Sustainable Design of Decarbonization Strategies via Process Integration

Mahmoud M. El-Halwagi
Professor and Holder of the Bryan Research and Engineering Chair
Managing Director, Gas and Fuels Research Centre
The Artie McFerrin Department of Chemical Engineering
Texas A&M University
College Station, Texas, USA

The Grand Challenge: Sustainability

https://www.dailymaverick.co.za/wp-content/uploads/Yogi-sisuluDrought-option-1.jpg6

https://www.reuters.com/article/us-coffeyville-refinery-flood-idUSN0343078420070703

com/i/sticker-earth-melting-planet-264227453005212

Complex Interactions

https://media.buzzle.com/media/images-en/gallery/earth-science/pollution/1200-4977477

http://www.azavea.com/wp-content/uploads/2017/09/fig1_tesoro_flaring.jpg

Systems-Based Paradigm Shifts & Enabling Design Concepts, Frameworks &Tools

KEY QUESTIONS

- How to create decarbonization strategies using multi-scale process integration?
- Can we identify performance benchmarks (targets) ahead of detailed design?
- How to use these targets in decision making?
- How to handles appropriate level of details at all scales?

OUTLINE

- ➔ **Overview of Sustainable Design Through Multiscale Process Integration**

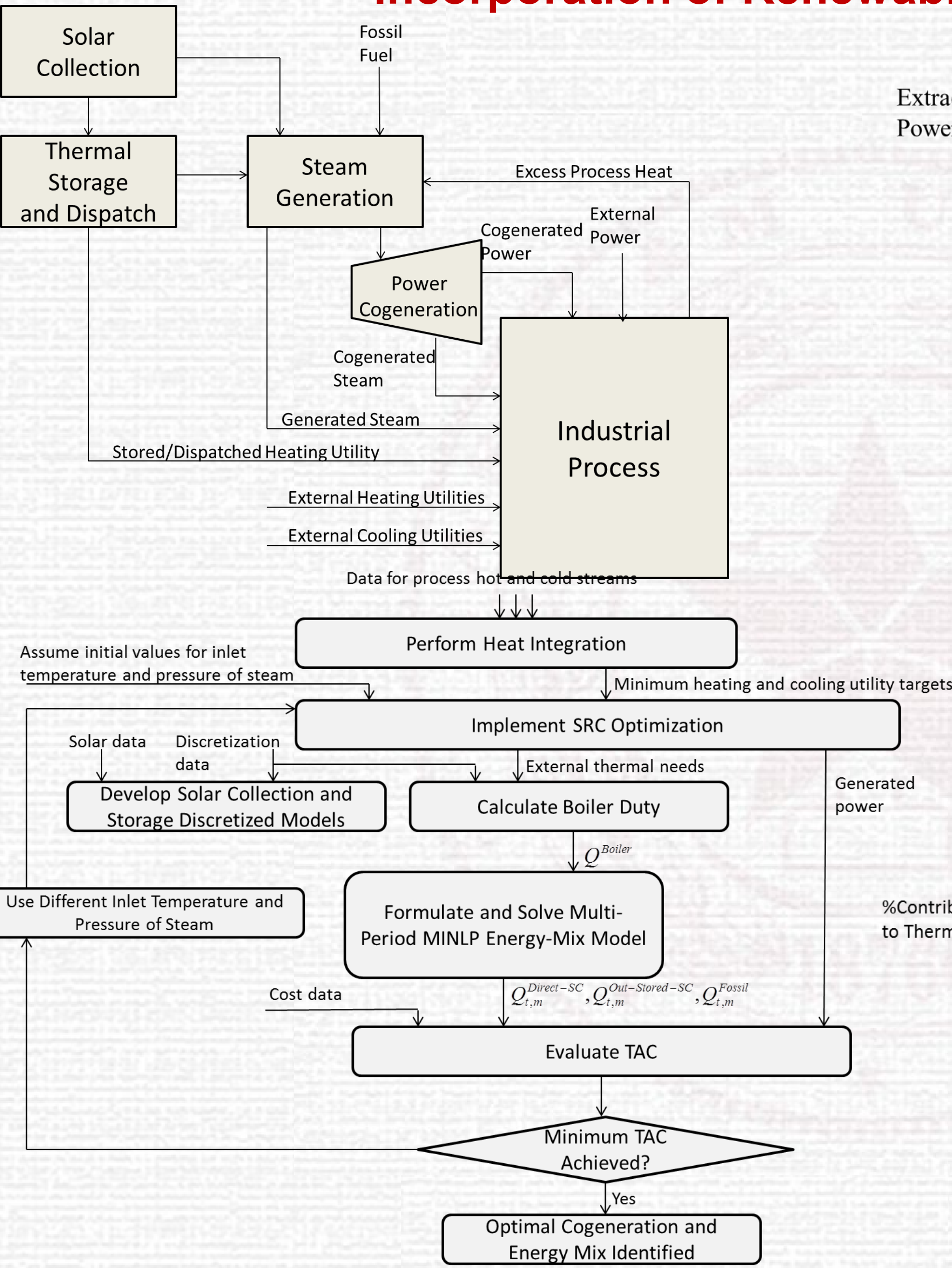
- o **Application Examples:**
  - o **Incorporation of renewables in energy integration and energy-water nexus**
  - o **CO_2 monetization and reduction of carbon footprint for energy carriers and chemicals**
- o **Use of Targets to Incorporate Sustainability in Decision Making**
- o **Multi-scale Integration and Industrial Symbiosis**
- o **Contemporary Challenges and Future Directions**

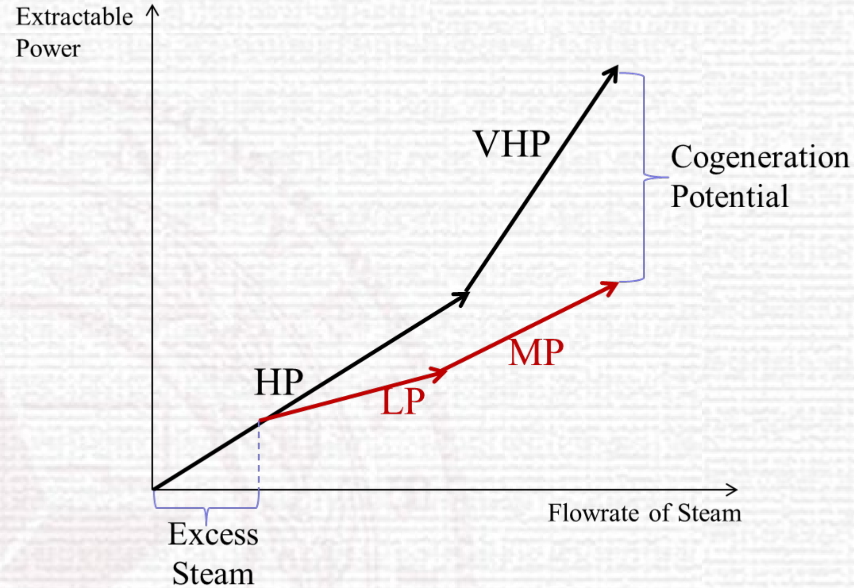
OUTLINE

- Overview of Sustainable Design Through Multiscale Process Integration

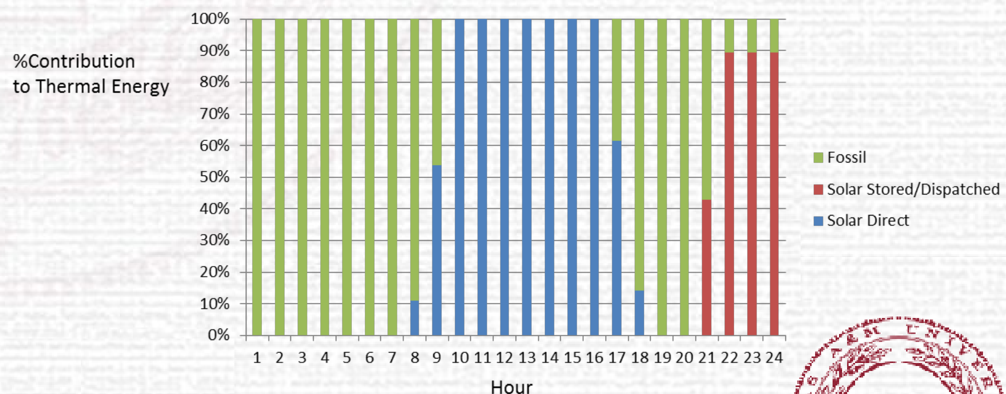
➔ **Application Examples:**
  - Incorporation of renewables in energy integration and energy-water nexus
  - CO_2 monetization and reduction of carbon footprint for energy carriers and chemicals
- Use of Targets to Incorporate Sustainability in Decision Making
- Multi-scale Integration and Industrial Symbiosis
- Contemporary Challenges and Future Directions

Incorporation of Renewables in Energy Integration/Cogeneration



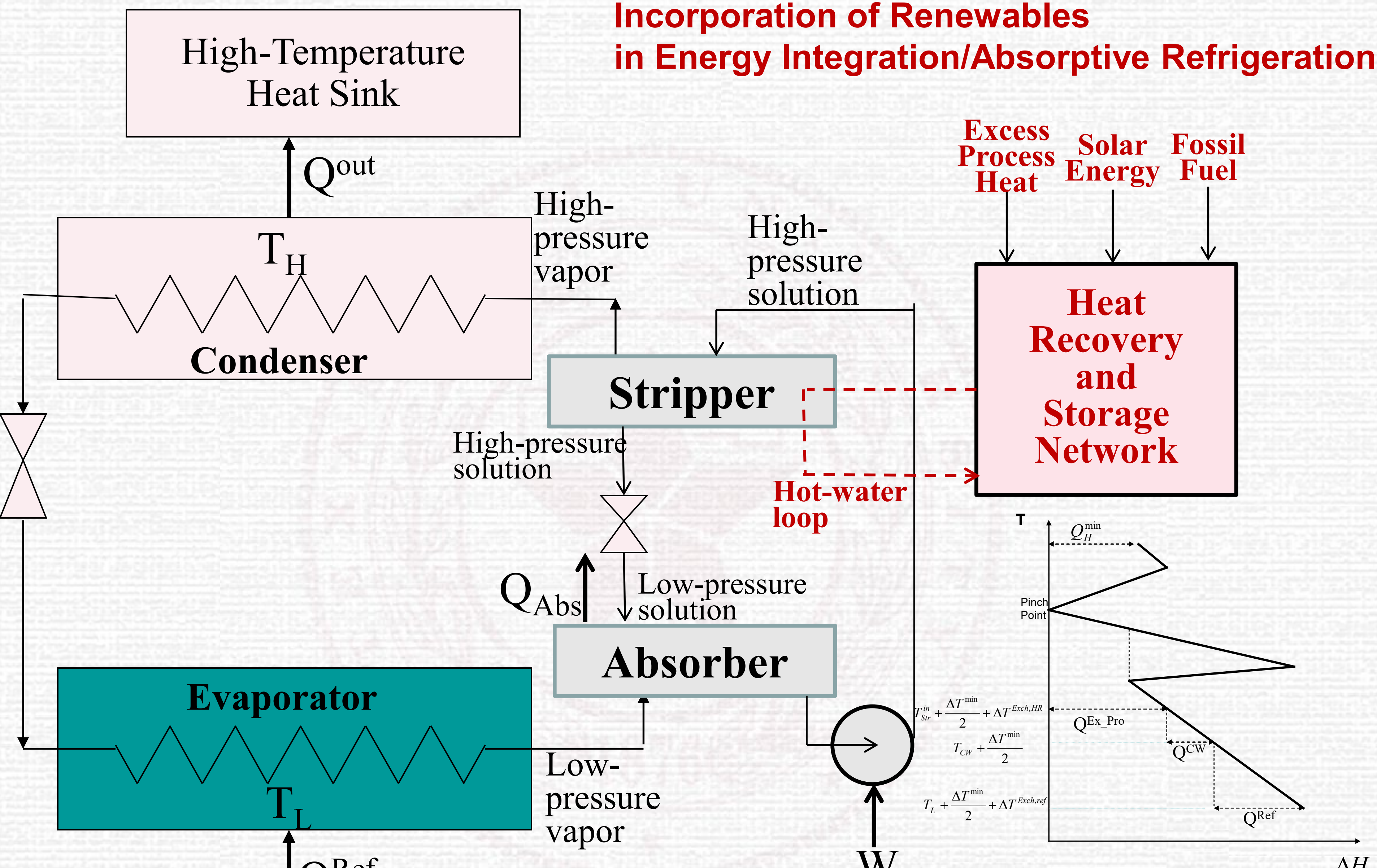


El-Halwagi, M. M., D. Harell, and H. D. Spriggs, “Targeting Cogeneration and Waste Utilization through Process Integration”, Applied Energy, 86(6), pp. 880-887 (2009)



Abdelhady, F., H. Bamufleh, N. M. El-Halwagi, and J. M. Ponce-Ortega, “Optimal Design and Integration of Solar Thermal Collection, Storage, and Dispatch with Process Cogeneration Systems”, Chem. Eng. Sci. 136, 158-167 (2015)

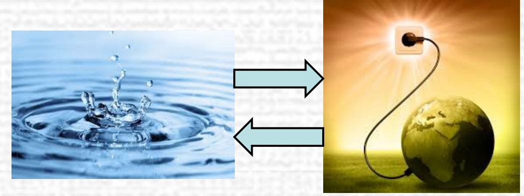
Incorporation of Renewables in Energy Integration/Absorptive Refrigeration

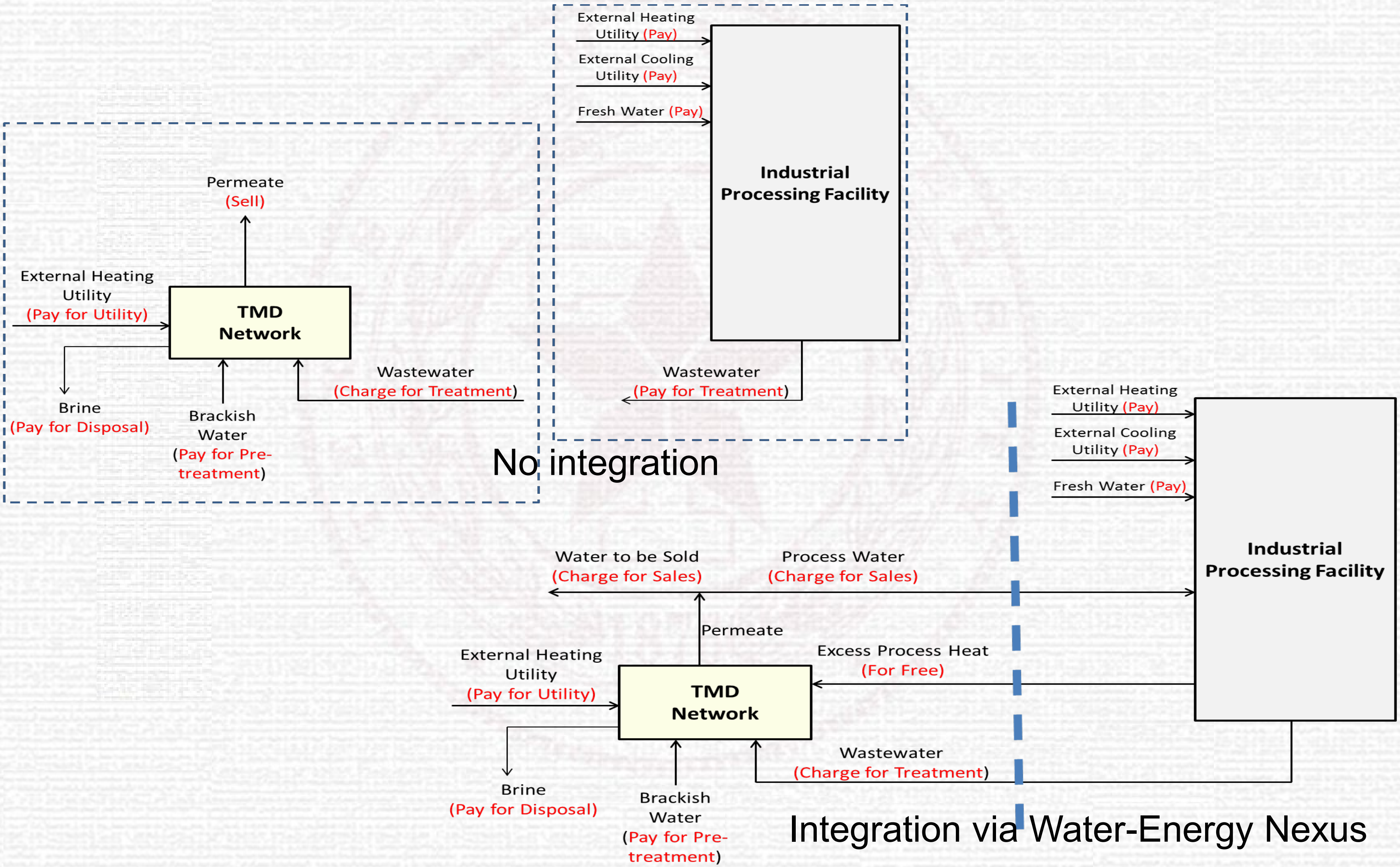


Pinch Analysis and Grand Composite Curve Including Solar Energy

Tora, E. A. and M. M. El-Halwagi, "Integrated Conceptual Design of Solar-Assisted Trigeneration Systems", Computers and Chemical Engineering, 35(9), 1807-1814 (2011)

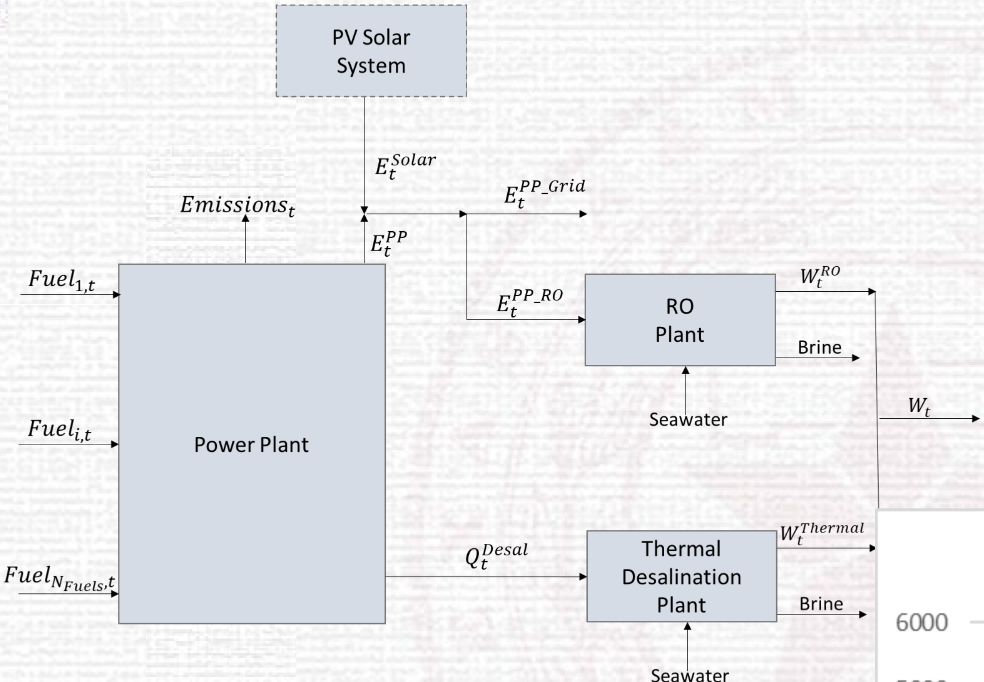
Water-Energy Nexus

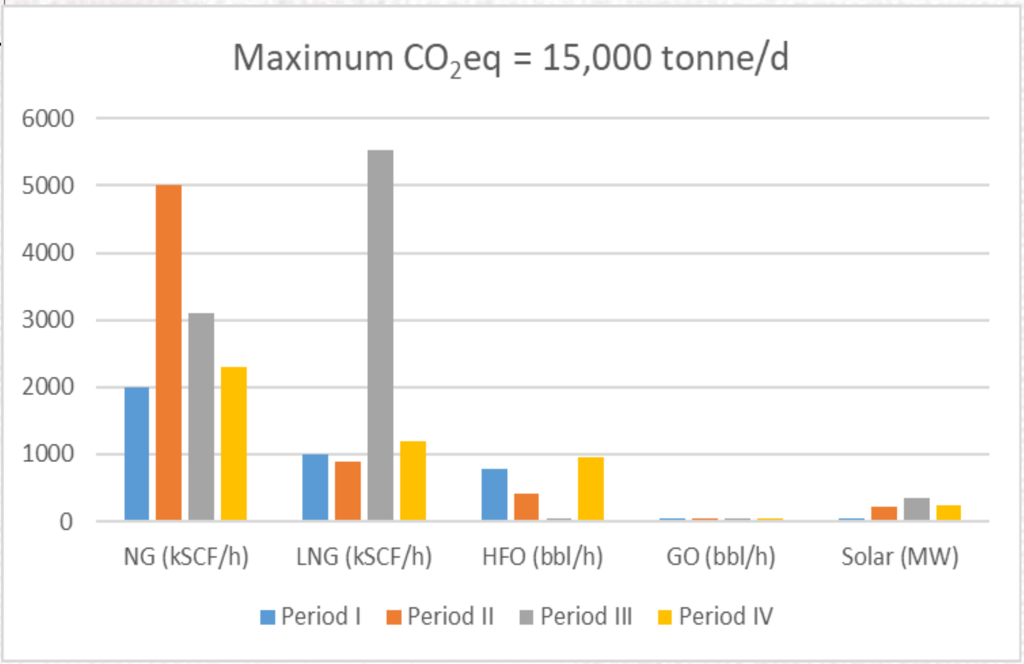




Source: Elsayed, N. A., Barrufet, M. A., & El-Halwagi, M. M. (2013). Integration of Thermal Membrane Distillation Networks with Processing Facilities. Industrial & Engineering Chemistry Research, 53(13), 5284-5298

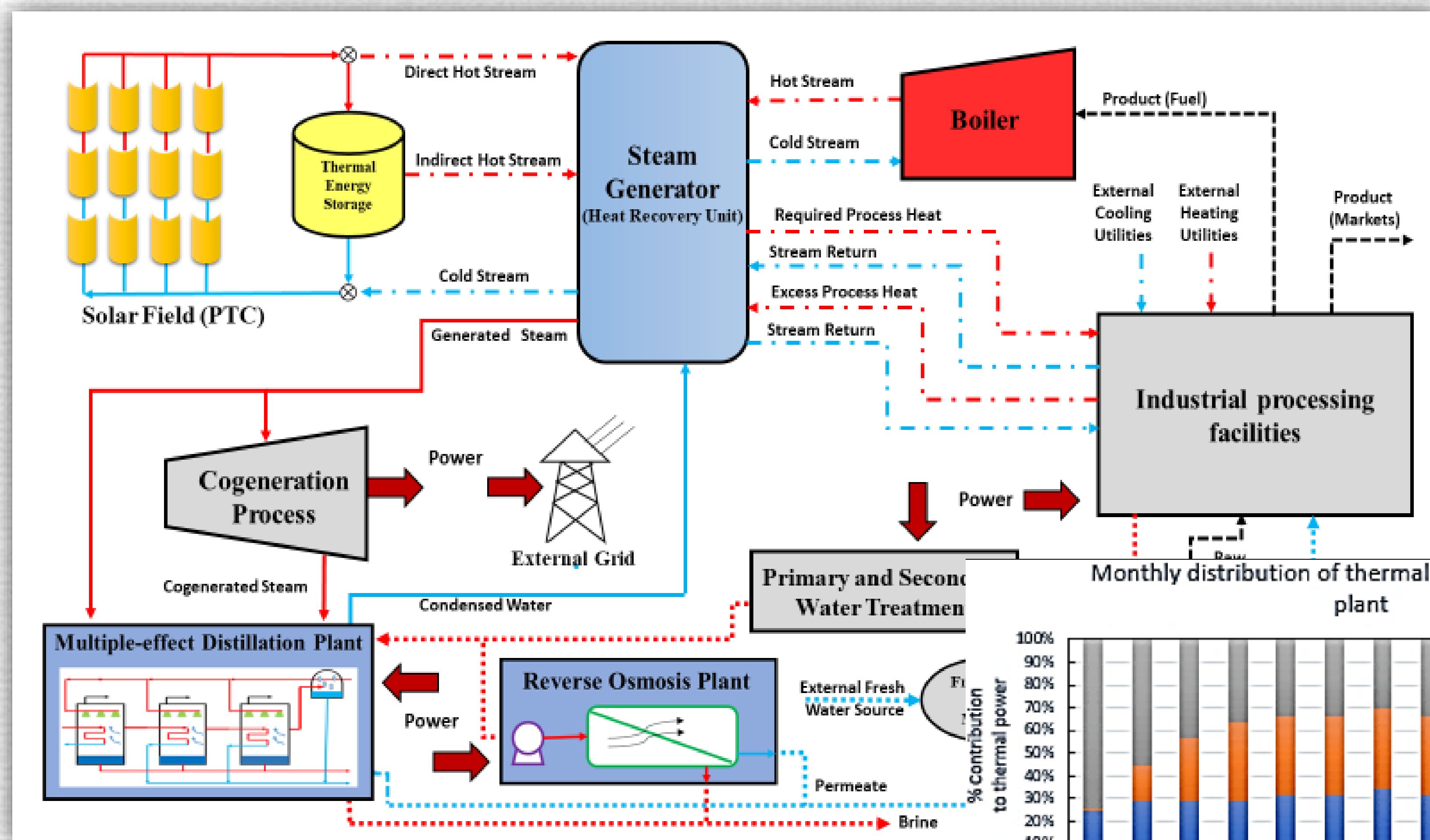
Incorporation of Solar Energy in Water-Energy Nexus

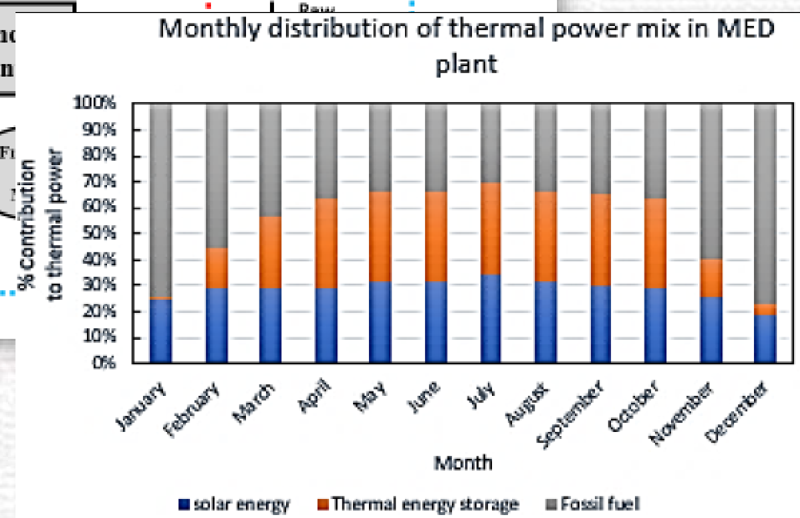




Al-Fadhli, F.M., N. Alhajeri, H. Ettouney, D. Sengupta, M. Holtzapple, and M. M. El-Halwagi, "Simultaneous optimization of power generation and desalination systems: a general approach with applications to Kuwait", Clean Techn Environ Policy (2022). https://doi.org/10.1007/s10098-022-02303-3

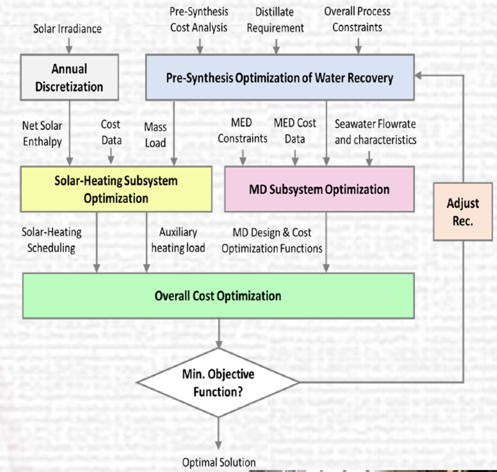
Water-Energy Nexus (with Solar and Symbiosis)

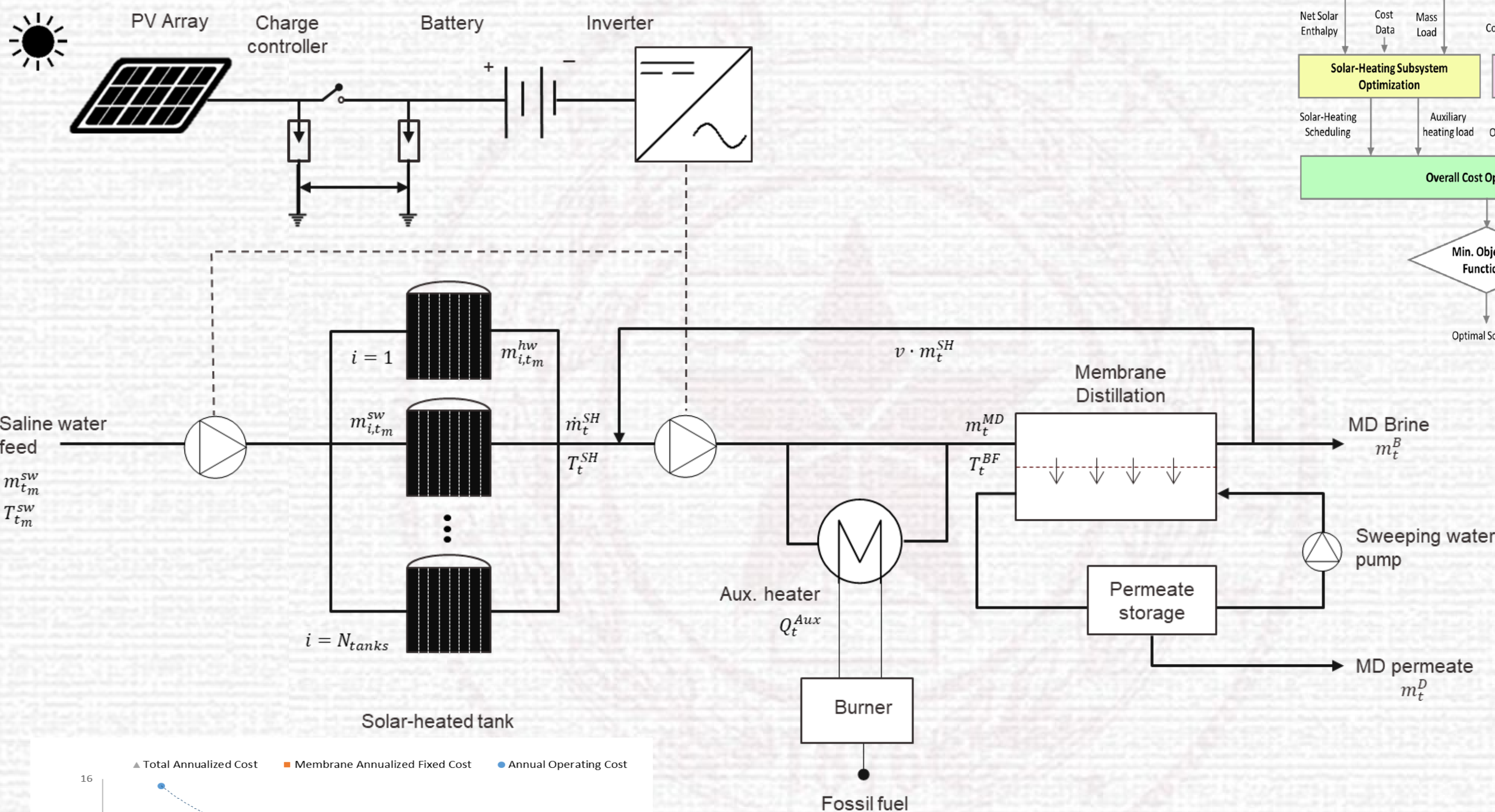


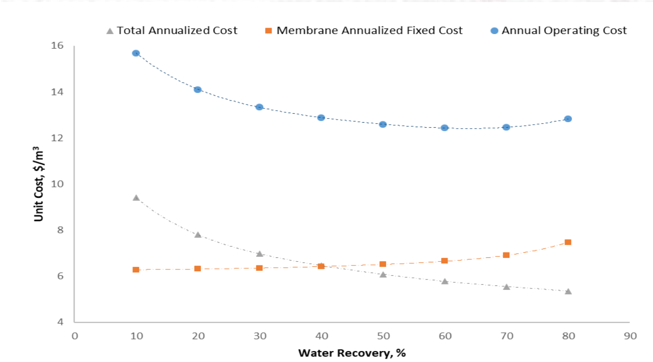


Al-Aboosi, F.Y. and M. M. El-Halwagi, "A Stochastic Optimization Approach to the Design of Shale Gas/Oil Wastewater Treatment Systems with Multiple Energy Sources under Uncertainty", Sustainability 2019, 11(18), 4865-4906. doi:10.3390/su11184865

Optimal Design and Scheduling of a Solar-Assisted Domestic Desalination System







Baaqeel, H., A. Alghamdi, F. Abdelhady, and M. M. El-Halwagi, "Optimal Design and Scheduling of Solar-Assisted Domestic Desalination Systems", Comp. Chem. Eng. 132, p.106605 (2020) https://doi.org/10.1016/j.compchemeng.2019.106605

OUTLINE

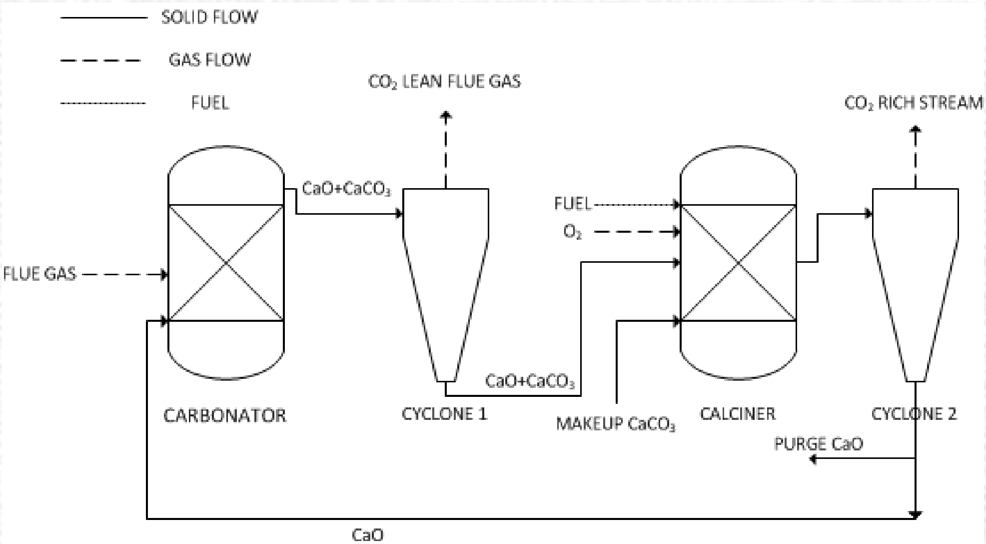
- Overview of Sustainable Design Through Multiscale Process Integration

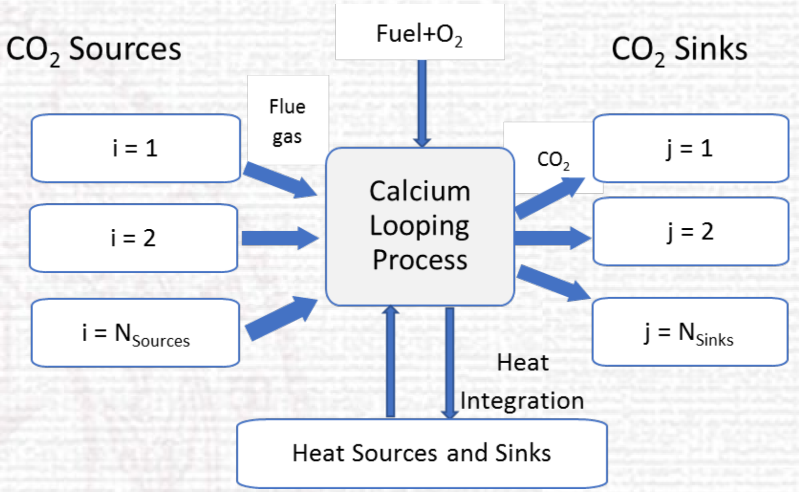
➔ **Application Examples:**

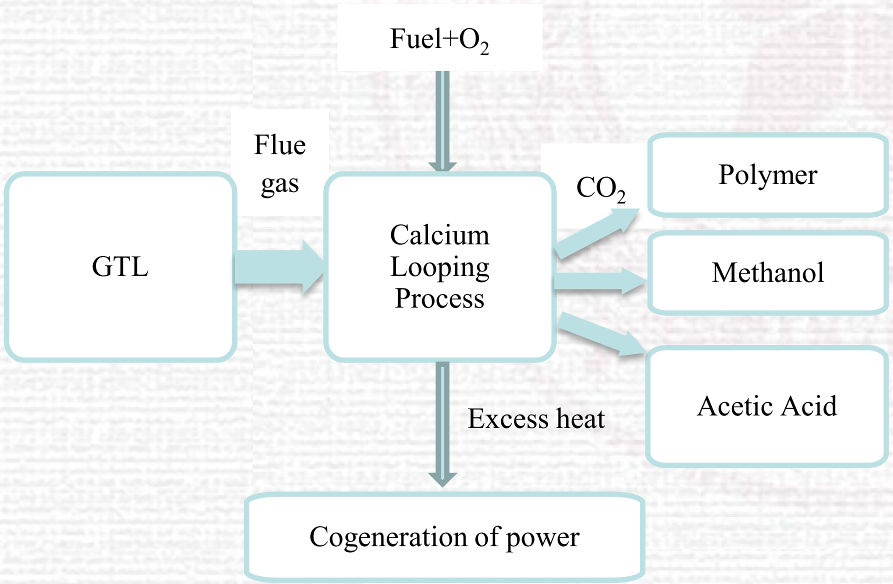
  - Incorporation of renewables in energy integration and energy-water nexus
  - CO_2 monetization and reduction of carbon footprint for energy carriers and chemicals

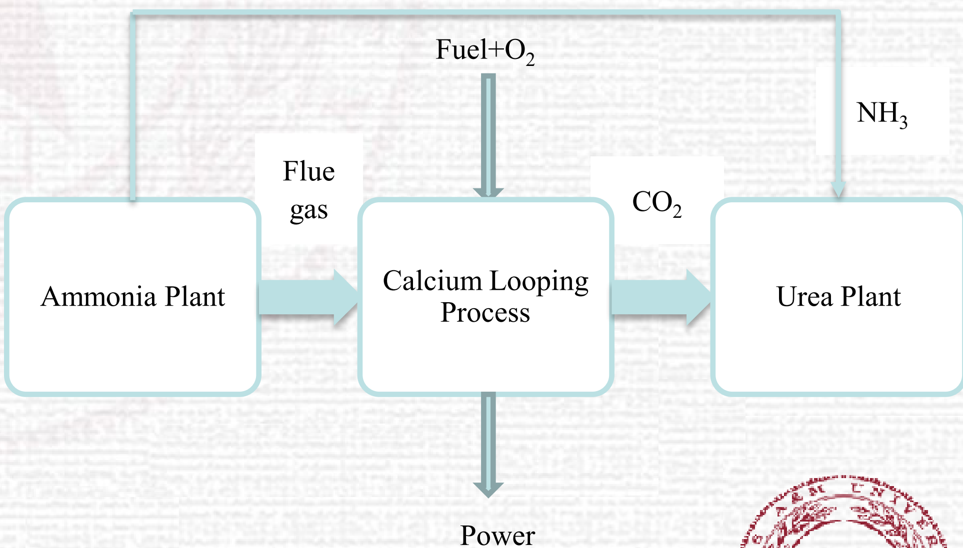
- Use of Targets to Incorporate Sustainability in Decision Making
- Multi-scale Integration and Industrial Symbiosis
- Contemporary Challenges and Future Directions

CO_2 Monetization via Mass/Energy Integration with Calcium Looping





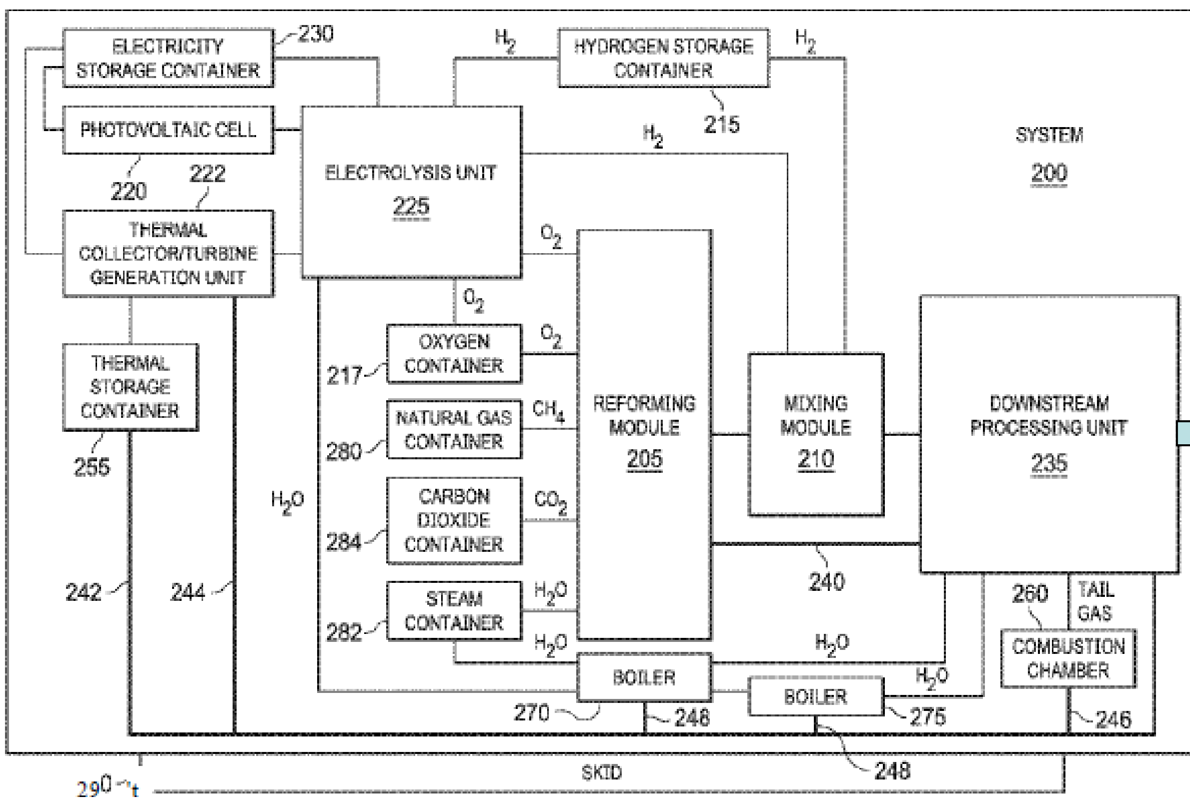




Tilak, P. and M. M. El-Halwagi, "Process Integration of Calcium Looping with Industrial Plants for Monetizing CO_2 into Value-Added Products", Carbon Resources Conversion, 1, 191-199 (2018)

Use of Mass and Energy Integration to Create Novel Configurations for Energy Carriers and Chemicals

(54) **Title:** AN INTEGRATED AND TUNABLE SYSTEM FOR THE PRODUCTION OF SYNGAS AND CHEMICALS
LAR-ASSISTED ELECTROLYSIS AND COMBINED REFORMING



Energy Carriers/ Chemical Supply Chains

Inventors: EL-HALWAGI, Mahmoud M.; 3369 TAMU, College Station, Texas 77843-3369 (US). **CAMPBELL, Juliet E.**; 3369 TAMU, College Station, Texas 77843-3369 (US).

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

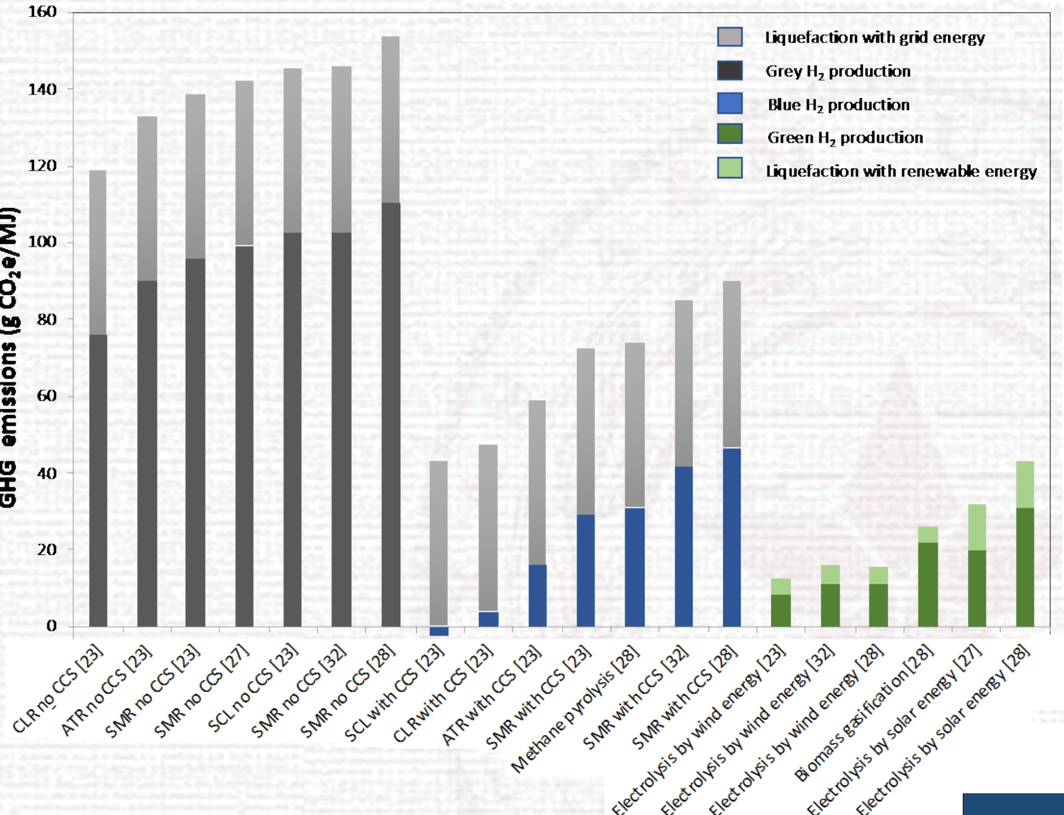
(19) World Intellectual Property Organization
International Bureau

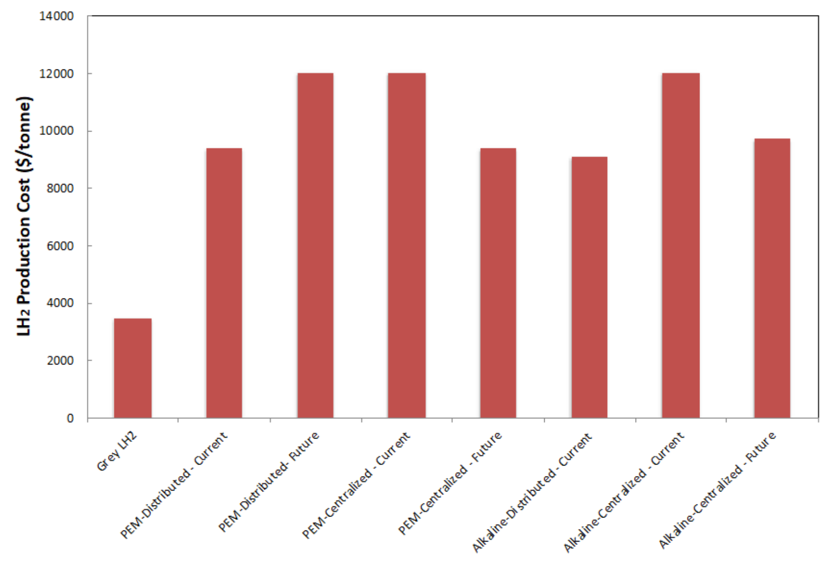
(43) International Publication Date
01 August 2019 (01.08.2019)

WIPO | PCT

(10) International Publication Number
WO 2019/147786 A1

Benchmarking Production of Green Hydrogen





Inherently safer

Inherently more hazardous

Hazard/Safety Category	Fuels							
	LH_2	HFO/MGO	Biodiesel	LPG	LNG	MeOH	EtOH	Ammonia
Criterion 1: Flammability limts- vapor-air mixtures will ignite and burn over a well-specified range fo compositions. A wider range increases the limits in which a fire or explosion could commence.								
Lower heating value [MJ/kg]	120	42.7	37.4	46	50	19.9	26.7	18.6
Flammable limit range	71.0	9.7	-	7.5	9.7	29.3	15.7	13.0
Criterion 2: the potential of self-ignition In presence of oxygen all materials heated above their ignition temperature will burn								
Auto ignition point [C°]	520	250	220	470	540	464	363	650.9
Boiling point [C°]	-252.9	175.0	315.0	-42	-161.5	64.7	78.0	-33.3
Flash point [C°]	-259.2	61	100	-104	-175	12	17	-64.2
Criterion 3: Cloud formation and Flame propagation - 'vapor density' or 'diffusion coefficient' would be related to buoyancy (e.g., LH2 evaporates for a short period due to its high buoyancy)								
Vapor Density air=1	0.10	5	0.88	0.56	0.55	1.10	1.60	0.80

Atilhan, S., S. Park, M. M. El-Halwagi, M. Atilhan, M. Moore, and R. B. Nielsen, "Green Hydrogen as an Alternative Fuel for the Shipping Industry", Current Opinion in Chemical Engineering, Vol. 31, 100668 (2021)

Integration of with Experimental Work

Input Data

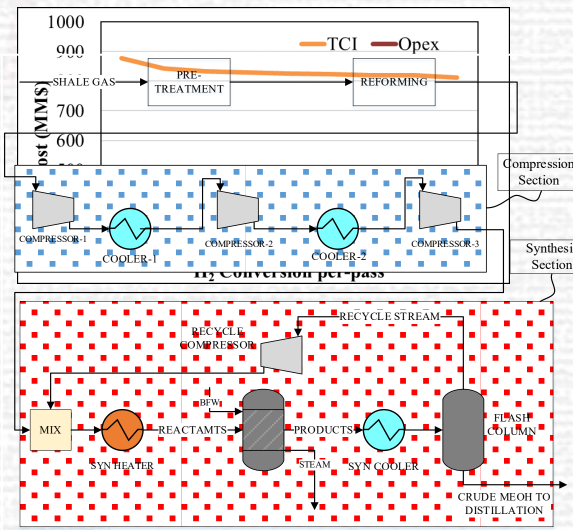
Process Synthesis, Simulation, and Integration

Alternative pathways, performance targets, global insights

Experimental Work

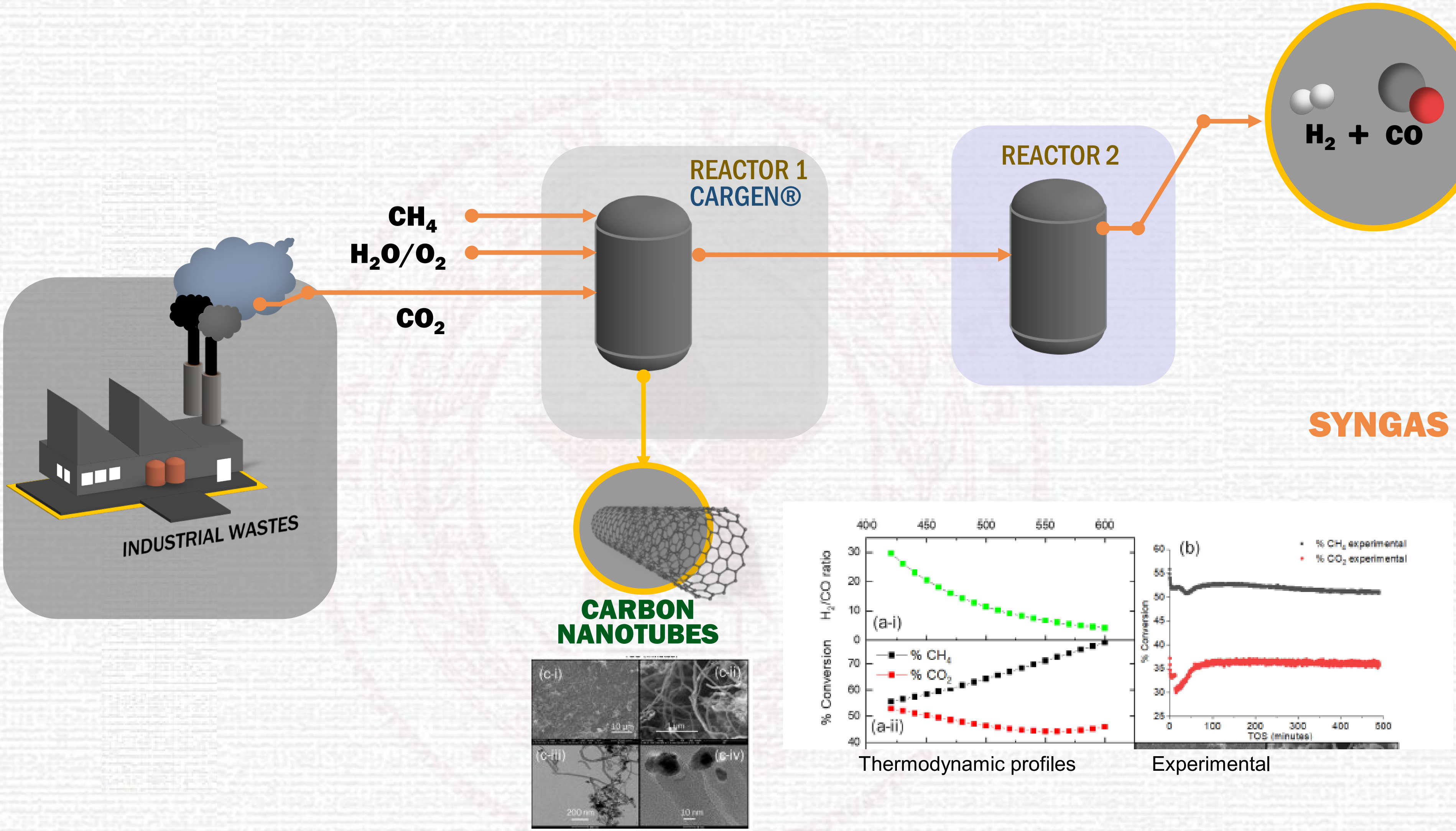
Catalyst design and selection, reaction kinetics, separation performance

Optimal Design



Alsuhaibani, A. S., S. Afzal, M. Challiwala, N. O. Elbashir, M. M. El-Halwagi, “The Impact of the Development of Catalyst and Reaction System of the Methanol Synthesis Stage on the Overall Profitability of the Entire Plant: A Techno-Economic Study”, Catalysis Today, 343, pp.191-198. 2020,

Monetizing CO_2 into Carbon Nanotubes and Syngas (CARGEN ®)



Chaliwalla, M. S., N. O. Elbashir, D. Sengupta, and M. M. El-Halwagi, “System and Method for Carbon and Syngas Production”, Patent Pub. No.: US 2020/0109050 A1, Apr. 9, 2020

Challiwala, M. S., H. Choudhury, D. Wang, M. El-Halwagi, E. Weitz, and N. Elbashir, “A novel CO2 utilization technology for the synergistic co-production of multi-walled carbon nanotubes and syngas”, Scientific Reports 11(1), 1-8 (2021)

OUTLINE

- Overview of Sustainable Design Through Multiscale Process Integration
- Application Examples:
  - Incorporation of renewables in energy integration and energy-water nexus
  - CO_2 monetization and reduction of carbon footprint for energy carriers and chemicals
- ➔ **Use of Targets to Incorporate Sustainability in Decision Making**
- Multi-scale Integration and Industrial Symbiosis
- Contemporary Challenges and Future Directions

INCORPORATING SUSTAINABILITY AND TARGETING IN PROFITABILITY CALCULATIONS

- Process improvement projects are typically driven/assessed by profitability criteria (e.g., return on investment, payback period, net present value)
- Sustainability goals are well aligned with process integration activities (natural-resource conservation, process-efficiency enhancement, pollution prevention, etc.)
- Targeting approaches can set goals for sustainability
- Sustainability considerations are best included in the early stages of decision making

How to use a consistent platform for including sustainability in development and assessment of process integration and improvement projects?

SUSTAINABILITY WEIGHTED RETURN ON INVESTMENT METRIC "SWROIM"

- consider a set of process integration project alternatives: $p = 1,2,\ldots, N_{Projects}$.
- For the p^{th} project, a new term called the ***Annual Sustainability Profit "ASP"*** is defined as follows

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

Value of the i^{th} sustainability indicator for the p^{th} project: may be positive, 0, or negative

Annual Economic Profit

Index for sustainability indicators

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

Target value of the i^{th} sustainability indicator (obtained from process integration benchmarking or taken as the largest value from all projects, or set by the company as a goal): always positive indicating improvement

$$SWROIM_p = \frac{ASP_p}{TCI_p}$$

El-Halwagi, M. M., "A Return on Investment Metric for Incorporating Sustainability in Process Integration and Improvement Projects", Clean Technologies and Environmental Policy 19:611-617 (2017)

OUTLINE

- Overview of Sustainable Design Through Multiscale Process Integration
- Application Examples:
  - Incorporation of renewables in energy integration and energy-water nexus
  - CO_2 monetization and reduction of carbon footprint for energy carriers and chemicals
- Use of Targets to Incorporate Sustainability in Decision Making

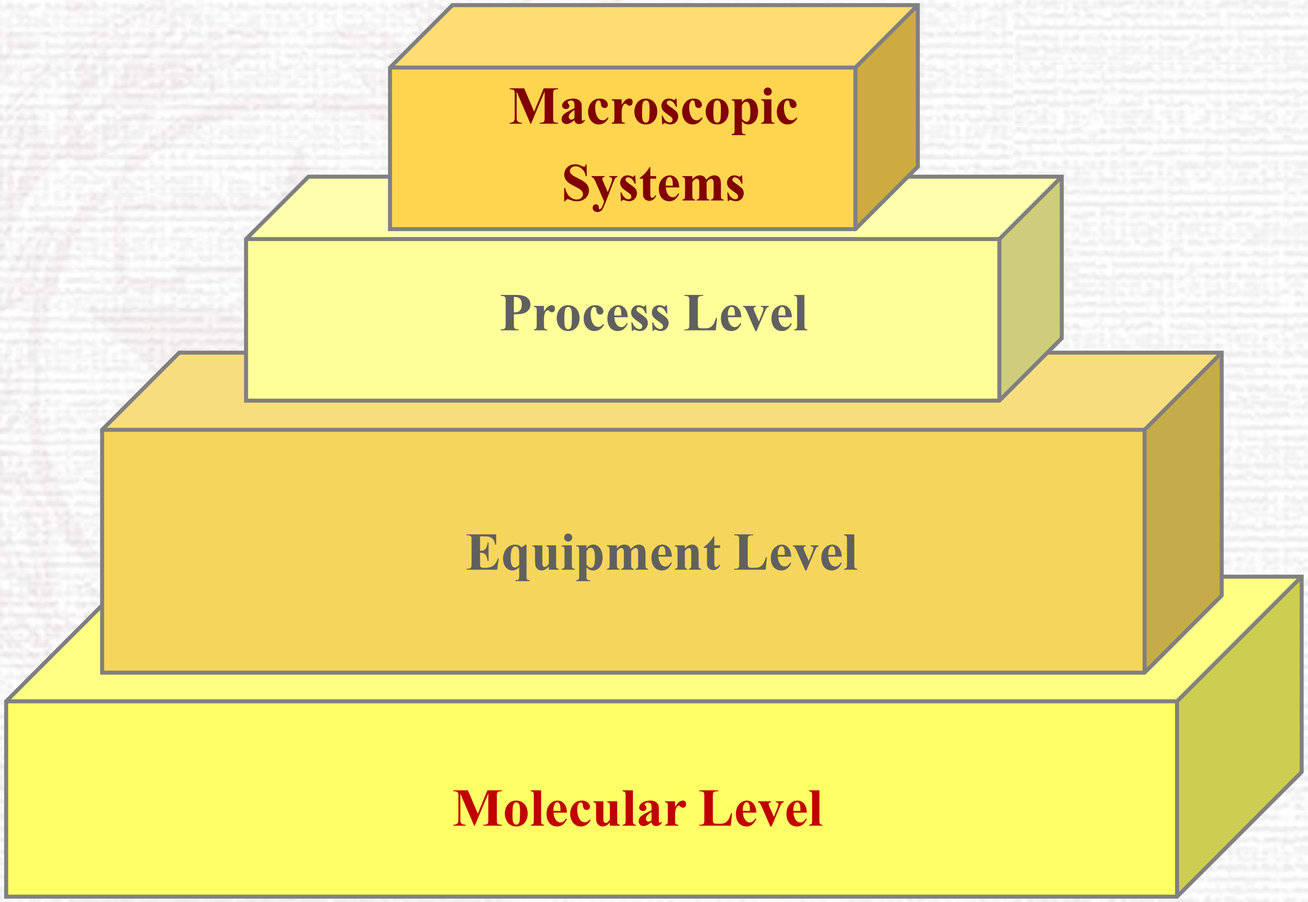
➔ **Multi-scale Integration and Industrial Symbiosis**

- Contemporary Challenges and Future Directions

THE MULTI-SCALE NATURE PROCESS INTEGRATION

Example:

- Eco-Industrial Parks



ECO-INDUSTRIAL PARKS (EIPs)

What is an EIP?

An EIP may be defined as “a community of manufacturing and service businesses located together on a common property. Members seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues”

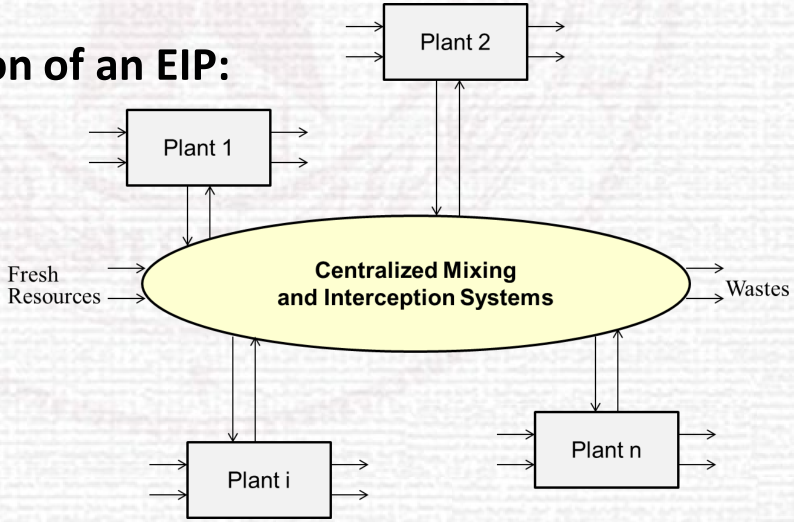
(Source: Lowe E. A, “Eco-Industrial Park Handbook for Asian Developing Countries”, A Report to Asian Development Bank. Indigo Development, Santa Rosa, California (2001)).

Key Characteristic of a Successful EIP:

Synergism to promote industrial symbiosis is essential for the creation of an EIP and “a key condition for an EIP to successfully attract industrial participants is that it should demonstrate that the sum of the benefits achieved by working as collective is greater than working as a stand-alone facility”

(Source: Lovelady, E. M. and M. M. El-Halwagi, “Design and Integration of Eco-Industrial Parks”, Environmental Progress and Sustainable Energy, 28(2), pp. 265-272 (2009))

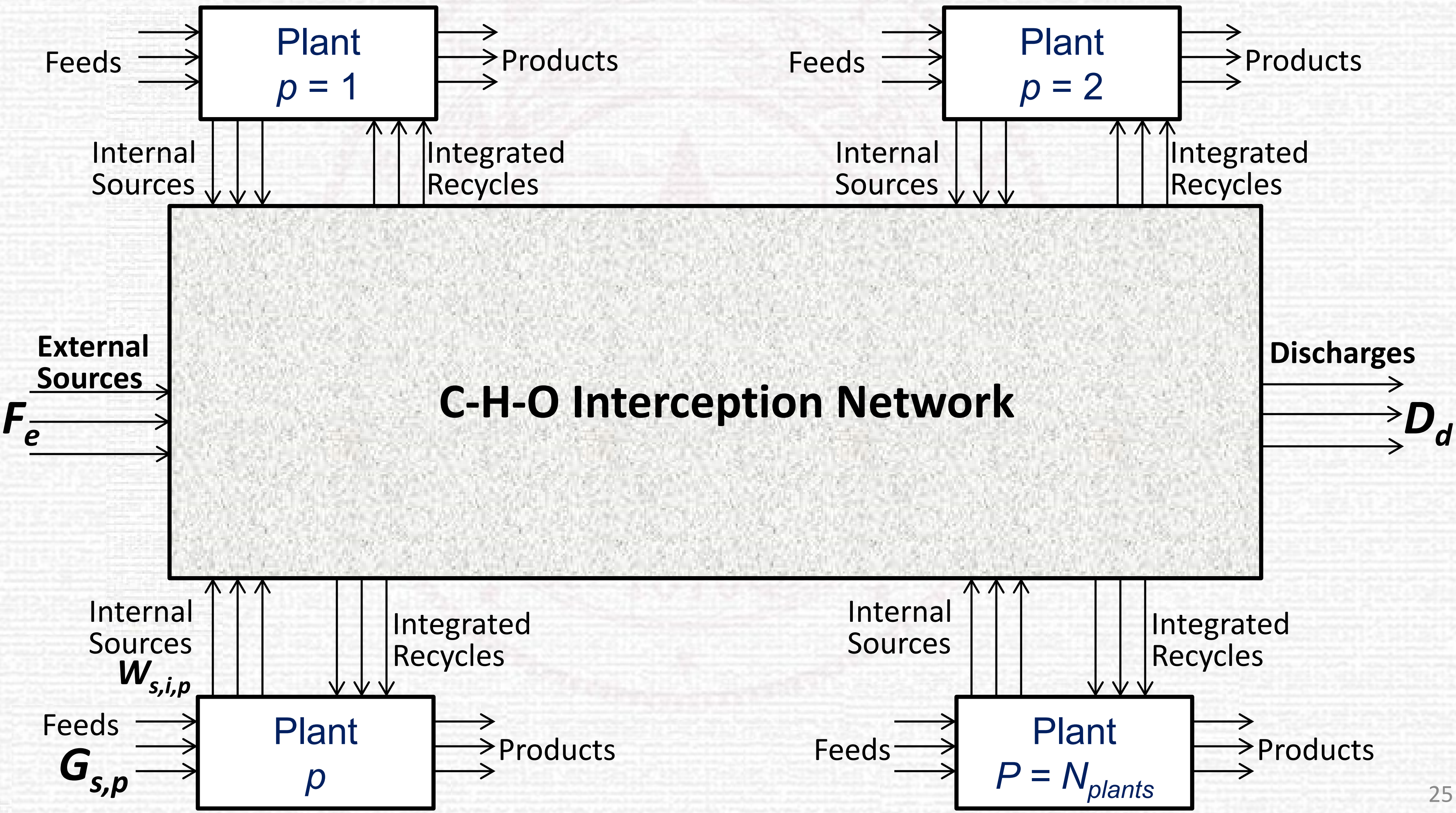
Mass Integration Representation of an EIP:



Source: Spriggs, H. D., E. A. Lowe, J. Watz, M. M. El-Halwagi, and E. M. Lovelady, “Design and Development of Eco-Industrial Parks”, paper #109a, AIChE Spring Meeting, New Orleans, April, (2004)

CARBON-HYDROGEN-OXYGEN SYBIOSIS NETWORK (CHOSYN)

"A cluster of multiple plants with shared centralized facilities to enable the exchange, conversion, separation, treatment, splitting, mixing, and allocation of streams containing C-H-O compounds"



Source: Noureldin, M. M. B. and M. M. El-Halwagi,"Synthesis of C-H-O Symbiosis Networks", AIChE J., 64(4), 1242-1262 (2015)

SUMMARY OF CHOSYN MULTI-SCALE TARGETING APPROACH

Flowrate & Composition Data of Internal Sources

Flowrate & Composition Requirements of Participating Plants

Atomic Scale

Calculate Atomic Flowrates of Internal Sources

$$A_{C,i,p}^{Internal\_Source} = \sum \alpha_s W_{s,i,p} \qquad A_{H,i,p}^{Internal\_Source} = \sum \beta_s W_{s,i,p} \qquad A_{O,i,p}^{Internal\_Source} = \sum \gamma_s W_{s,i,p}$$

$$A_{C,p}^{Internal\_Source} = \sum_i A_{C,i,p}^{Internal\_Source} \qquad A_{H,p}^{Internal\_Source} = \sum_i A_{H,i,p}^{Internal\_Source} \qquad A_{O,p}^{Internal\_Source} = \sum_i A_{O,i,p}^{Internal\_Source}$$

Calculate Atomic Flowrates for Demands of Participating Plants

$$A_{C,p}^{Demand} = \sum_s \alpha_s G_{s,p} \qquad A_{H,p}^{Demand} = \sum_s \beta_s G_{s,p} \qquad A_{O,p}^{Demand} = \sum_s \gamma_s G_{s,p}$$

Composition Data of External Sources

Determine Atomic Deficit/Surplus of C, H, and O

$$\Delta A_C^{Net} = \sum_{p=1}^{N_{Plants}} A_{C,p}^{Internal\_Source} - \sum_{p \in P^{Targeted}} A_{C,p}^{Demand} \qquad \Delta A_H^{Net} = \sum_{p=1}^{N_{Plants}} A_{H,p}^{Internal\_Source} - \sum_{p \in P^{Targeted}} A_{H,p}^{Demand} \qquad \Delta A_O^{Net} = \sum_{p=1}^{N_{Plants}} A_{O,p}^{Internal\_Source} - \sum_{p \in P^{Targeted}} A_{O,p}^{Demand}$$

Species Scale

Solve Atomic Balance Equations to Determine Minimum Usage/Discharge Targets of Species

$$\Delta A_C^{Net} + \sum_e \alpha_e F_e - \sum_d \alpha_d D_d + = 0 \qquad \Delta A_H^{Net} + \sum_e \beta_e F_e - \sum_d \beta_d D_d = 0 \qquad \Delta A_O^{Net} + \sum_e \gamma_e F_e - \sum_d \gamma_d D_d = 0$$

Multi-Plant Scale

Combine Identified Targets, Internal Sources, and Process Demands to Develop an Overall Stoichiometric Equation for the CHOSYN

Candidate Reactions

Synthesize Reaction Pathways and Develop Conceptual Designs

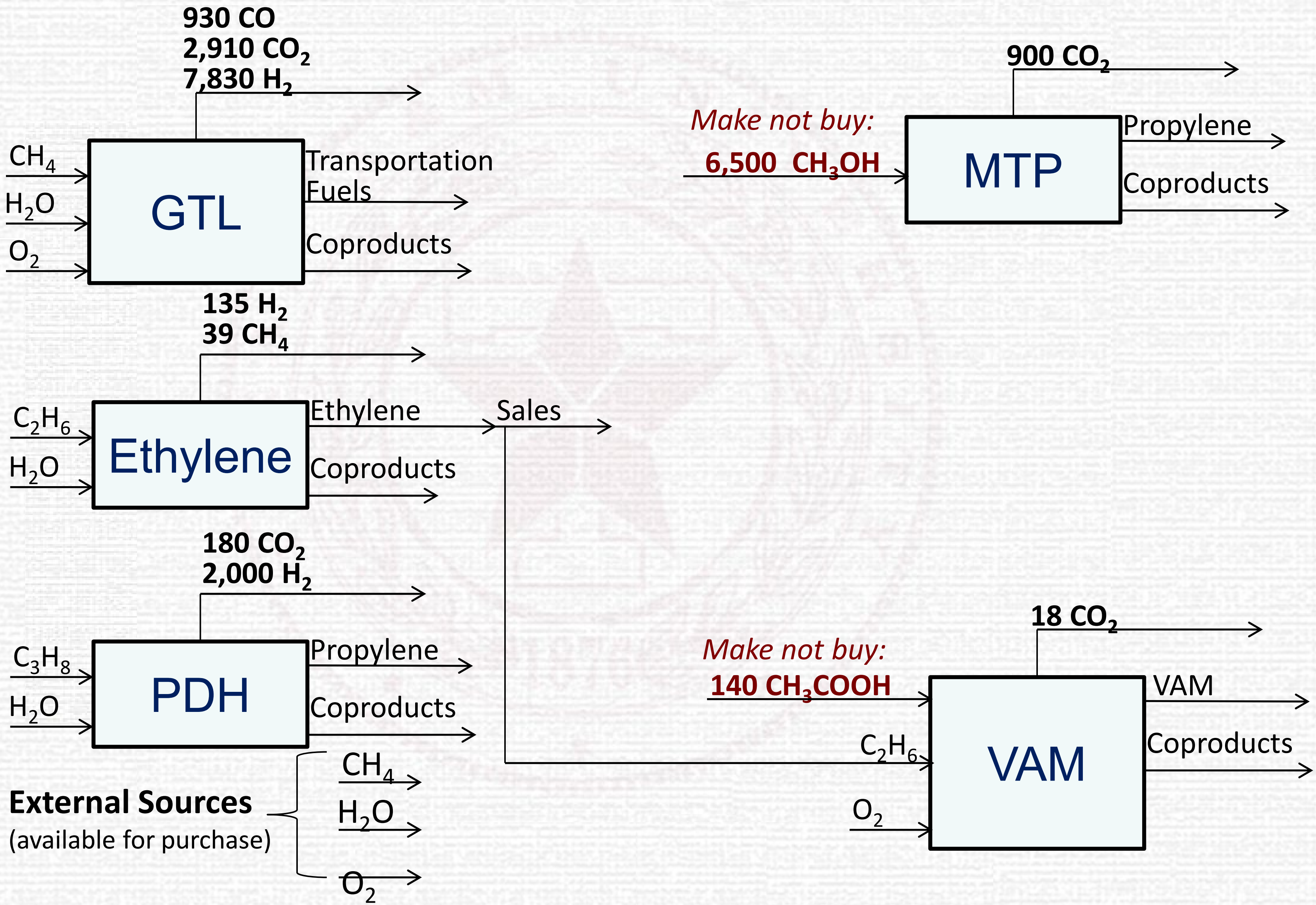
CHOSYN Conceptual Design Alternatives

Source: El-Halwagi, M. M., "A Shortcut Approach to the Multi-Scale Atomic Targeting and Design of C-H-O Symbiosis Networks", Process Integration and Optimization for Sustainability 1(1), 3-13 (2017)

EXAMPLE

1. How to Best Integrate Discharges and Feedstocks?

2. How to Establish Targets (Atomic, Chemical Species, and Multi-Plant)for Integration Opportunities?



Source: El-Halwagi, M. M., "A Shortcut Approach to the Multi-Scale Atomic Targeting and Design of C-H-O Symbiosis Networks", Process Integration and Optimization for Sustainability 1(1), 3-13 (2017)

Key Targeting Results for the CHOSYN Case Study

Atomic Targeting

ΔA_C^{Net} = **-1,803 kmol C/h (target for deficit in carbon)**

ΔA_H^{Net} = **- 6,474 kmol H/h (target for deficit in hydrogen)**

ΔA_O^{Net} = **2,166 kmol O/h (target for surplus oxygen)**

Molecular Targeting

F_{CH4} = 2,252.25 (external)
F_{H2O} = -1,267.50 (-ive → net discharge)
D_{CO2} = - 449.25 (-ive → net discharge)

Chemical Species Targets for Minimum External Resource Usage and Discharge

How to achieve?

Overall stoichiometric equation for the internal streams & external (fresh + discharges) :

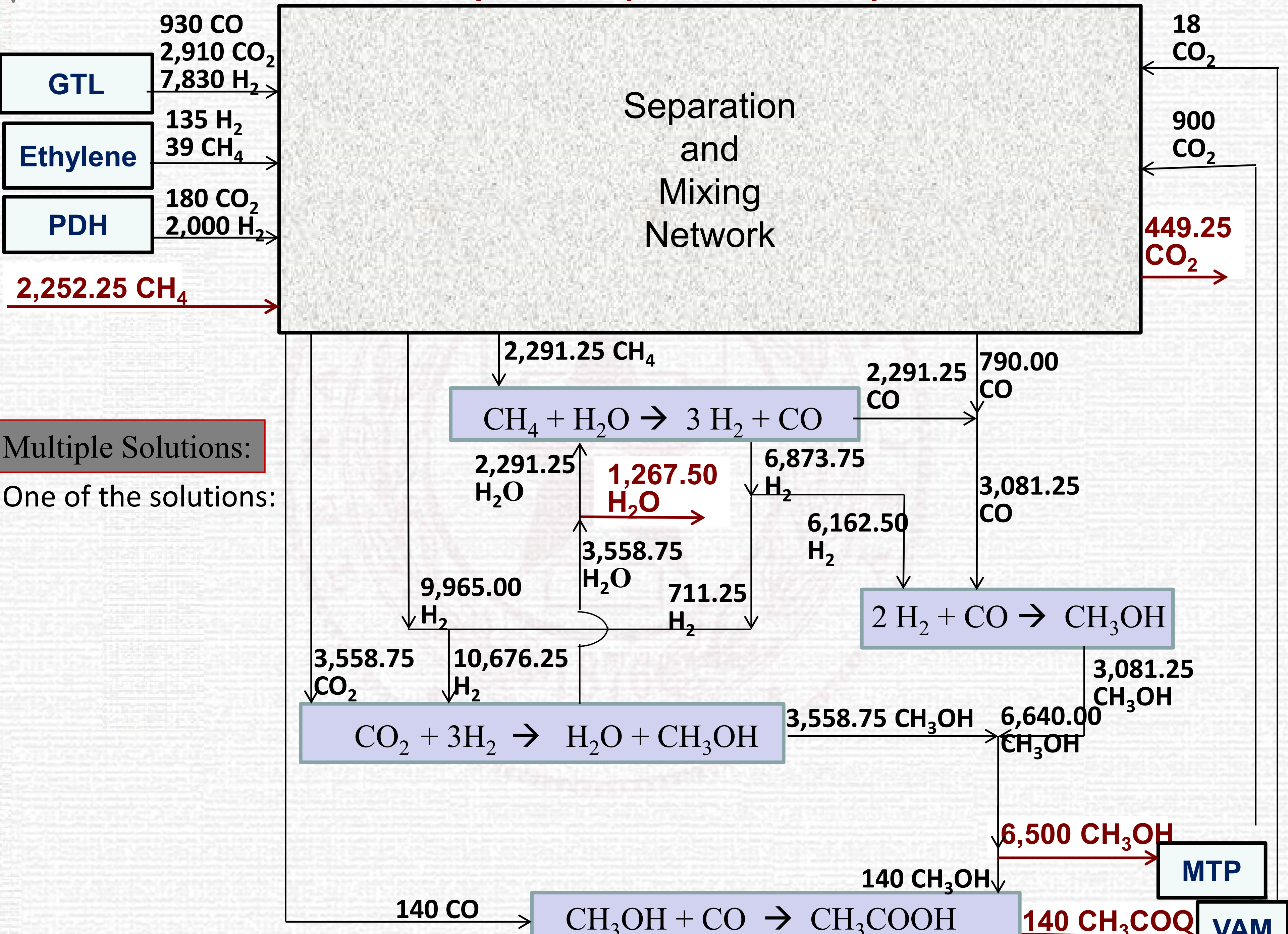
$$2{,}291.25\ CH_4 + 930.00\ CO + 3558.75\ CO_2 + 9{,}965.00\ H_2 = 6{,}500.00\ CH_3OH + 140.00\ CH_3COOH + 1{,}267.50\ H_2O$$

Next, Reaction Pathway Synthesis

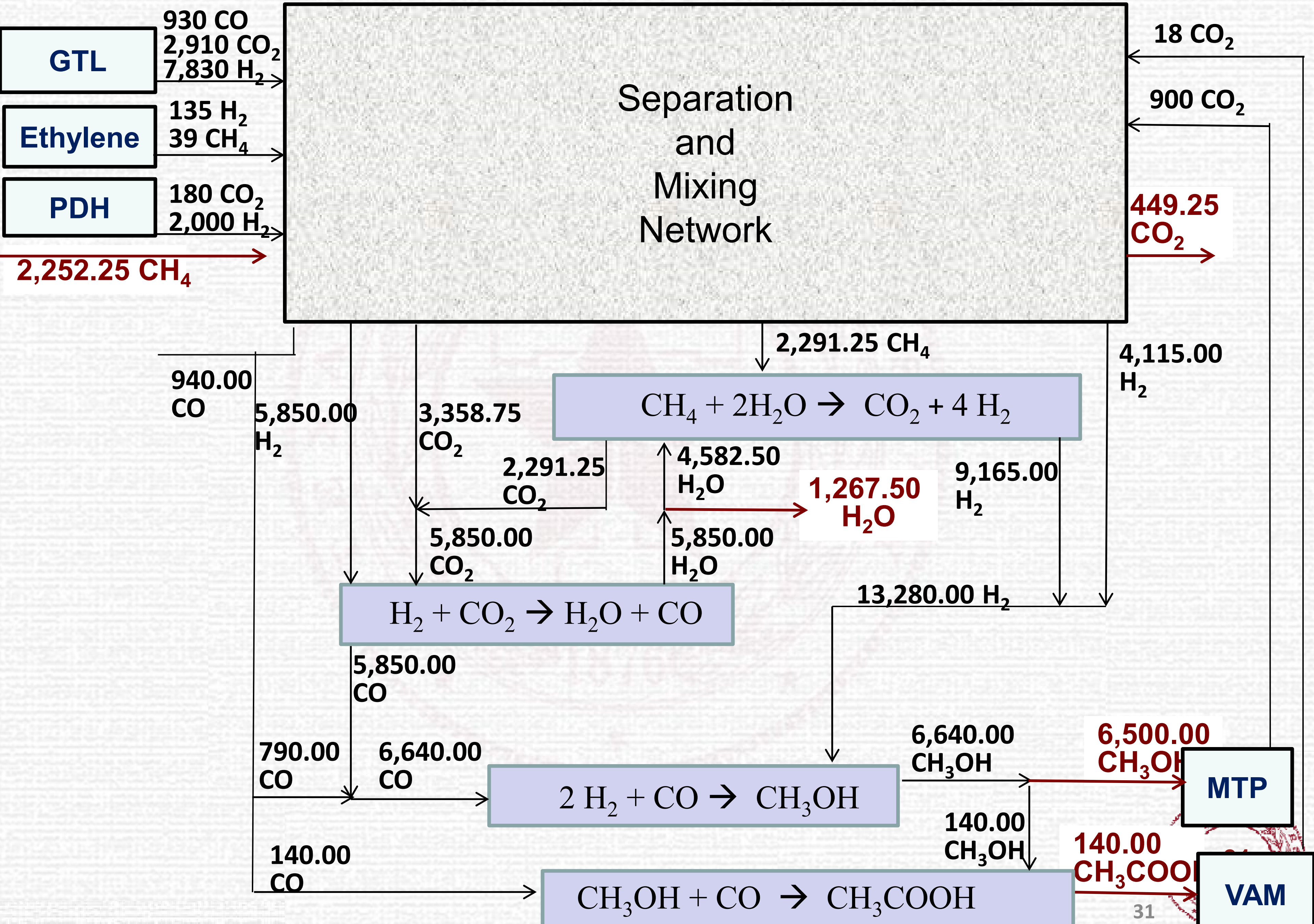
Examples of Implementation: Option 1

Multiple Solutions:

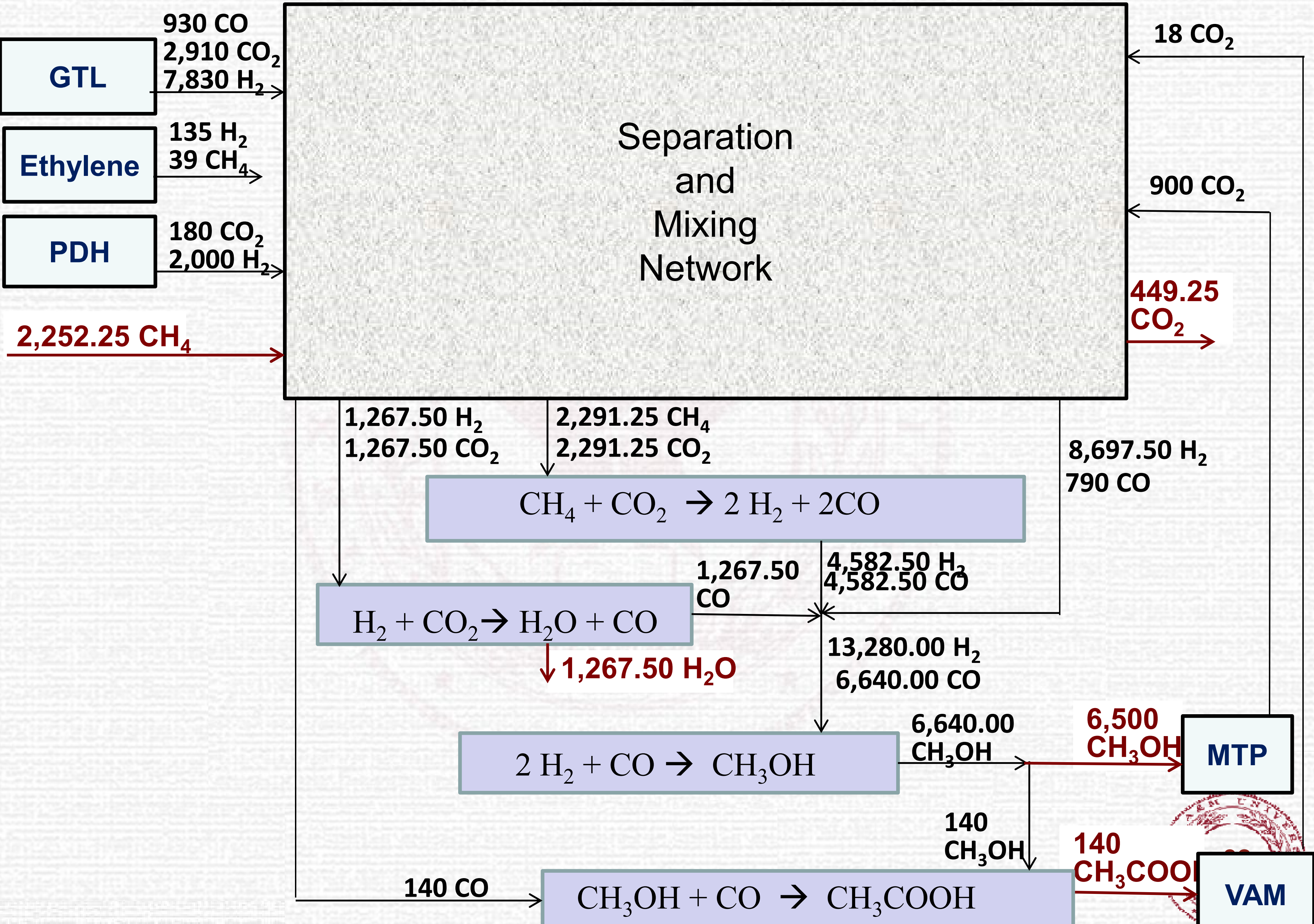
One of the solutions:

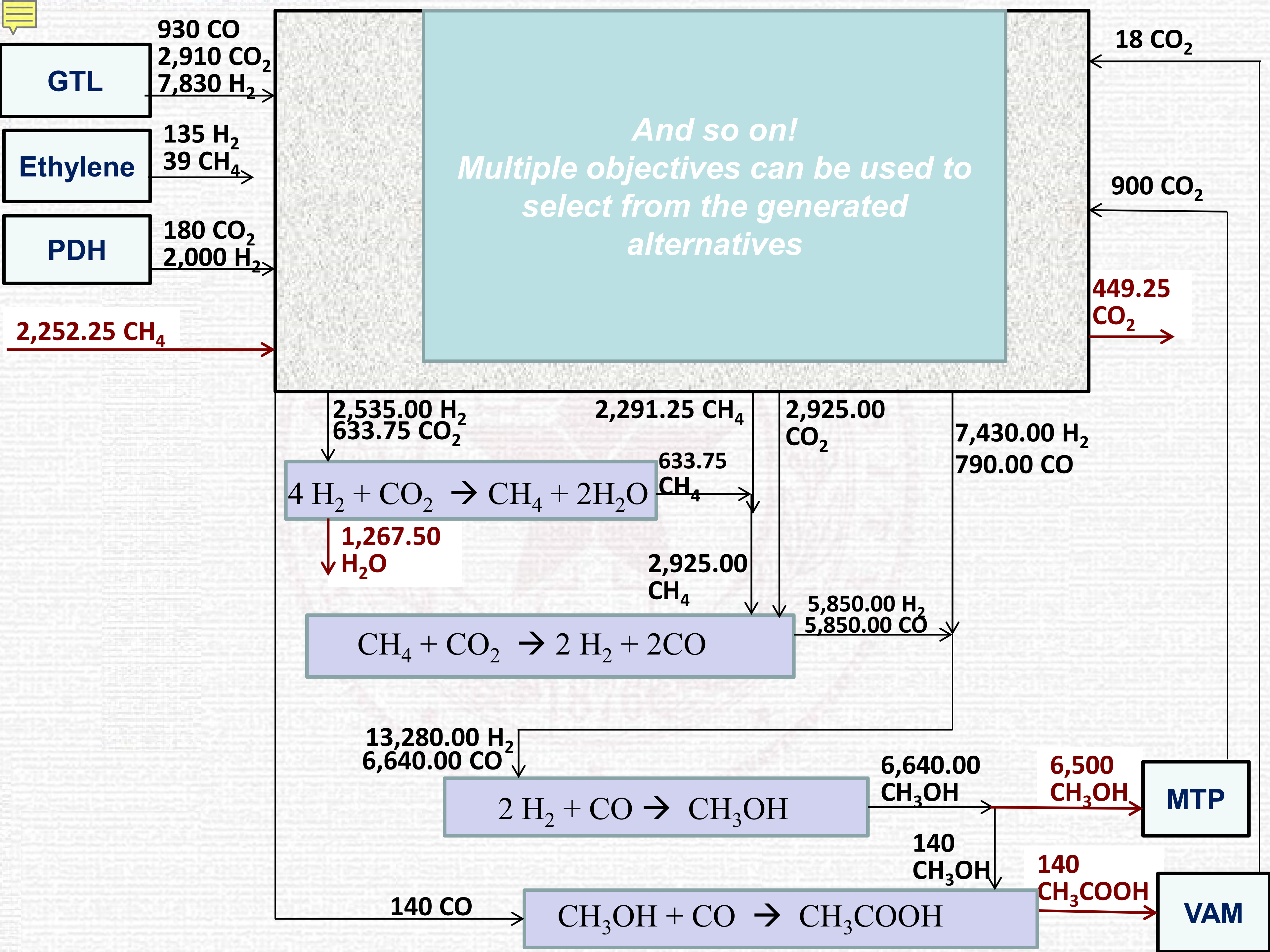


Examples of Implementation: Option 2



Examples of Implementation: Option 3




GTL
930 CO
2,910 CO_2
7,830 H_2
Ethylene
135 H_2
39 CH_4
PDH
180 CO_2
2,000 H_2
2,252.25 CH_4
And so on!
Multiple objectives can be used to select from the generated alternatives
18 CO_2
900 CO_2
449.25 CO_2
2,535.00 H_2
633.75 CO_2
2,291.25 CH_4
2,925.00 CO_2
7,430.00 H_2
790.00 CO
$4 H_2 + CO_2 \rightarrow CH_4 + 2H_2O$
633.75 CH_4
1,267.50 H_2O
2,925.00 CH_4
5,850.00 H_2
5,850.00 CO
$CH_4 + CO_2 \rightarrow 2 H_2 + 2CO$
13,280.00 H_2
6,640.00 CO
$2 H_2 + CO \rightarrow CH_3OH$
6,640.00 CH_3OH
6,500 CH_3OH
MTP
140 CH_3OH
140 CH_3COOH
140 CO
$CH_3OH + CO \rightarrow CH_3COOH$
VAM

Sample Categories of CHOSYN Synthesis

AIChE

Synthesis of C-H-O Symbiosis Networks

Mohamed M. B. Noureldin and Mahmoud M. El-Halwagi
:Ferrin Dept. of Chemical Engineering, Texas A&M University, College Station, TX 77843

DOI 10.1002/aic.14714

Process Integr Optim Sustain (2017) 1:3–13
DOI 10.1007/s41660-016-0001-y

ORIGINAL RESEARCH PAPER

A Shortcut Approach to the Multi-scale Atomic Targeting and Design of C–H–O Symbiosis Networks

Mahmoud M. El-Halwagi[1]

Process Integration and Optimization for Sustainability (2019) 3:199–212
https://doi.org/10.1007/s41660-018-0065-y

ORIGINAL RESEARCH PAPER

A Disjunctive Programming Approach for Optimizing Carbon, Hydrogen, and Oxygen Symbiosis Networks

Maricruz Juárez-García[1] · José María Ponce-Ortega[1] · Mahmoud M. El-Halwagi[2,3]

Contents lists available at ScienceDirect
ELSEVIER
Computers and Chemical Engineering
journal homepage: www.elsevier.com/locate/compchemeng

An anchor-tenant approach to the synthesis of carbon-hydrogen-oxygen symbiosis networks☆

Kevin Topolski[a], Mohamed M.B. Noureldin[b], Fadwa T. Eljack[c], Mahmoud M. El-Halwagi

Contents lists available at ScienceDirect
ELSEVIER
Chemical Engineering Science
journal homepage: www.elsevier.com/locate/ces

CO_2 footprint reduction via the optimal design of Carbon-Hydrogen-Oxygen SYmbiosis Networks (CHOSYNs)

Marc Panu[a], Kevin Topolski[a], Sarah Abrash[a], Mahmoud M. El-Halwagi[a,b,*]

Chemical Engineering & Processing: Process Intensification 141 (2019) 107535
Contents lists available at ScienceDirect
ELSEVIER
Chemical Engineering & Processing: Process Intensificatior
journal homepage: www.elsevier.com/locate/cep

M
T
F

Smart and Sustainable Manufacturing Systems

Rajib Mukherjee[1] and Mahmoud M. El-Halwagi[1,2]

DOI: 10.1520/SSMS20180022

Reliability of C-H-O Symbiosis Networks under Source Streams Uncertainty

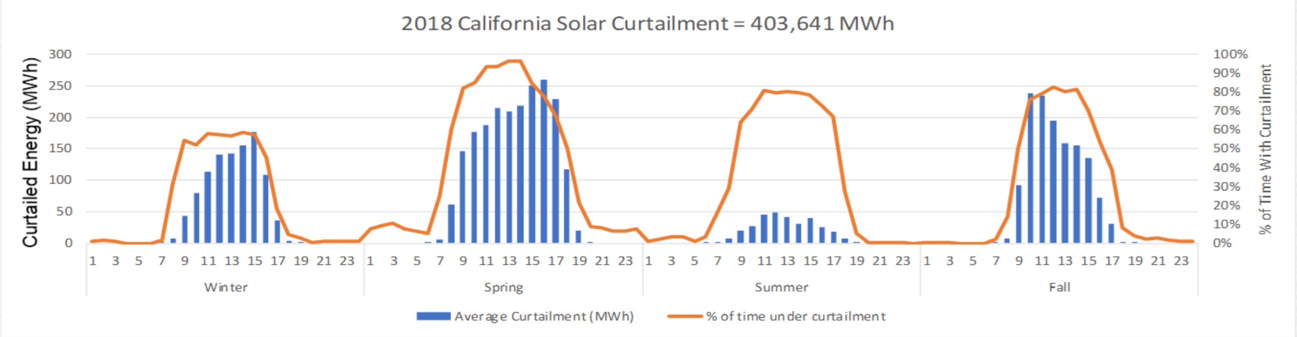
I&EC research
Industrial & Engineering Chemistry Research
Article
Cite This: Ind. Eng. Chem. Res. 2019, 58, 16761−16776
pubs.acs.org/IECR

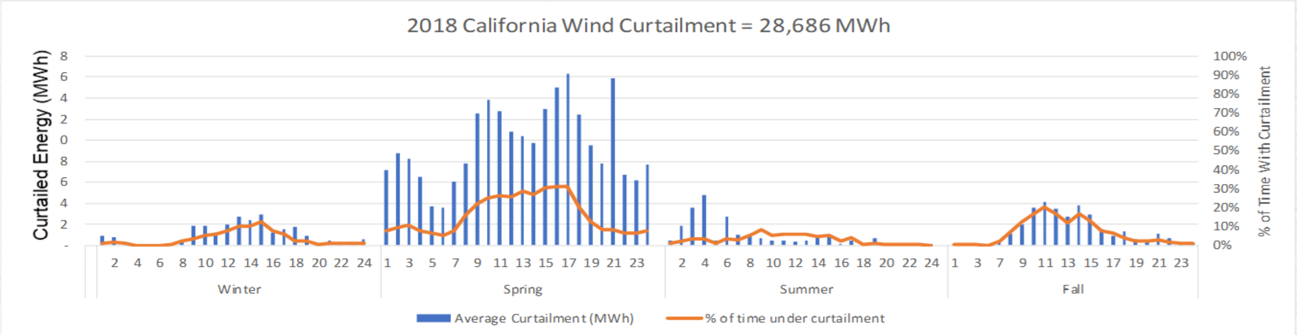
Integrating Mass and Energy through the Anchor-Tenant Approach for the Synthesis of Carbon-Hydrogen-Oxygen Symbiosis Networks

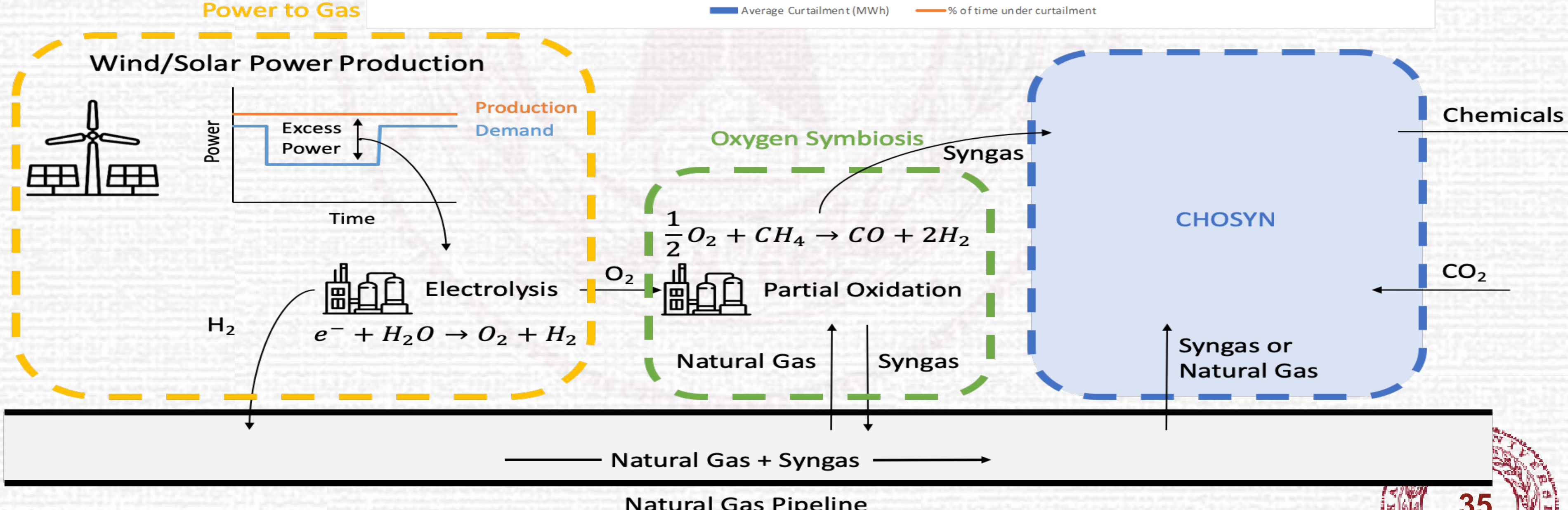
Kevin Topolski,[†] Luis Fernando Lira-Barragán,[‡] Marc Panu,[†] José María Ponce-Ortega,[‡] and Mahmoud M. El-Halwagi[*,†,§]

Curtailed Wind/Solar Energy Integration with CHOSYN (PtG)

"Curtailment of energy which is the activity of lowering the delivery of energy from a source (e.g., solar energy collector) to the electric grid. Curtailment may be driven by limited capacity of the grid, energy supply exceeding demand, and the desire to avoid unfavorable selling price of energy. "







Panu, M., Zhang, C., El-Halwagi, M.M., Davies, M. and Moore, M., 2021. Integration of Excess Renewable Energy with Natural Gas Infrastructure for the Production of Hydrogen and Chemicals. Process Integration and Optimization for Sustainability, pp.1-18.

OUTLINE

- Overview of Sustainable Design Through Multiscale Process Integration
- Application Examples:
  - Incorporation of renewables in energy integration and energy-water nexus
  - CO_2 monetization and reduction of carbon footprint for energy carriers and chemicals
- Use of Targets to Incorporate Sustainability in Decision Making

➔ Multi-scale Integration and Industrial Symbiosis

➔ **Contemporary Challenges and Future Directions**

Contemporary Challenges and Future Directions

- Process intensification and modular integration
- Scaleup of decarbonization technologies
- Integration of Renewable Energy and Creation of Global Chains of Energy Carriers
- Process Safety
- Disaster-Resilient Design

Process Intensification

- Reduce plant size for a given throughput
- Increase throughput (raw materials or products) for a given size of plant
- Reduce number of processing steps
- Increase performance of the process (as a whole):
  - Higher profit
  - Lower cost (CAPEX/OPEX)
  - Higher mass intensity (e.g., process yield, use of material utilities per unit product, less waste per unit product)
  - Higher energy intensity

Enhanced Sustainability

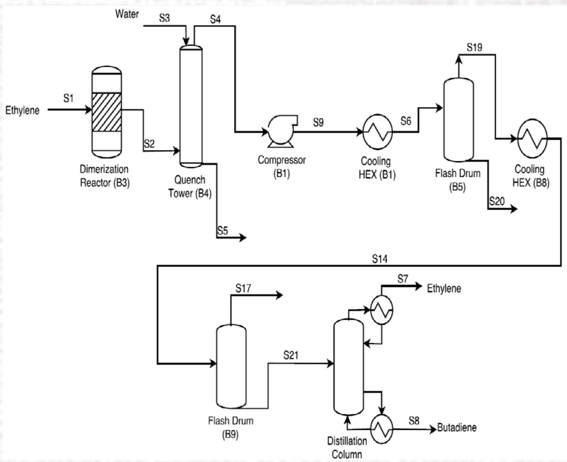
Reference: Ponce-Ortega, J. M., M. M. Al-Thubaiti, M., and M. M. El-Halwagi, “Process Intensification: New Understanding and Systematic Approach”, Chemical Engineering and Processing, 53, 63-75 (2012), DOI: 10.1016/j.cep.2011.12.010

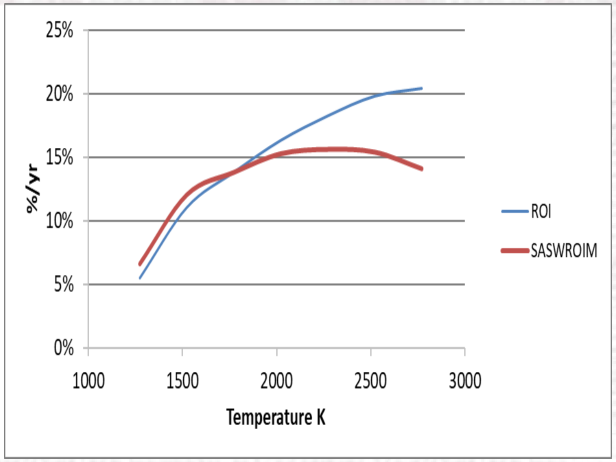
Process Safety: e.g., Sustainability and Safety Weighted Return on Investment Metric "SASWROIM"

- consider a set of process integration project alternatives: $p = 1,2,\ldots, N_{Projects}$.
- For the p^{th} project, a new term called the ***Annual Sustainability and Safety Profit* "*ASSP*"** is defined as follows

$$ASSP_p = AEP_P \left[1 + \sum_{i=1}^{N_{Indicators}} w_i \left(\frac{Indicator_{Base,i} - Indicator_{p,i}}{Indicator_{Base,i} - Indicator_{Target,i}} \right) \right]$$

$$SASWROIM_p = \frac{ASSP_P}{TCI_P}$$





Guillen-Cuevas, K., A. P. Ortiz-Espinoza, E. Ozinan, A. Jiménez-Gutiérrez, N. K. Kazantzis, M. M. El-Halwagi, "Incorporation of Safety and Sustainability in Conceptual Design via A Return on Investment Metric ", ACS Sustainable Chemistry and Engineering 6, 1411-1416 (2018)

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: http://www.elsevier.com/locate/jlp

Incorporating inherent safety during the conceptual process design stage: A literature review

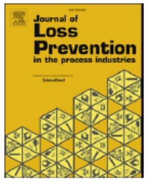
Sunhwa Park [a,b], Sheng Xu [b], William Rogers [a,b], Hans Pasman [a], Mahmoud M. El-Halwagi [a,b,c,*]

Journal of Loss Prevention in the Process Industries 67 (2020) 104261

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: http://www.elsevier.com/locate/jlp



Mitigation of operational failures via an economic framework of reliability, availability, and maintainability (RAM) during conceptual design

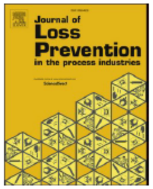
n [a,d,1], Mahmoud M. El-

Journal of Loss Prevention in the Process Industries 74 (2022) 104635

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp



Integrating flare gas with cogeneration system: Hazard identification using process simulation

Sankhadeep Sarkar [a,b], Noor Quddus [a,*], M. Sam Mannan [a,b], Mahmoud M. El-Halwagi [b]

Disaster-Resilient Design through Process Integration

12 principal strategies for creating disaster-resilient designs:

(1) Fail-safe by design

(2) Redundancy

(3) Reconfigurability

(4) Modularity/Mobility/Distributability

(5) Repurposability,

(6) Flexibility,

(7) Controllability,

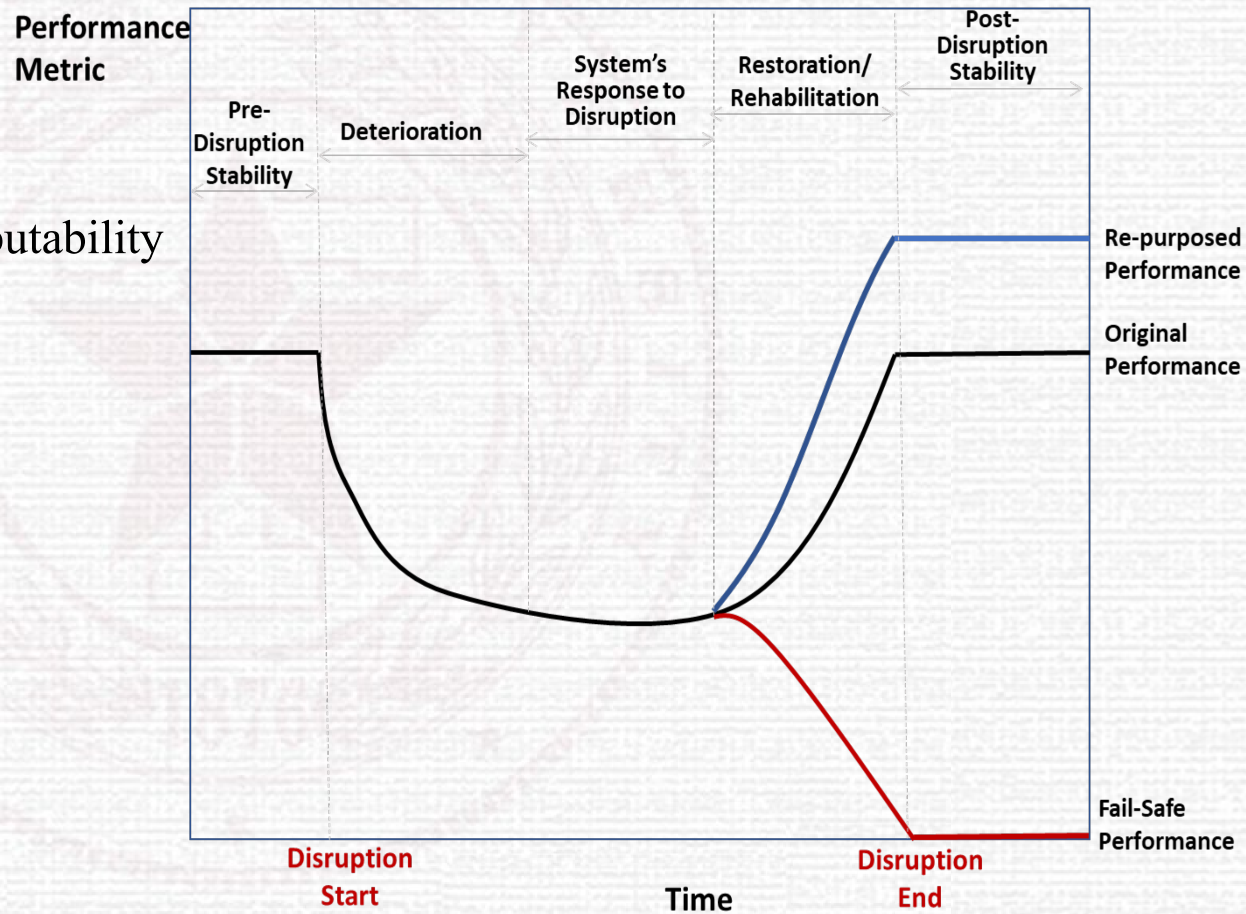
(8) Reliability,

(9) Recoverability/restorability,

(10)Rapidity,

(11)Robustness, and

(12)Resourcefulness.



El-Halwagi, M. M., D. Sengupta, E. N. Pistikopoulos, J. Sammons, F. Eljack, and M. K. Kazi, "Disaster-Resilient Design of Manufacturing Facilities Through Process Integration: Principal Strategies, Perspectives, and Research Challenges", Sustainable Chemical Process Design, Frontiers in Sustainability, 1:8 (2020). https://doi.org/10.3389/frsus.2020.595961

CONCLUDING THOUGHTS

- Effective decarbonization requires a systems approach

- Multi-scale system integration provides a powerful framework at atomic, unit, process, and macroscopic scales with multiple objectives

- Paradigm shift of integrating energy and monetizing CO_2 and other GHG gases creates exciting opportunities

Thank you!

Questions?