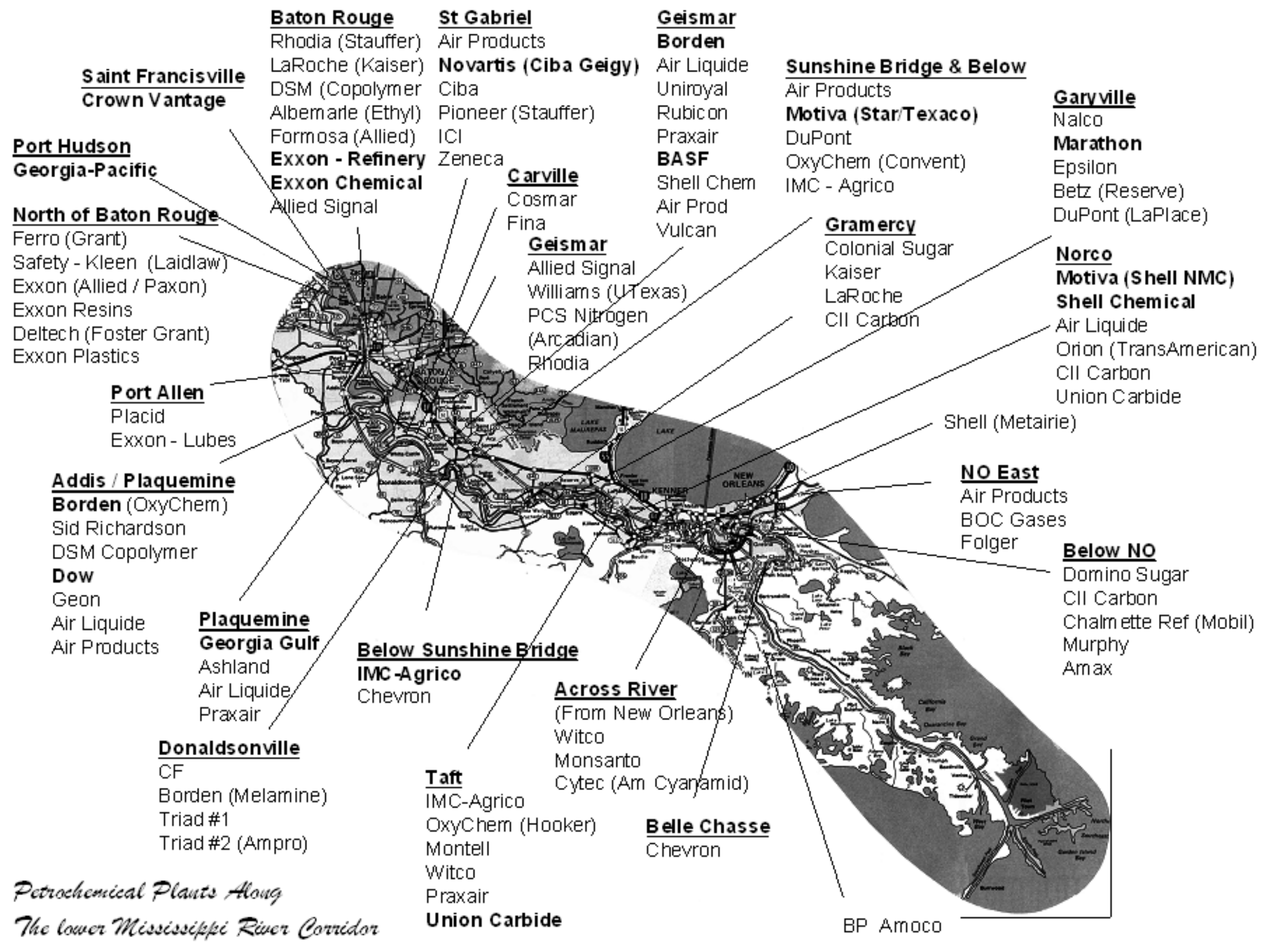
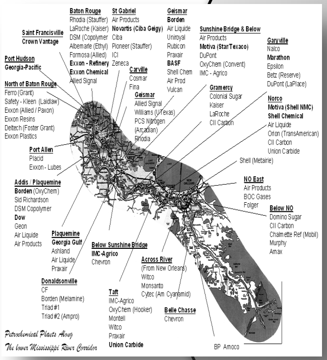
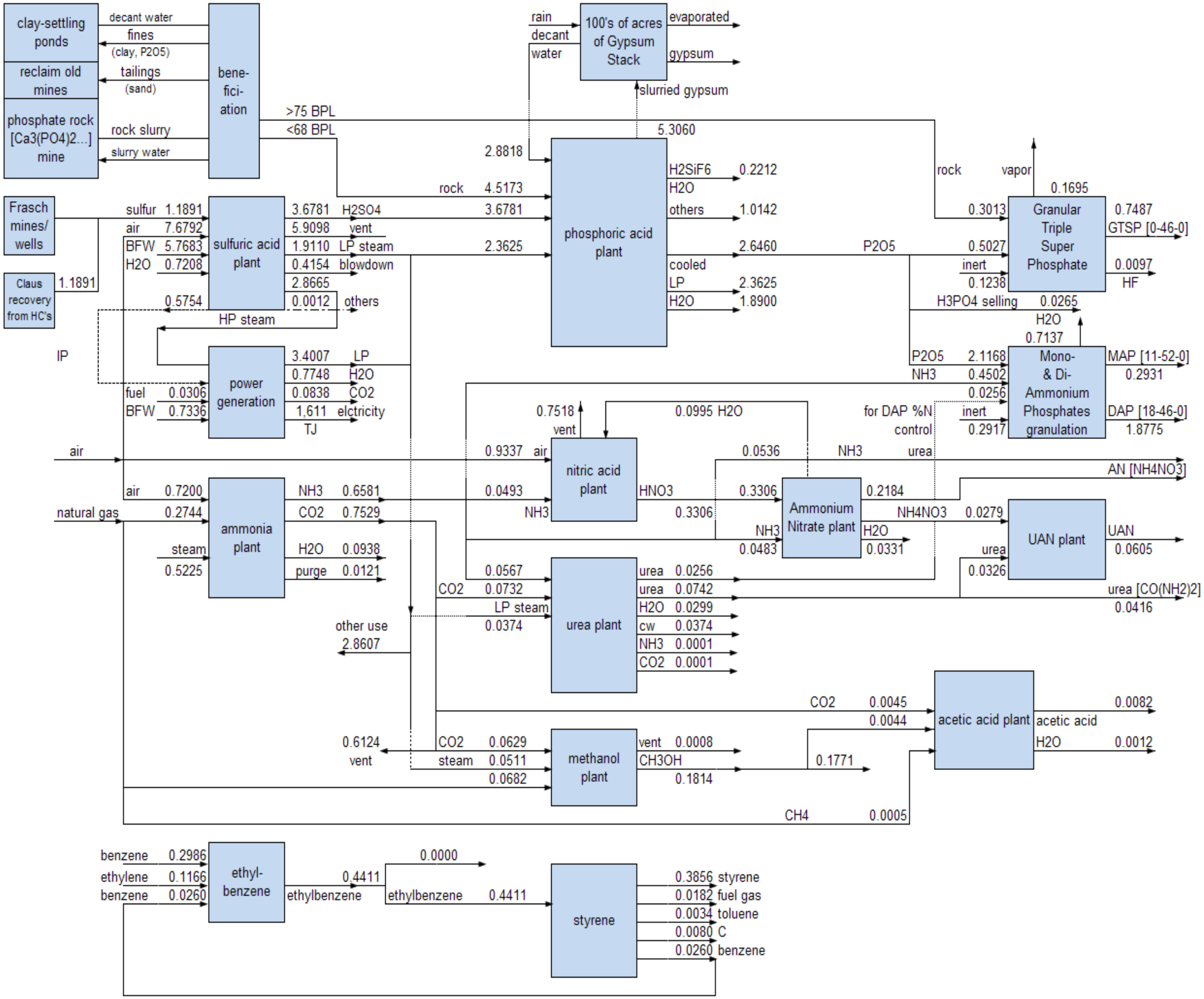


Photo: Peterson, 2000

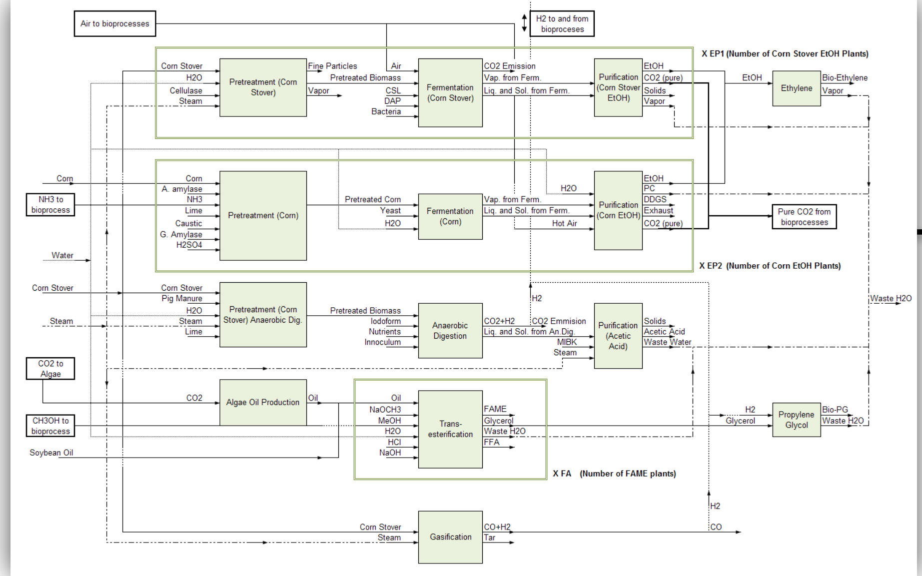
Base Case of Plants in the Lower Mississippi River Corridor





Eco-Industrial Park

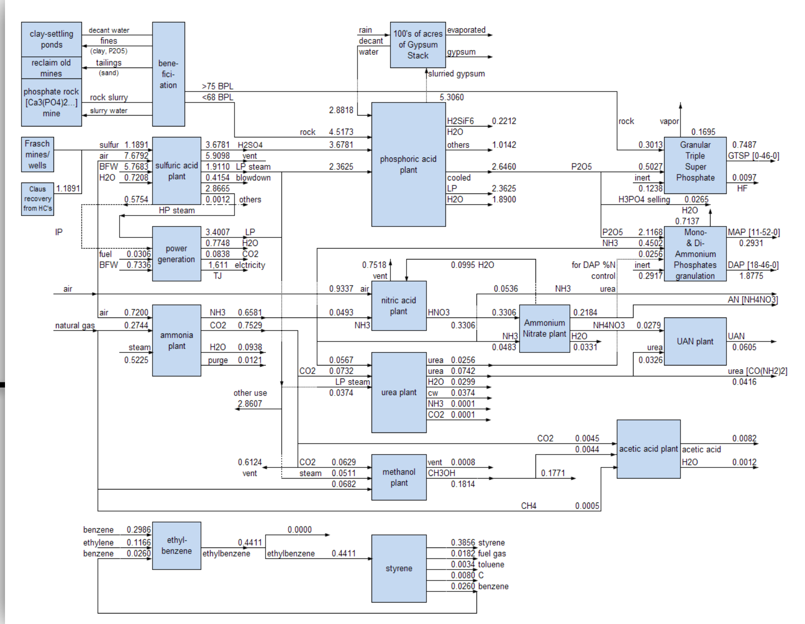
Integrated Chemical Production Complex



Biomass Complex

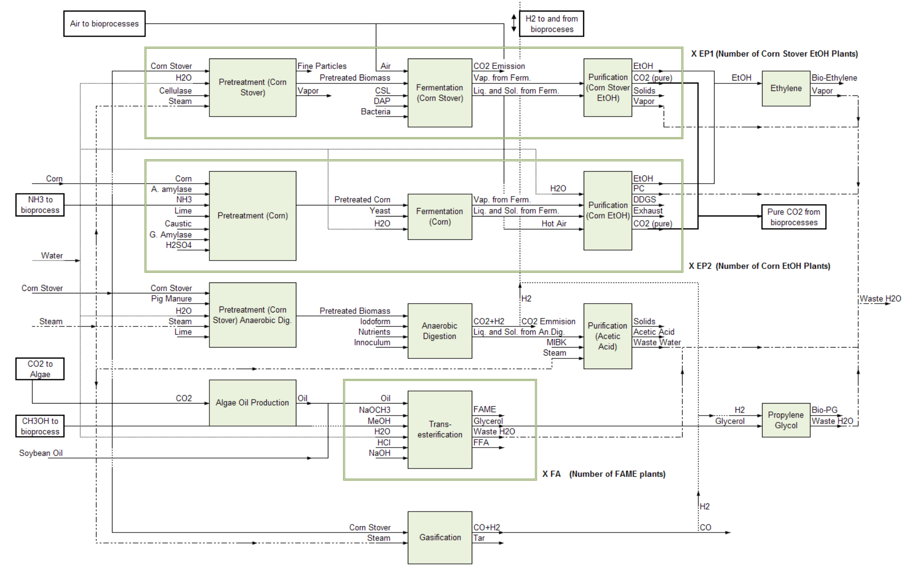
Hydrogen,CO$_2$

Air, Methanol, Ammonia



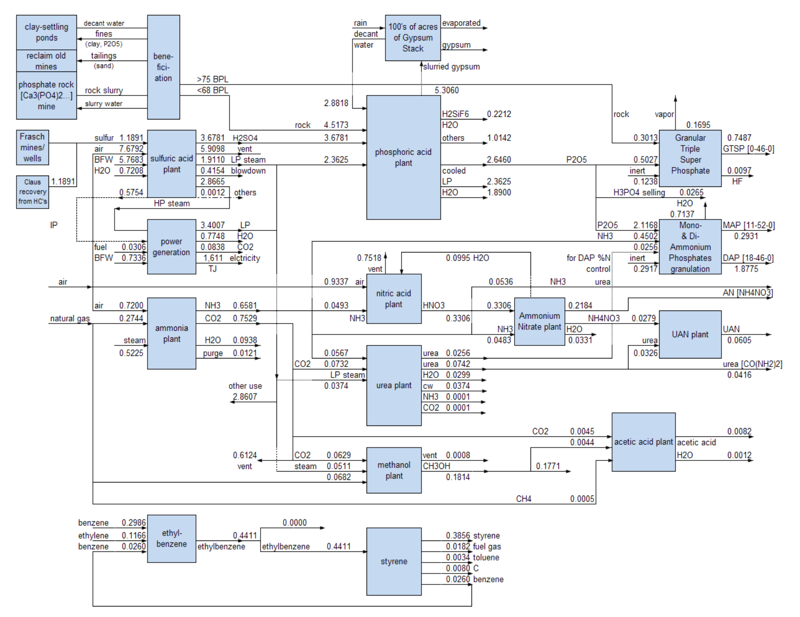
Base Case Complex

Integrated Chemical Production Complex



Biomass Complex

Hydrogen,CO_2

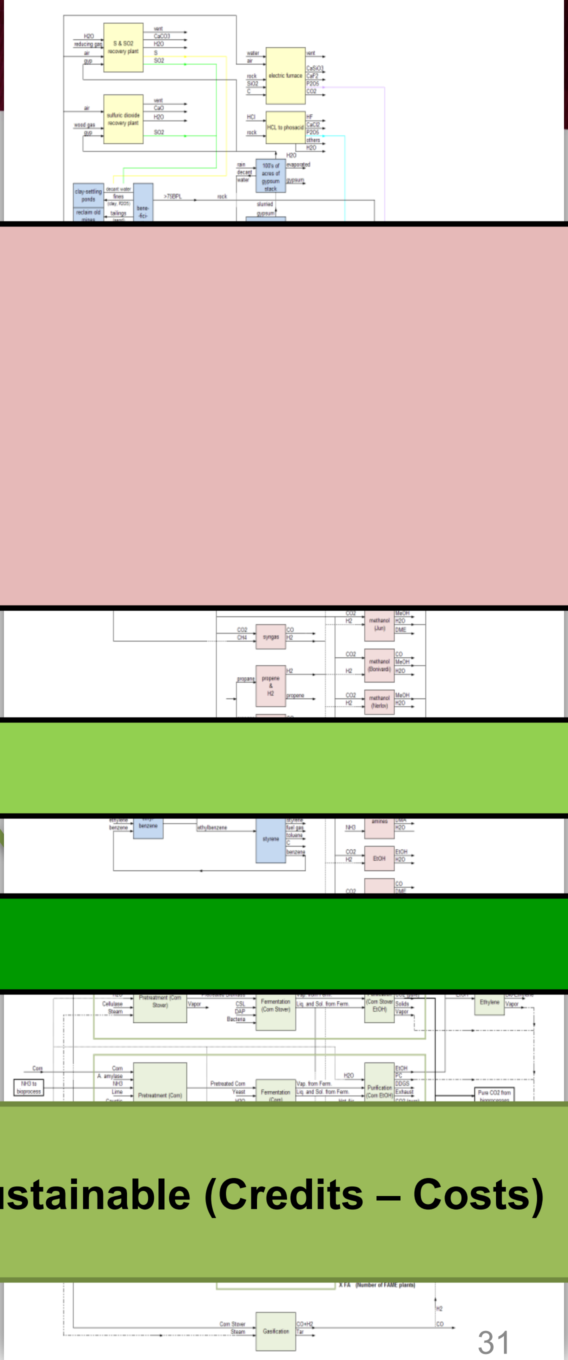


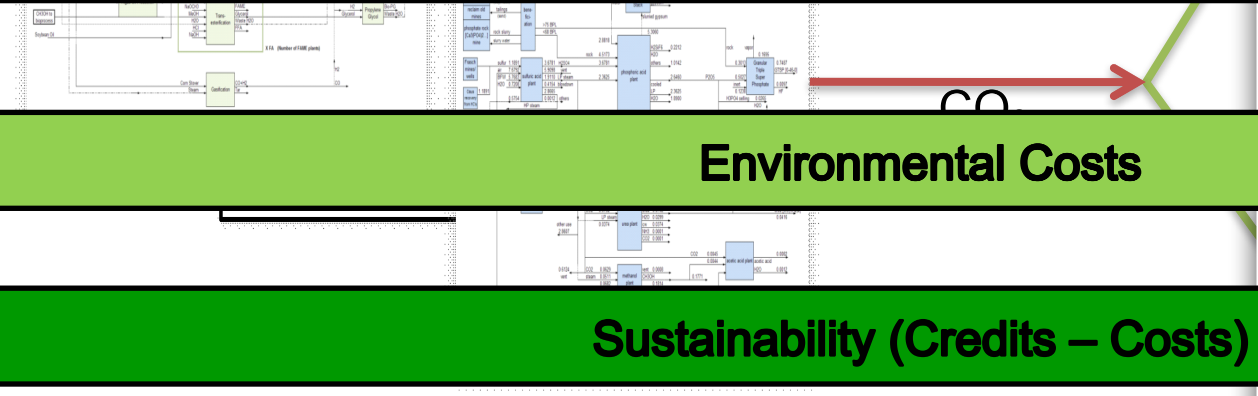
Base Case Complex

Air, Methanol, Ammonia

Eco-Industrial Park

Superstructure





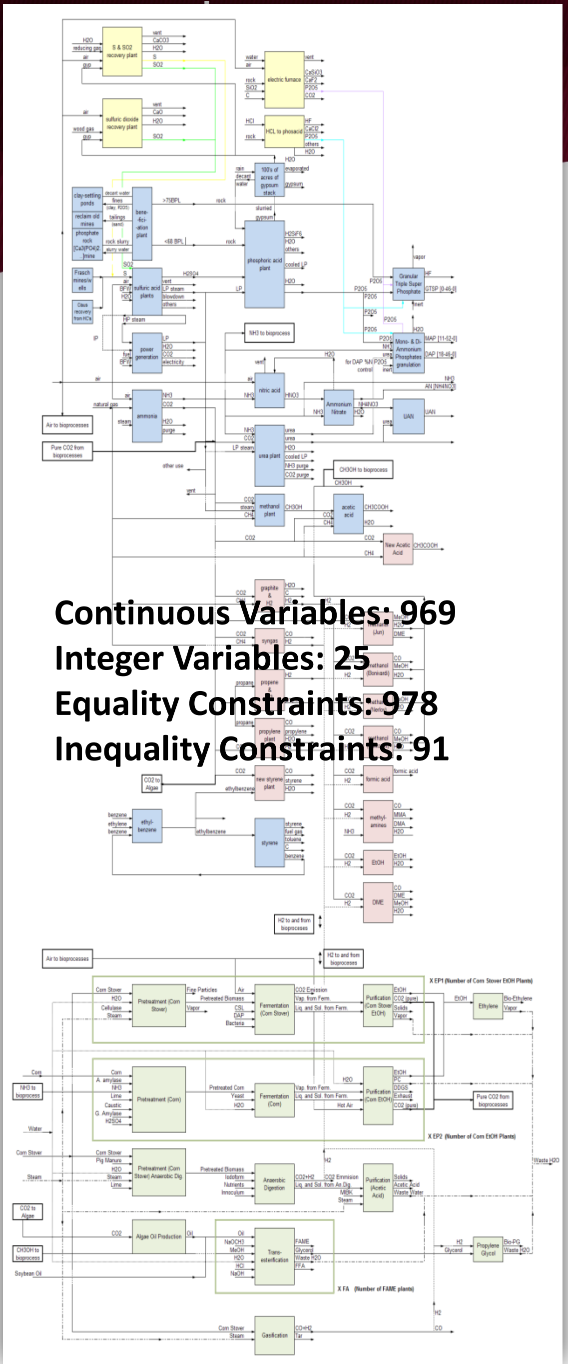
Profit

Environmental Costs

Sustainability (Credits – Costs)

Triple Bottom Line = Σ Profit - Σ Environmental Costs + Σ Sustainable (Credits – Costs)

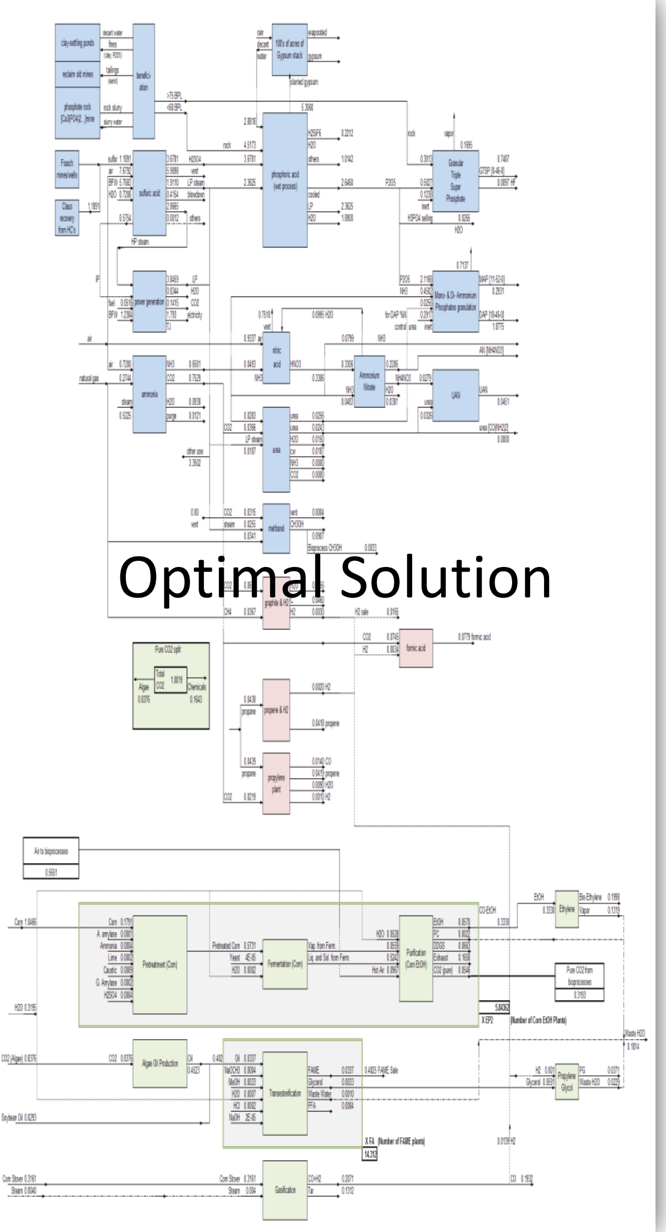
Eco-Industrial Park



Continuous Variables: 969
Integer Variables: 25
Equality Constraints: 978
Inequality Constraints: 91

Plants in Base Case	**Plants Added to Form the Superstructure**
(blue) Ammonia Nitric acid Ammonium nitrate Urea UAN Methanol Granular triple super phosphate (GTSP) MAP and DAP Contact process for sulfuric acid Wet process for phosphoric acid Acetic acid – conventional method Ethyl benzene Styrene Power generation	**Bioprocesses and CO_2 consumption by Algae (green)** Fermentation ethanol (corn stover) Fermentation ethanol (corn) Anaerobic Digestion to acetic acid (corn stover) Algae Oil Production Transesterification to FAME and glycerol (soybean oil and algae) Gasification to syngas (corn stover) Ethylene from dehydration of ethanol Propylene glycol from glycerol **CO_2 consumption for Chemicals (red)** Methanol – Bonivardi, et al., 1998 Methanol – Jun, et al., 1998 Methanol – Ushikoshi, et al., 1998 Methanol – Nerlov and Chorkendorff, 1999 Ethanol Dimethyl ether Formic acid Acetic acid - new method Styrene - new method Methylamines Graphite Hydrogen/Synthesis gas Propylene from CO_2 Propylene from propane dehydrogenation **Choice for phosphoric acid production and SO_2 recovery (yellow)** Electric furnace process for phosphoric acid Haifa process for phosphoric acid SO_2 recovery from gypsum waste S and SO_2 recovery from gypsum waste

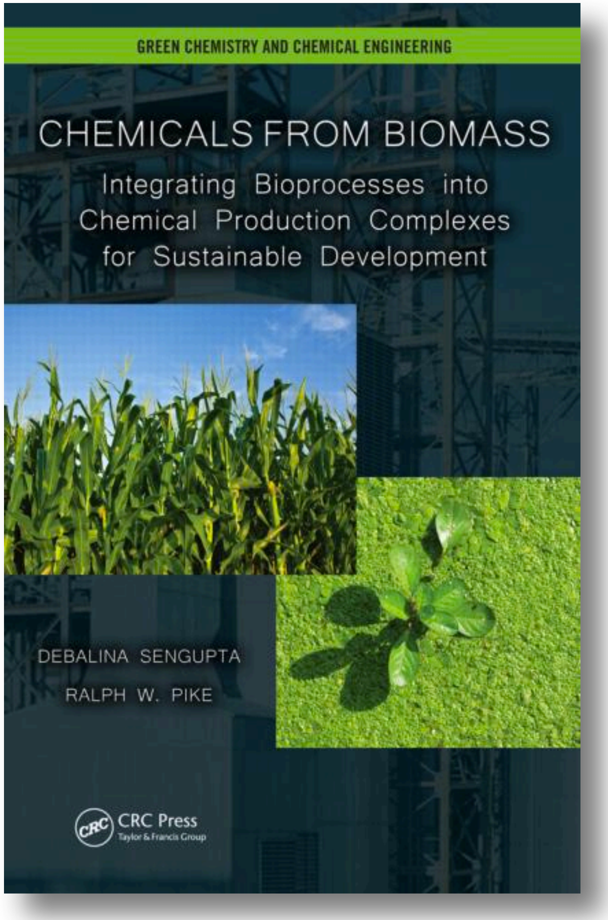
Eco-Industrial Park



Optimal Solution

Existing Plants in the Optimal Structure	**New Plants in the Optimal Structure**
Ammonia Nitric acid Ammonium nitrate Urea UAN Methanol Granular triple super phosphate (GTSP) MAP and DAP Contact process for Sulfuric acid Wet process for phosphoric acid Power generation	Fermentation to ethanol (corn) Bio-ethylene from dehydration of bio-ethanol Transesterification to FAME and glycerol (soy oil and algae) Algae oil production Bio-propylene glycol from glycerol Gasification to syngas (corn stover) Formic acid Graphite Propylene from CO2 Propylene from propane dehydrogenation
Existing Plants Not in the Optimal Structure	**New Plants Not in the Optimal Structure**
Acetic acid Ethylbenzene Styrene	Fermentation to ethanol (corn stover) Anaerobic Digestion to acetic acid (corn stover) Methanol – Bonivardi, et al., 1998 Methanol – Jun, et al., 1998 Methanol – Ushikoshi, et al., 1998 Methanol – Nerlov and Chorkendorff, 1999 Methylamines (MMA and DMA) Ethanol Dimethyl ether Hydrogen/synthesis gas Acetic acid – new process Styrene - new method Electric furnace process for phosphoric acid Haifa process for phosphoric acid SO2 recovery from gypsum waste S and SO2 recovery from gypsum waste

Eco-Industrial Park



GREEN CHEMISTRY AND CHEMICAL ENGINEERING

CHEMICALS FROM BIOMASS

Integrating Bioprocesses into
Chemical Production Complexes
for Sustainable Development

DEBALINA SENGUPTA
RALPH W. PIKE

CRC Press
Taylor & Francis Group

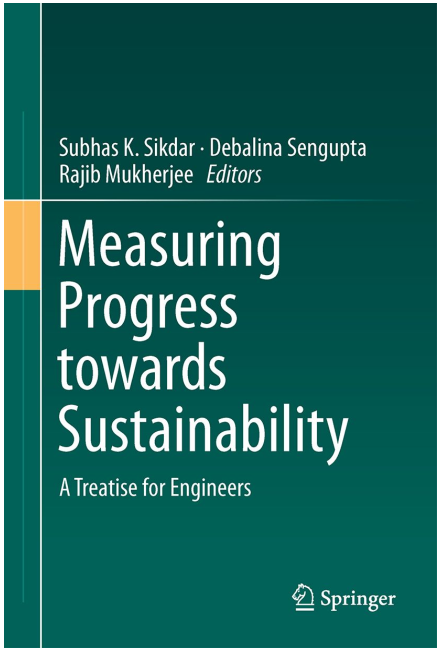
Recap:

- Eco-industrial parks provide shared resources, outlets for byproducts, and utilities
- The Louisiana Case Study demonstrated that a biomass based chemical complex can be sustainable, provided there is an outlet for the CO_2
- A Triple Bottomline Profit allows the screening of potential processes for further evaluation
- Model reduction methods can be applied to high fidelity process models and used for optimization model
- An optimization based mathematical framework for a region allows for relatively simple analysis for potential process plants

Measuring Progress Towards Sustainability

Remember?

- Measuring Progress Towards Sustainability was written for Engineers, giving them a way to quantify sustainability for engineering decisions
- Key impact areas can be identified, and improved based on the Sustainability Footprint Method


Subhas K. Sikdar · Debalina Sengupta
Rajib Mukherjee *Editors*

Measuring Progress towards Sustainability

A Treatise for Engineers

Springer

"Measure what is measurable, and make measurable what is not so” - Galileo Galilei

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GAS & FUELS
RESEARCH CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

We look forward to collaborating with talents and leaders in academia, industry, and government in a true partnership to achieve advancement and make a difference in the area of gas and fuels.

Questions, Comments:

debalinasengupta@tamu.edu
(225) 223 - 9046

Comparison of Base Case with Optimal Structure (Triple Bottomline)

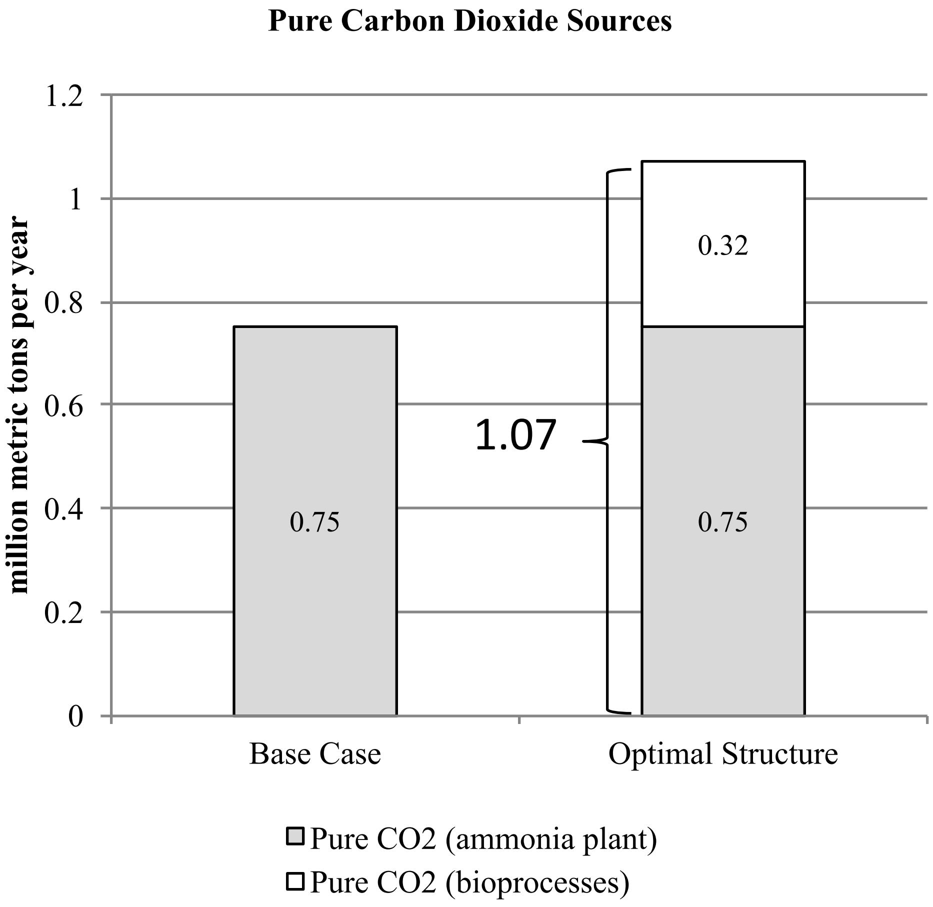
	Base Case Million $/year	**Optimal Structure Million $/year**
Income from Sales	2,026	2,490
Economic Costs	697	516
Raw Material Costs	685	470
Utility Costs	12	46
Environmental Costs	457	313
Sustainable Credits(+)/Costs(-)	-18	-10
Triple Bottomline	**854**	**1,650**

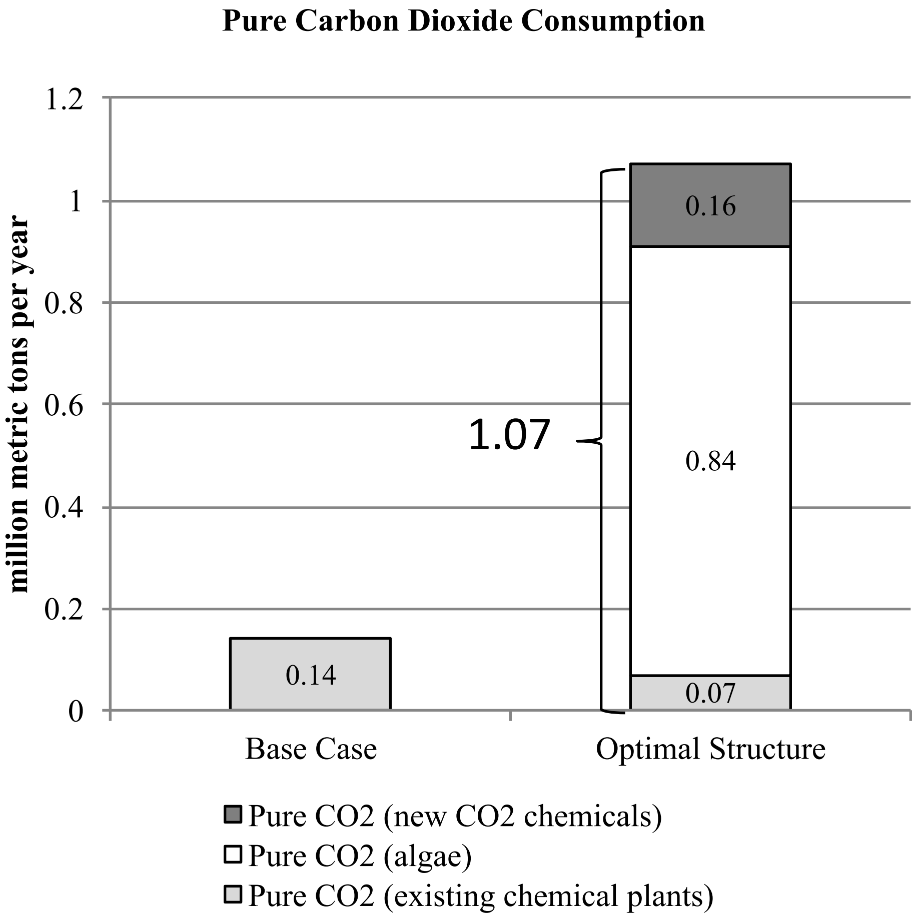
Comparison of Base Case with Optimal Structure (Energy Requirement)

	Base Case (TJ/yr)	Optimal Structure (TJ/yr)
Ammonia	3,820	3,820
Methanol	2,165	1,083
Sulfuric acid	-14,642	-14,642
Wet process phosphoric acid	5,181	5,181
Corn Ethanol	na	4,158
Fatty Acid Methyl Esters	na	1,293
Others	4,374	5,512
Total Energy	**898**	**6,405**

Comparison of CO_2 use in Base Case and Optimal Structure

Base Case CO_2 Emission (million metric tons per year) : 0.75-0.14 = **0.61**
Optimal Structure CO_2 Emission (million metric tons per year) : 1.07-1.07 = **0**

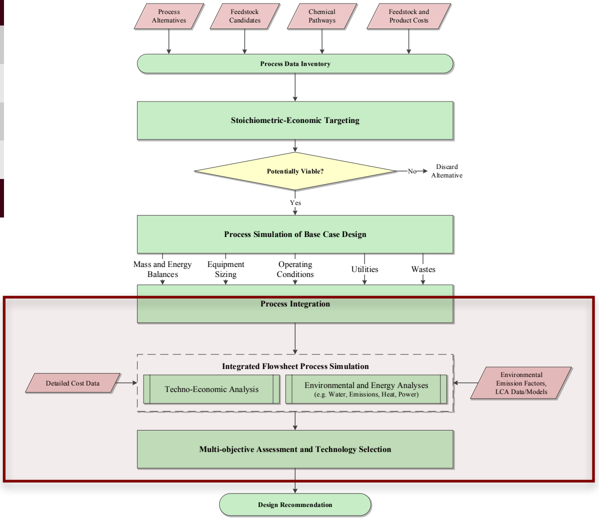




On-purpose Propylene Production

Utility Type	Base Case Utility Cost (MM$/yr)	Integrated Case Utility Cost (MM$/yr)	Integrated and Intensified Case Utility Cost (MM$/yr)
Cooling Water	8.4	3.6	1.2
LP steam	35.5	31.9	4.0
Natural Gas Firing	15.7	7.1	7.1
Electricity	19.2	19.2	27.1
Total Utility	78.8	61.8	39.4

Equipment Type	Base Case Capital Cost ($MM, 2016)	Integrated and Intensified Case Capital Cost ($MM, 2016)
Columns	90	71
Vessels	14	14
Reactors	46	46
Exchangers	100	54
Pumps	1	0.5
Compressors	34	54
Fired Heaters	19	11
Refrigeration Equipment	17	17
Total Installed Capital Cost	**321**	**268**
Outside Battery Limits(OSBL) 30% (as a percentage of Total Installed Cost)		
Detailed Engineering and Construction 30 % (as a percentage of Total Installed Cost + OSBL)		
Contingency 10% (as a percentage of Total Installed Cost + OSBL)		
Total Fixed Capital Investment	585	488



Process Alternatives
Feedstock Candidates
Chemical Pathways
Feedstock and Product Costs
Process Data Inventory
Stoichiometric-Economic Targeting
Potentially Viable?
No
Discard Alternative
Yes
Process Simulation of Base Case Design
Mass and Energy Balances
Equipment Sizing
Operating Conditions
Utilities
Wastes
Process Integration
Integrated Flowsheet Process Simulation
Detailed Cost Data
Techno-Economic Analysis
Environmental and Energy Analyses (e.g. Water, Emissions, Heat, Power)
Environmental Emission Factors, LCA Data/Models
Multi-objective Assessment and Technology Selection
Design Recommendation