Integrated System Approach to Sustainability; Bio-fuels and Bio-refineries

Said S.E.H. Elnashaie
Quentin Berg University Chair Professor
of
Environmental and Sustainable Engineering
Pennsylvania State University at Harrisburg, USA
sse10@psu.edu

Presented by Tom Richard
Associate Professor of Agricultural and Biological Engineering
Director, Biomass Energy Center
Penn State University

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Main Topics

1- Sustainable Development: Multidisciplinary by Its Very Nature

2- Sustainable Engineering: A Subset of Sustainable Development

3- System Theory and the Integrated System Approach

4- Sustainable economy and the role of biomass efficient utilization

- Biomass and Bio-energy
- The matrix of biofuels

5.Multidisciplinary research, sequential de-bottlenecking, innovation and optimal configurations

6-Examples of Innovative Designs

- Hydrogen Reformers
- Bio-ethanol Fermenters
- Bio-diesel from biomass ++

7- Integrated Bio-Refineries (IBRs)

8- Heterogeneous Reactors & Bioreactors. The Heart of Bio-fuels Development.

- Principles of Pre-design Calculations
- Principles of Sizing
- From Sizing to Design
- Training Courses

1- Sustainable Development. Multidisciplinary by Its Very Nature

- **Main Components of Sustainable Development:**

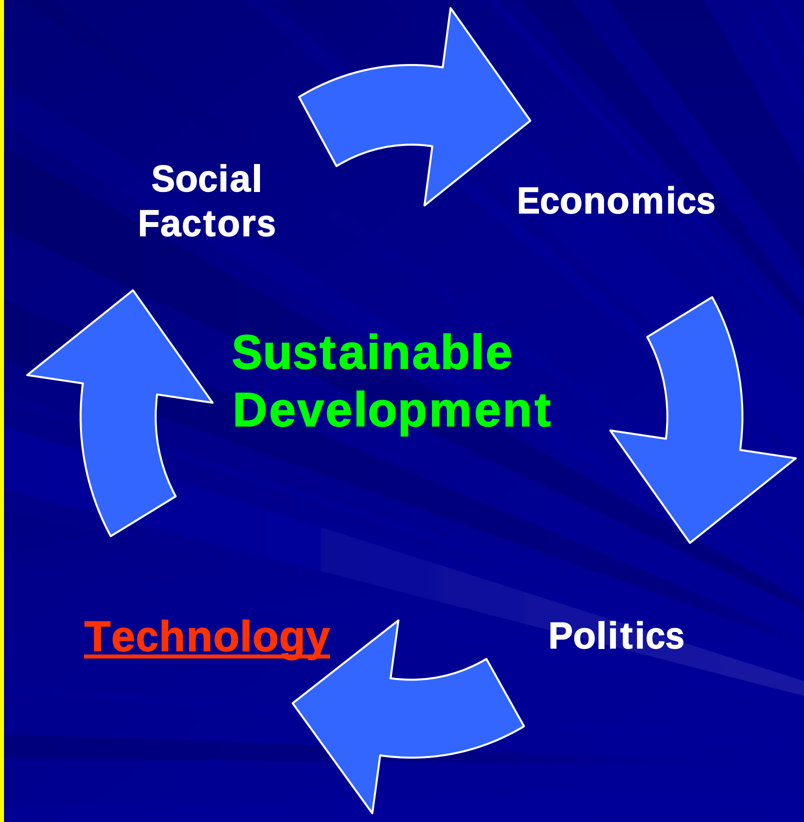
1- Political: e.g., legislations and strategic decisions…..

2-Economical: e.g., investment in novel new technologies……

3-Social: e.g., consumption Trends, acceptance of novel clean technologies and products...

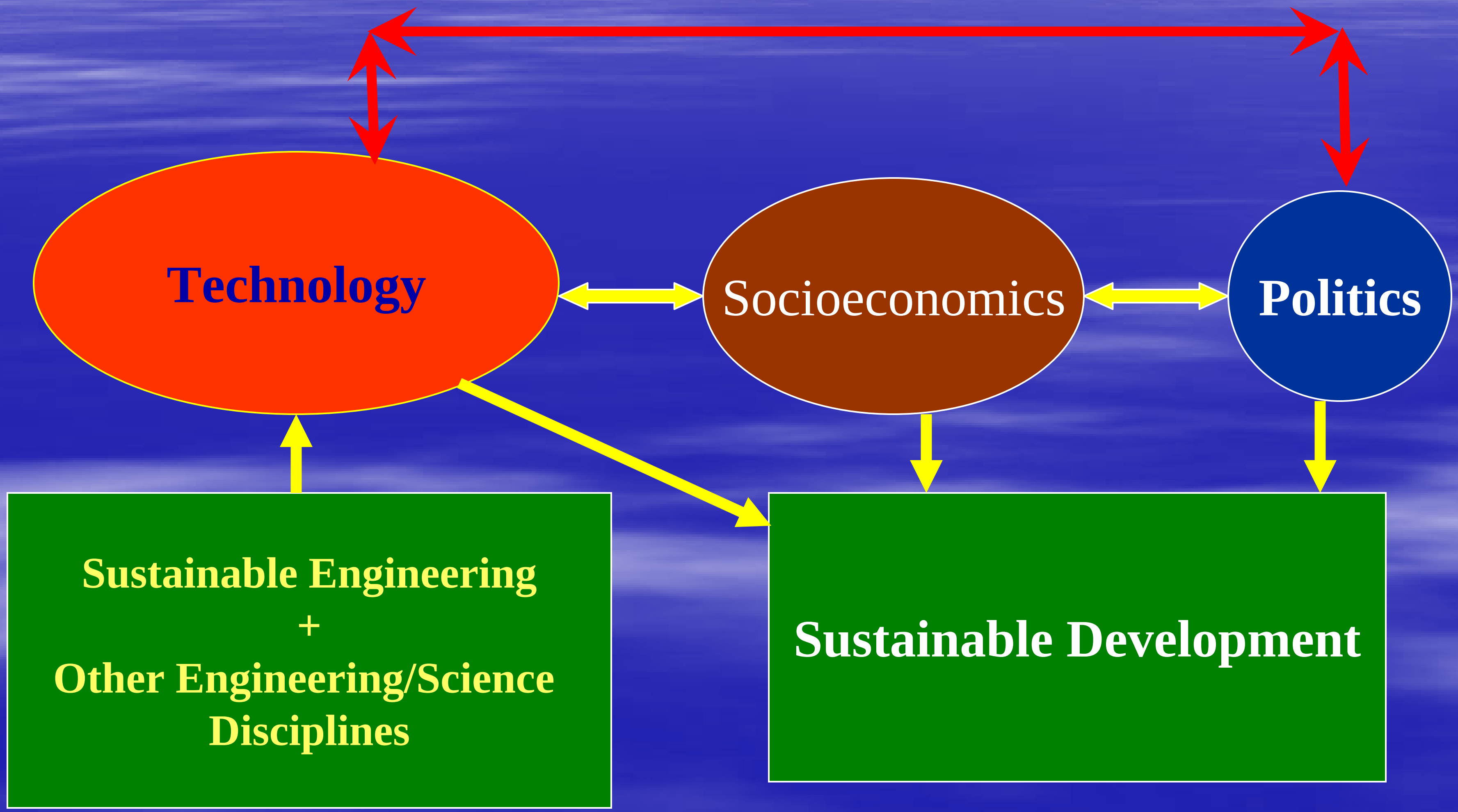
4-Technological: e.g., novel efficient clean technologies, clean fuels, efficient utilization of renewable feedstocks, new environmentally friendly products, In-process Modification for MPMP, efficient waste treatment…….

- **Ethical and Moral Factors (Don Brown's Book: *American Heat*, 2003)**



2-Sustainable Engineering Subset of Sustainable Development

As Engineers we Focus on Technology within the Frame Work of Other Components



Some Fundamental Principles

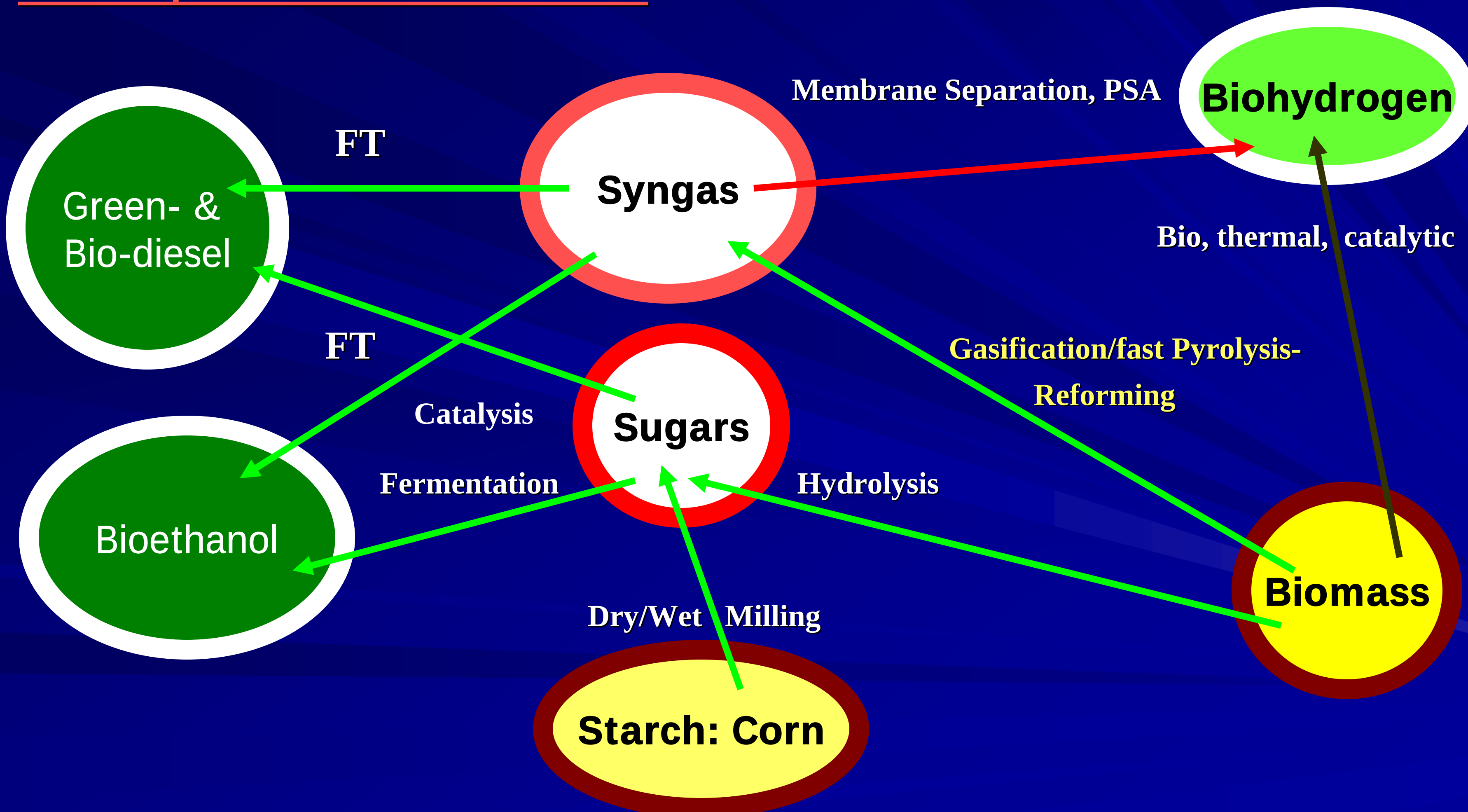
- **Sustainable Development Relies on Sustainable Engineering + other Socio-economical, Political and Moral/Ethical Factors**
- **Efficient Engineering is Necessary but Not Sufficient for Sustainable Engineering**
- **Clean Technology is Not Sustainable Technology**
- **Sustainability Depends Mainly Upon the Use of Sustainable Raw Materials**

3- System Theory and the Integrated System Approach

- Integrated System Approach (ISA) based on System Theory is the best to organize knowledge and exchange it.
- It depends on defining every system through its boundary, main processes within this boundary, exchange with the environment through this boundary and its subsystems/ elements
- Depends upon thermodynamics and information theory.
- Applicable to all kinds of systems which makes it most suitable for multidisciplinary investigations.

The matrix of biofuels

Bio= the process and/or the feedstock



5.Multidisciplinary research, sequential de-bottlenecking, innovation and optimal configurations

Integrated Biorefinery Research Should Be :

1- Multidisciplinary: different engineering and scientific disciplines as well as humanities.

2- Innovative: novel units and processes development utilizing sequential de-bottlenecking

3- Combined processes in single units, e.g., membrane reactors for breaking thermodynamic barriers.

4- Integrated designs, e.g., Integrated autothermal membrane coupled reactors

5- Utilization of fundamental research into applied research (e.g., Chaotic Fermenter)

6- Optimal combination of experimental and mathematical techniques

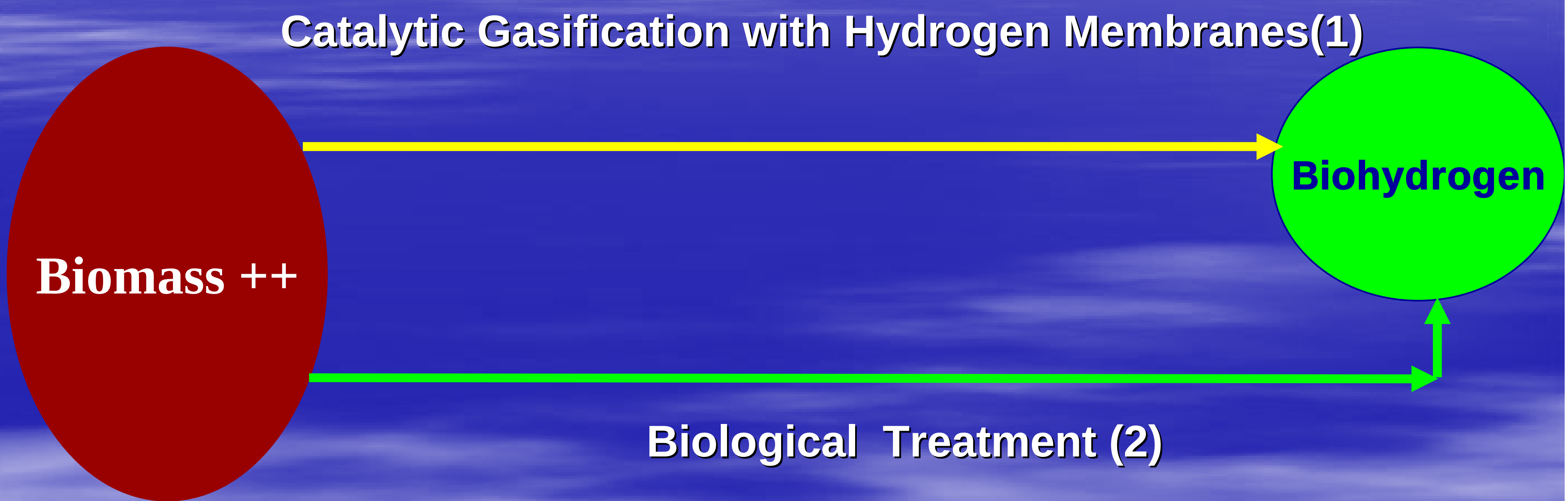
7- Close co-operation with industry

8- Minimum data collection (extensive utilization of published and industrial data)

6-Examples of Innovative Designs

- **Hydrogen Reformers**
- **Bio-ethanol Fermenters**
- **Bio-diesel from biomass ++**

Direct Biohydrogen



(1) **Elnashaie and co-workers**
(2) **Bruce Logan (Penn State), and co-workers**

Hydrogen. Membrane Fluidized Bed Reformers (MFBRs)

- **First Generation:** Inefficient Fixed Bed Reformers
- **Second Generation:** Bubbling Fluidized Membrane Reformer (Grace, Jim Lim Alaa Adris, Elnashaie,UBC)
- **Third Generation:** Circulating Fluidized Bed Membrane Reformer (Elnashaie, Chen, Pradeep, AU)
- **Further Developments for Third Generation:**

1. At UBC(Rakib, Andres, Grace, Jim Lim and Elnashaie)
2. At Penn State (Elnashaie, Ciocci, Issam and Abdelhady (Minnesota)

The success story of the "chaotic fermenter" for bioethanol

- **Basic idea is:**

1. **Operate fermenter dynamically (periodic/chaotic) at high feed sugar concentration.**
2. **Use pervaporation membranes to prevent inhibitory effect of ethanol and stabilize the fermenter.**

- **Said S.E.H.Elnashaie and Parag Garhyan, Chaotic Fermentation of Ethanol, US Full Patent #10/978,293 filled on 10/29/2004.Published 4th August 2005**
- **See a summary of the many mathematical and experimental papers in:**

Said Elnashaie and Parag Garhyan, "Bioethanol Production-Solving the Efficiency Bottleneck" The Chemical Engineer(tce), 755, May Issue, pp.30-32, 2004

- **Invention is product of PhD work of my student: Dr.Parag Garhyan (Now researcher with Lilly in Indianapolis). He won the award of the best PhD in Auburn University, 2004.**
- **Patent bought in March 2006 by investors.**
- **Investors formed a company, INFINOL, on this patent.**

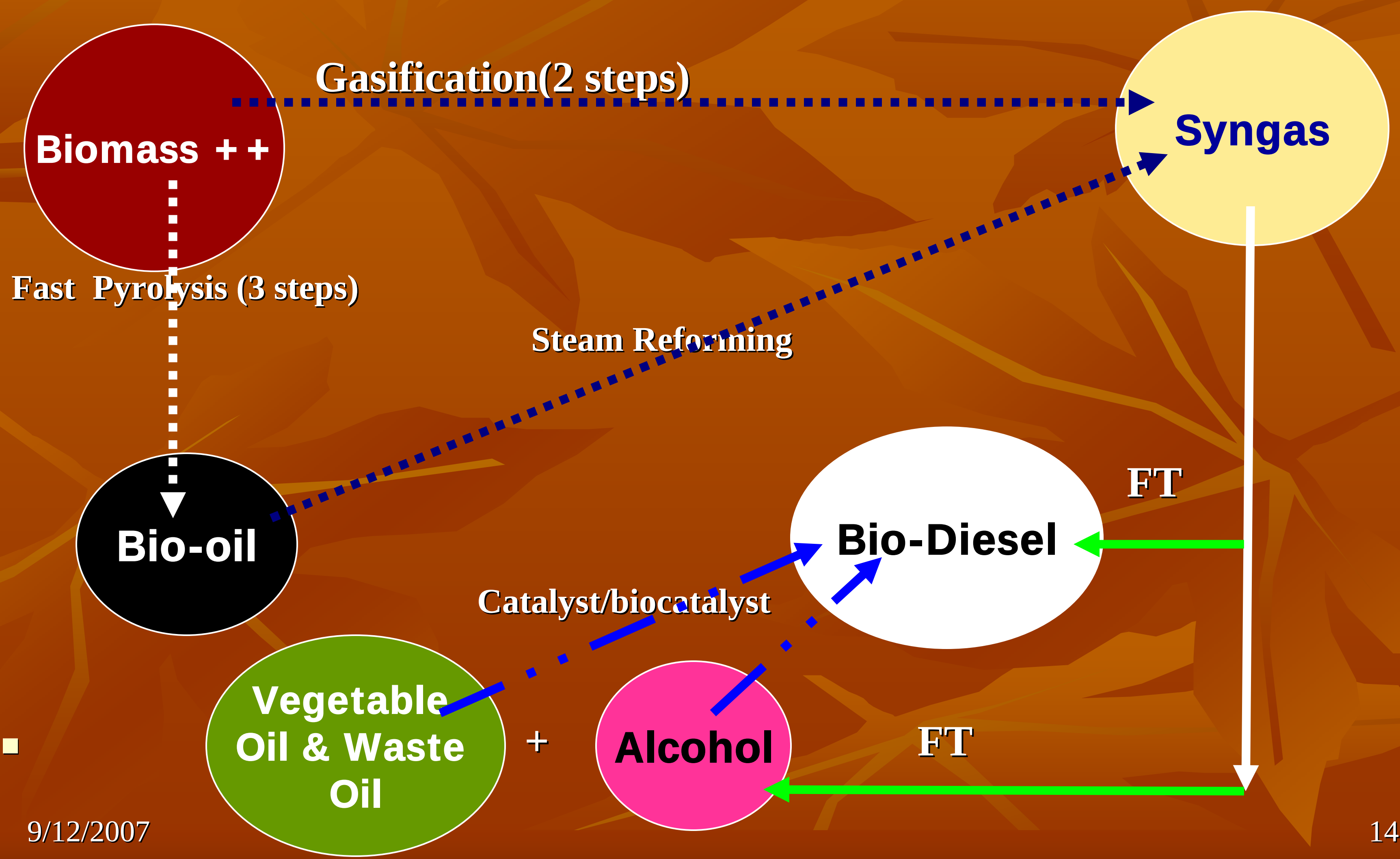
Much more improvement is still possible.

Biomass to Biodiesel Group (BMTBDG).
Penn State University, Harrisburg

The Multidisciplinary Group

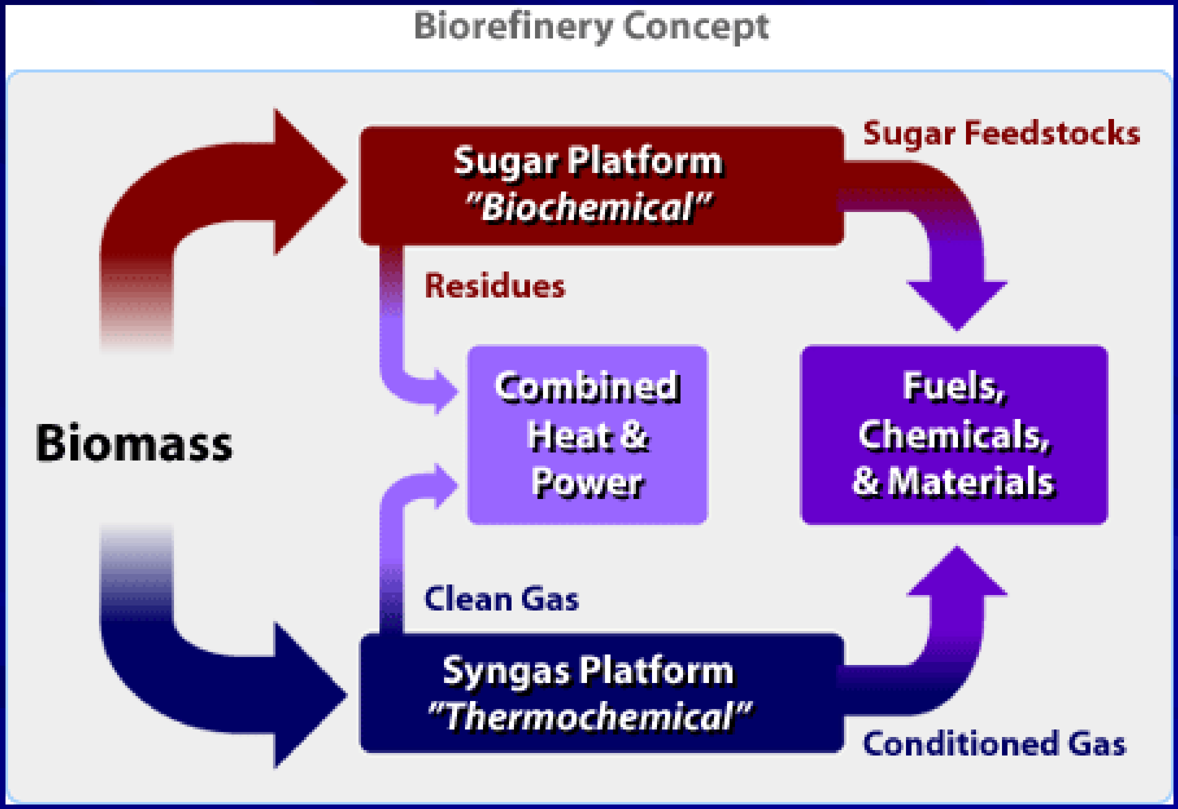
- Elnashaie (Chemical/Sustainable Engineering)
- Eberlein (Chemistry)
- Goel (Mechanical Engineering)
- Imadojemu (Mechanical Engineering)
- Funck (Project Management)

Compact Units for Biomass to Biodiesel and the Vegetable Oil Route



7- Integrated Bio-Refineries (IBRs)

- **Fuel is a major part of economy, but it is not all the economy.**
- **A biorefinery integrates biomass conversion processes to produce; fuels, power, and chemicals from biomass; as shown below (DOE):**



- **The biorefinery concept is analogous to today's petroleum refineries/petrochemical complexes, which produce multiple fuels and other products from petroleum.**

- **Industrial bio-refineries are the most promising route to the creation of a new domestic sustainable bio-based industry.**

- **Bio-fuel(s)(including bio-diesel) plants as nucleus for bio-refineries**

8- Heterogeneous Reactors & Bioreactors The Heart of Bio-fuels Development

- **Kinetics/bio-kinetics& Catalysis/bio-catalysis**
- **Mass and Heat Transfer**
- **Momentum Transfer**
- **Non-linear Coupling between all**
- **Reactor/bioreactor Configurations**
- **Optimization and Conceptual Optimization**
- **Role of R&D and cross-disciplinary research integrated in design and development.**
- **Innovation and sequential de-bottlenecking**

Principles of Pre-design Calculations

- Material and Enthalpy Balances for Heterogeneous Systems.
- Momentum Balances
- Mainly formulation and solution of non-linear algebraic equations and/or general software (e.g.: Hysis , Aspen,etc)

Principles of Sizing

- Transformation of materials and enthalpy balances into sizing equations(some times called design or modeling equations):

1. Lumped systems. (Formulation and solution of non-linear algebraic equations)
2. Distributed systems (Formulation and solution of non-linear Ordinary(initial value and boundary value) and Partial differential equations)

- Thermodynamic equilibriums and their limitations:

1. Reversible reactions
2. Mass and heat transfer between phases

- Software uses and limitations: from Hysis /Aspen to FEMLAB (COMSOL) and CFD (e.g.: Fluent).

From Sizing to Design

- Simplest is: sizing to dimensions(for given configuration and mode of operation)

- Examples of other design issues : Configuration, mode of operation, material(s) of construction, breaking of Th.D.E. barriers (e.g.: membrane reactors/ bioreactors), material and thermal integration (e.g.: membrane auto-thermal reactors), mixing, catalyst regeneration/recycle, biocatalyst immobilization, etc.

- Dynamics, stability and control.

- The strong relation between design/operation and R&D.

Next Generation Education?

A curriculum for integrated biorefinery engineering:

- Integrated System Approach (ISA) to Catalytic and Bio-catalytic heterogeneous systems.
- Molar and Enthalpy Balances and sizing equations for one phase and multiphase reacting systems.
- From sizing to design for catalytic and bio-catalytic heterogeneous reactors
- Dynamic behavior, stability and control of catalytic and bio-catalytic reactors.
- Training on software simulators, e.g.: Hysis , Aspen
- Training on software packages suitable for catalytic reactors, e.g.: FEMLAB (COMSOL)
- Training on CFD software packages, e.g.: Fluent
- Training on cross-disciplinary work (R&D, Design and operation).

Thank You

Said S.E.H. Elnashaie

sse10@psu.edu

Appendix:
Integrated Bio-Refineries (IBRs)

- **Basic Principles:**

Integrated bio-refineries is a very important concept. Both NSF and DOE are putting lots of research funds into development of bio-refineries. The present few bio-refineries are still very limited because of a limited understanding of bio-products. There are a number of basic principles that need to be very clear from the beginning:

1- Integrated Bio-Refineries (IBRs) is an integral critical part (subsystem) of Sustainable Development (SD), which is multidisciplinary system by its very nature (typical subsystems are: technology, politics, socio-economics, etc)

2- It is best to use Integrated System Approach (ISA) to study this complex multidisciplinary system and its subsystems.

3- We engineers are most interested in the technology part (subsystem of the SD system), but with a background understanding of other subsystems and collaboration with other disciplines.

4- It is very useful in another dimension to divide **SD** into **production SD** and **consumption SD**. This approach is strongly adopted by European researchers and helps to complete the picture regarding the relation between **IBRs** and **SD**

5- **S**ustainable **E**ngineering (**SE**) is the most important **subsystem** of the **technology** part (subsystem of **SD**) which is itself a subsystem of the **SD** system. So the sequence is: **SD** is a system, **Technology** is a subsystem of **SD** and **SE** is a subsystem of **Technology**.

6- **Efficient Engineering** is **necessary but not sufficient** for **clean technology**. In other words, it can give excellent yields and productivity but does not satisfy the requirements of **Environmental Engineering.**

7- **E**nvironmental **E**ngineering (**EE**) is a subsystem of **SE**, for the clear reason that very clean **technology** (environmentally perfect) may not be **sustainable** because **its raw materials are not sustainable(depletable).** Therefore **EE** is again necessary but not sufficient for **sustainability.**

8-These organizational principles show clearly the fact that efficient utilization of **R**enewable **R**esources (**RR**) is at the heart of **sustainability.**

9- **RR** should be defined very clearly, for it is strongly related to the cycle of renewability, i.e.: fossil fuels are renewable, but over a cycle of hundreds of thousands of years. **RR** should be renewable over a period of **6-18 months.**

10- **RR** can be any kind of renewable waste, e,g.: agricultural waste, municipal waste, etc or **special (energy) crops** produced specifically to be used for this purpose, e.g.: **switch-grass** cultivated and produced specially for **bio-fuels.**

11- Useful **agricultural products** used today for **bio-fuels**, e.g.: corn for ethanol; vegetable oil for trans-esterification bio-diesel, etc., are not strategic solutions for **R**enewable **F**uels**(RFs)** and **sustainability** because of its consumption of **important edible products** at a time of food shortage every where especially in developing nations.

12- **Bio-fuels** represent a subsystem of **RF**s, there are other subsystems, e.g.: wind energy, hydro energy, etc.

13- Although the interest in **bio-fuels** is dominating now because of energy and fuels problems especially in the Middle East (ME).We do not live only on fuels, other products and consumables should be sustainable.

14-**IBR**s should be able to contribute towards sustainability and not only renewable **bio- fuels**, although renewable **bio-fuels** represent essential parts of it.

15- It is important for IBRs to include all what is bio, whether with regard to feedstock, or processes or both, e.g.:

- Biomass utilizing sequential thermal catalytic processes to produce FT-bio-diesel(the processes are not bio, but the feedstock is bio)
- **Biological treatment of CO** and water to produce CO_2 and hydrogen(bio-catalyzed Water Gas Shift-WGS-reaction). The feed is not bio, but the process is bio).
- **Ligno-cellulose** utilizing sequential bi-processes to produce **cellulosic bio-ethanol**(both feedstock and processes are bio).
- Utilization of bio processes to transfer one form of energy to another, e.g.: **I**ntegrated **B**io-**E**lectrolysis coupled to **B**io-**F**uel-**C**ells(**IBE-BFCs**) to change **intermittent solar energy** into **continuous electric energy**, for many applications including **auto-thermal housing.**

16- IBRs can grow with time either as parts of existing plants (e.g.: Pulp and Paper Industry), or start as IBR based on renewable fuels production and grow into a complete IBR.

17- Other forms of **renewable fuels** (when suitable, e.g.: wind energy) can be integrated with the **bio-fuels** to generate the total renewable energy profile of an **IBR.**

18- The central intermediates for the **bio-fuels** part of the **IBR**s seem to be **fermentable sugars** suitable for fermentation to **bio-ethanol** and/or **bio-butanol** and **syngas** suitable for both **hydrogen** extraction and use in **FT** process for producing **fuels from methanol up to diesel.**

19-**Bio-diesel** can also be produced from the growth of **Algae** under favorable conditions for it which are not favorable for agriculture.

20-**Renewable biomass** the main **RR** is a storage tank for **solar energy** through **biosynthesis**;CO2 and other nutrients.

21-The ultimate aim for **bio-fuels** is to produce as much CO2 as consumed in the **biosynthesis** of the biomass that produced it. This with maximum efficiency may lead to the approach of **zero net CO2 emission.**

22- **We can not really dispose of any CO_2 resulting from fossil fuel,** it only keep circulating from one form/place to the other, except with **sequestration** by injection under the bottom of the oceans which is expensive; its side effects are not known and can only be practiced by very large companies. All other techniques just **move the CO_2 from one location/form to the other** without reducing the **earth CO_2 added inventory** from the carbon source that came from under the ground.

23- **Hydrogen is a good clean fuel** and will occupy its part in the clean fuels matrix. However, although **the claim that it is 100% clean is locally true** ; it is **actually not globally true** if its source is **fossil fuel**, whether directly through catalytic steam reforming (95% of hydrogen produced in USA is through catalytic steam reforming) or indirectly through production of electricity (90% of electricity in the USA is from Coal) followed by electrolysis. It can only be globally clean only if the source is bio, nuclear, wind, hydro, etc.

24- Direct utilization of **solar energy** through different direct techniques (e.g.: **photocells**) without passing through the **biosynthesis** stage is a possibility, but it has its own bottlenecks.

25- The range of **fermentable sugars** is expanding due to the development in microbiology and the discovery of efficient mutated microorganisms capable of fermenting the wide range of sugars produced from cellulose/hemi-cellulose hydrolysis.

26- A strong challenge with lots of intensive research nowadays is in the field of **efficient and clean hydrolysis of cellulose/hemi-cellulose,** important improvements are achieved in the enzymatic hydrolysis of cellulose/hemi-cellulose.

27-The process of fermentation is improving continuously using **novel membrane immobilized fermenters and novel modes of operation.**

28- **Lignin** from Ligno-cellulose is used as a cheap fuel to improve the energy efficiency of the **IBRs**, however the future potential is to use it as a **platform for a wide range of products to** replace certain petroleum refining and petrochemical products.

29-Important improvement are introduced to **syngas** production from biomass through both one step process (biomass gasification to **syngas**) and two step process(biomass fast pyrolysis to **bio-oil** followed by **C**atalytic **S**team **R**eforming[**CSR**] of **bio-oil** to **syngas**). The two steps process seems to better with regard to the **% of H2** in the **syngas**.

30- Certain difficulties associated with **CSR** of bio-oil are solvable through novel reformers configurations such as **C**irculating **F**luidized **B**ed(**CFB**) reformers

31-An important challenge in the biomass to **FT-bio-fuels process** is the integration of the endothermic **CSR** process with the exothermic catalytic **FT** process into **one integrated membrane catalytic auto-thermal process.**

32- The choice of bio-fuels is strongly **location sensitive** and is also affected by many other factors including, but not limited to, available capital investment, size of market, etc.

33- For the same **bio-fuel** the technology to be used also depends upon the above factors and others.

34- From the above it is clear that no single bio-fuel, nor one technology will dominate. We will move from today's **matrix of dirty fuels** to a future **matrix of clean fuels** with the sub-matrix of **different bio-fuels** from **different technologies** occupying a large portion of the **clean fuels matrix**.