Thermodynamic Analysis of Industrial Ecological Systems

Bhavik R. Bakshi
Department of Chemical & Biomolecular Engineering
The Ohio State University, Columbus, OH 43210
Why Thermodynamics?

- Thermodynamics governs the behavior of all systems

  - Energy available for doing useful work (exergy) is the ultimate limiting resource
  - Provides **common currency** for the joint analysis of industrial and ecological systems
  - Relevant for assessing static and dynamic properties
The Concept of Exergy

- Exergy is energy available for doing useful work

\[ B = \Delta \left( H - T_0 S + \frac{v^2}{2} + zg \right) \]

- Measures distinguishability or thermodynamic distance from surroundings
- Captures first and second laws of thermodynamics
- Energy is not conserved - neither created nor destroyed
- Exergy is always lost
- Types of exergy - thermal, chemical, kinetic, potential, ...
Exergy and Life Cycle Assessment

- LCA focuses on inventory of emissions and their impact
  - Output-side method
  - Extremely data intensive
  - Multidimensional results
  - Ignores quality of resource consumption and contribution of ecosystem goods and services

- Exergy analysis focuses on material and energy inputs
  - Input-side method
  - Input data are often easier to obtain than output data
  - Scientifically rigorous approach for combining all types of material and energy streams
  - Can account for resource quality and ecosystems
Material and Energy Flow - NH₃ Process

- Inputs and outputs are available in different units

- Difficult to:
  - Combine disparate units
  - Capture quality of resources
  - Identify opportunities for improvement

- Exergy analysis can overcome these challenges

Maples, 2000; Morris, 1991; DOE, 1997; Shreve et al., 1977; Szargut et al., 1988; Odum, 1986
Ammonia Process - Exergy Flow

- Captures material and energy in consistent units
- Accounts for first and second laws
- Ignores life cycle

\[ \text{Exergy Flow (MW)} \]

\[ C_p = 436 \text{ MW} \]

\[ \eta_p = 52\% \]

Maples, 2000; Morris, 1991; DOE, 1997; Shreve et al., 1977; Szargut et al., 1988; Odum, 1986
**Industrial Cumulative Exergy Consumption (ICEC)**

- Considers processes from natural resources to products
  
  \[ C_{p,j} = \sum B_{n,j} \]

- Cumulative Degree of Perfection,
  
  \[ ICDP = \frac{\text{Exergy of products}}{\text{Cumulative exergy of products}} \]

- Shortcomings
  - Ignores ecological goods and services
  - Ignores impact of emissions
  - Narrow boundary (Process LCA)

- Sustainability requires joint consideration of industrial and ecological systems

---

Szargut et al., *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, 1988
Ecological CEC (ECEC)

- Expands ICEC to include ecosystems
- Accounts for exergy consumed by ecosystem processes needed to make natural resources
- Thermodynamic analysis of many natural processes is available
- Can become equivalent to emergy analysis without relying on its controversial aspects

Thermodynamic Model of IE Systems

Solar Energy → Crustal Energy → Tidal Energy

**Ecosystem**
- Lithosphere
- Atmosphere
- Biosphere
- Hydrosphere

**Economy**
- Natural Resources as raw materials
- Ecosystem services for dissipation, ecosystem impact
- Emission
- Impact of emission on human health
- Final Demand
- Value Added

**Human Resources**
- Consumption of natural resources (O₂ in air)
- Emissions (CO₂ in respiration)
- Ecosystem impact due to anthropogenic emissions

**Emergy Analysis**

**LC Impact Analysis**

Natural vs. Economic Throughput in Supply Chains

Increasing economic prosperity
environmental load

Major Subdivisions of U.S. economy
- Mining, Utilities
- Basic Manufacturing
- Advanced Manufacturing
- Service Industry
Application to Electricity LCA

- Considered electricity from Coal, Hydro, Wind, Geothermal, Natural Gas, Oil
- Traditional LCA indicates following order in terms of increasing life cycle impact
  - Hydro
  - Wind
  - Geothermal
  - Natural Gas
  - Oil
  - Coal
- Performed ThermoLCA at different scales
Hybrid ThermoLCA at Different Scales
- Electricity Generation

**Exergy Anal.**

**ICDP**
- Economy Scale

**ECDP**
- Ecosystem Scale

**Ecosystems**

**Process**

**Economy**

---

**Exergetic Efficiency**
- Process Scale

**Hydro**

**Wind**

**Geo**

**NG**

**Oil**

**Coal**

---

**Hydro**

**Wind**

**Geo**

**NG**

**Oil**

**Coal**

---

**Hydro**

**Wind**

**Geo**

**NG**

**Oil**

**Coal**

---

**Hydro**

**Wind**

**Geo**

**NG**

**Oil**

**Coal**

---

**Hydro**

**Wind**

**Geo**

**NG**

**Oil**

**Coal**

---

**Hydro**

**Wind**

**Geo**

**NG**

**Oil**

**Coal**

---

**Hydro**

**Wind**

**Geo**

**NG**

**Oil**

**Coal**

---
Conclusions & Future Work

- ThermoLCA can complement traditional LCA
- Attractive when output-side information is not easily available
  - Emerging technologies
  - Streamlined LCA
- Hypothesis for ThermoLCA
  - Between alternatives for making the same product or service, the one with a higher ECDP has a smaller life cycle environmental impact
- Relevance of exergy to SOHO systems, resilience