Integrated Hybrid Life Cycle Optimization for Multi-Scale Sustainability Analytics of Energy Systems

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3rd SEE SDEWES, Novi Sad, July 2018
Environmental Sustainability Issues
Life Cycle Analysis (LCA) – “Cradle to Grave”
Life Cycle Analysis (LCA)

- Quantifying environmental impacts of complex systems
- Modeling the entire product/process life cycle
- Holistic view of the system
Life Cycle Optimization (LCO)

Integrating life cycle analysis approach with multi-objective optimization techniques

Life Cycle Analysis

PHASE I
Goal and Scope

PHASE II
Inventory Analysis

PHASE III
Impact Assessment

PHASE IV
Interpretation

Multi-Objective Optimization

Automatic alternative generation and improvement

Pareto frontier
Suboptimal solutions

Economic objective

Environmental objective

Life Cycle Optimization
Life Cycle Optimization: Theory and Methods

• **Life Cycle Optimization**
  - Life Cycle Analysis + Techno-economic Analysis + Design Optimization

• **Research Challenges**
  - How to **seamlessly** integrate LCA into process systems optimization?
  - How to define the “optimal” systems boundary and functional unit?
  - How to incorporate state-of-the-art inventory analysis methods in LCO?
  - How to deal with uncertainty and solve large-scale LCO problems?
• Systems boundary must be defined in Phase I of LCA
• Functional unit serves as the basis for calculation and comparison
• **Algae**
  - Microalgae, cyanobacteria, & macroalgae
  - Non-food; high yield; rich in oil

• **Algae-based biorefinery**
  - Consume and utilize CO$_2$; recycle nutrients & water
  - Produce fuels and value-added products
  - **Process economics? Environmental sustainability?**

• **Chlorella Vulgaris**

**Motivation**

**Biofuels**

**Bioproducts**
Algal Biorefinery Process Design and Optimization

• Optimal design and synthesis of algal biorefinery
  • Selection of technology, pathway, and processing methods
  • Determination of product portfolio under the given feed
  • Recycling nutrients, water and carbon dioxide
  • Mass balance, capacity, and equipment sizing
  • Energy and utility consumption
  • Process economics → Techno-economic analysis
  • Environmental sustainability → Life cycle analysis
  • Cost-effective & sustainable design
Superstructure of Algae Process

- Cultivation
- Harvesting
- Lipid extraction
- Biogas utilization
- Remnant treatment
- Biofuel production
- Bioproduct manufacturing
- Hydrogen
- Propylene glycol
- Glycerol-tert-butyl ether
- Poly-3-hydroxybutyrate
- Biodiesel
- Diesel
Superstructure of Algae Process

- **<1,2> Flat plate photobioreator**
- **<1,3> Bubble column photobioreator**
- **<1,4> Tubular photobioreator**

7,800+ processing pathways
Optimization Model: Constraints for ONE Unit

Mass and material balance
Process network design specifications
Technology and pathway selection
Equipment sizing and capacity

Energy balance
Utility consumption

Techno-economic analysis

Life cycle environmental impact analysis
**Objectives:**

- **Minimize:** Unit cost of fuel product ([techno-economic analysis](#))
  - CAPEX + OPEX
  - Credit from selling by-products (glycerol, fertilizer, biogas, …)
- **Minimize:** Unit life cycle GHG emission ([life cycle analysis](#))
  - Direct emissions: Cultivation, remnant treatment, & utility generation
  - Indirect emissions: External utility, e.g. electricity and steam, …

Systems boundary and life cycle stages of LCA.
Pareto Optimal Curve

Minimum unit GWP

Suboptimal region

1 cost ($/GGE)

12

11

10

9

8

Flue gas

Open pond

Flocculation with poly-γ-glutamic acid

Storage tank

Recycling water

Purge

Remnant treatment

HTL

HZSM-5-catalyzed hydroprocessing

Natural gas

Fired heater

Steam boiler

Off-gas

Fertilizer

Renewable diesel

Fertilizer

Gas product
Pareto Optimal Curve

Flue gas → Open pond → Flocculation with polyelectrolyte → Pressure filtration → Storage tank

Recycling water → Purge

Off-gas → Remnant treatment

Butanol extraction → Sodium-methoxide-catalyzed transesterification

Biodiesel → Glycerol

Unit annualized:

Infeasible region

Minimum unit annualized cost
Superstructure of Algae Process

Cultivation

Harvesting

Lipid extraction

Biofuel production

Bioproduct manufacturing

Remnant treatment

Biogas utilization

17
# Optimal Design of Minimum Unit Biofuel Cost

<table>
<thead>
<tr>
<th>Unit cost of biofuel ($/GEG)</th>
<th>Unit GHG emissions (kg CO$_2$-eq/GEG)</th>
<th>Biodiesel Throughput (million GGE)</th>
<th>Bioproduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.79</td>
<td>7.21</td>
<td>47</td>
<td>Propylene glycol</td>
</tr>
</tbody>
</table>

| 2.71 – 3.78                     | 14.43                                   | Petroleum-derived diesel           |
Alternative bio-based propylene glycol is derived from soybean by ADM(R).
Value-Added Chemicals from Microalgae: Greener, More Economical, or Both?

Jian Gong and Fengqi You*

Department of Chemical and Biological Engineering, Northwestern University, 2145 Sheridan Road, Evanston, Illinois 60208, United States

Supporting Information

ABSTRACT: This paper addresses the sustainable design and synthesis of manufacturing processes for making algal bioproducts. We propose by far the most comprehensive superstructure capable of producing biodiesel, hydrogen, propylene glycol, glycerol-tert-butyl ether, and poly-3-hydroxybutyrate from microalgae. The major processing sections include cultivation, harvesting, lipid extraction, remnant treatment, biogas utilization, biofuel proneduction, and bioproduct manufacturing. On the basis of the superstructure, we integrate a cradle-to-gate life cycle analysis and techno-economic analysis with multiobjective optimization to simultaneously optimize the environmental and economic performance. We also apply a tailored global optimization algorithm to efficiently solve the problem in reasonable computation times. Results show that the most environmentally sustainable processes reduce life cycle greenhouse gas emissions per kilogram of the algal bioproducts by 5% to 63%, compared with petrochemical counterparts. In addition, the coproduction of value-added bioproducts in the algal glycerol process helps reduce the biodiesel production cost to as low as $2.79 per gasoline-gallon-equivalent.

KEYWORDS: Life cycle analysis, glycerol, bioproduct, algal biofuels, global optimization
Alternative approaches for Life Cycle Inventory (LCI) analysis

- Process-based LCA (most widely used)
- Economic Input-Output (EIO)-based LCA (for macroscopic analysis)
- Hybrid LCA (state of the art)
Process-based LCA

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Bottom Up</td>
</tr>
<tr>
<td>Scope</td>
<td>Selected Processes</td>
</tr>
</tbody>
</table>

Process system boundary

Detailed process inventories
EIO-based LCA

Process-based | EIO-based
---|---
Resolution | Process | Sector
Construction | Bottom Up | Top Down
Scope | Selected Processes | Entire Economy

Transactions among sectors
Entire macroeconomy

Sectors:
Agriculture, mining, construction, manufacturing, wholesale trade, retail trade, transportation, etc.
Integrated Hybrid LCA

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Process</th>
<th>Sector</th>
<th>Process (foreground) Sector (background)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Bottom Up</td>
<td>Top Down</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Scope</td>
<td>Selected Processes</td>
<td>Entire Economy</td>
<td>Entire Economy</td>
</tr>
</tbody>
</table>

**Process-based**

**EIO-based**

**Integrated Hybrid**
Process-based LCA

Drawbacks:
• System boundary truncation
• Underestimation of the true impact

Advantage:
• Specificity of process analysis
EIO-based LCA

Drawbacks:
• Loss of precision at process level

Advantage:
• Completeness of life cycle boundary
Integrated Hybrid LCA

Integrates process- and IO-based LCA

Advantages:
• Completeness of life cycle boundary
• Specificity of foreground processes
Toaster Example

Comparing two toasters
(Functional unit: produce 1,000 pieces of bread)
Toaster Example
Toaster Example

Direct emission (process system)

![Graph showing Life Cycle CO₂ Emission (kg) for Toaster A and Toaster B]

- **Toaster A**: 18.7 kg
- **Toaster B**: 17.7 kg

Legend:
- **Steel**
- **Electricity**
- **Toaster**
- **Toaster use**
- **Waste disposal**
- **Agricultural products**
- **Mining products**
- **Manufacturing products**
- **Construction**
- **Financial services**
- **Other products and services**
Toaster Example

Full emission (process + IO systems)

Neglected indirect emission (IO system)

Direct emission (process system)
Integrated Hybrid LCA:

- Explicit process analysis – foreground process systems (precision of analysis)
- EIO analysis – background macroeconomic systems (complement the truncated system boundary)
Mathematical Foundation

\[ E_p \]  Environmental extension factor (process systems)

\[ A_p \]  Process matrix

\[ C_u \]  Upstream cutoff matrix

Total environmental impact = \[
\begin{bmatrix}
E_p & E_{io}
\end{bmatrix}
\begin{bmatrix}
A_p & -C_d \\
-C_u & I - A_{io}
\end{bmatrix}^{-1}
\begin{bmatrix}
y \\
0
\end{bmatrix}
\]

\[ E_{io} \]  Environmental extension factor (EIO systems)

\[ A_{io} \]  Direct requirements matrix

\[ C_d \]  Downstream cutoff matrix
Application to Shale Gas

- Unconventional natural gas from shale rocks
- Large-scale production due to hydraulic fracturing and horizontal drilling
- Half of the NG production in the U.S.
- Over 63,000 shale wells in the U.S.

U.S. natural gas production
Hybrid LCA of Shale Gas

- Climate change

- Water consumption

- Energy consumption
Goal and scope

- UK shale gas
- System boundary: well-to-wire
- Functional unit: 1 MWh electricity generation from shale gas

Life cycle inventory

- 40 basic processes in the process systems
- Two-region IO model (UK-ROW) with 224 industrial sectors
- Three cases from literature: best, balance, and worst cases corresponding to the lowest, the medium, and the highest environmental impacts

Impact assessment

- GHG emissions (100-year GWP factors; CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆)
- Water consumption
- Energy consumption
<table>
<thead>
<tr>
<th>Process ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>Steel production, converter, chromium steel 18/8</td>
</tr>
<tr>
<td>m2</td>
<td>Concrete production, for civil engineering, with cement CEM I</td>
</tr>
<tr>
<td>m3</td>
<td>Tap water production, direct filtration treatment</td>
</tr>
<tr>
<td>m4</td>
<td>Diesel production, low-sulfur</td>
</tr>
<tr>
<td>m5</td>
<td>Diesel, burned in building machine</td>
</tr>
<tr>
<td>m6</td>
<td>Diesel, burned in diesel-electric generating set, 18.5kW</td>
</tr>
<tr>
<td>m7</td>
<td>Barite production</td>
</tr>
<tr>
<td>m8</td>
<td>Bentonite quarry operation</td>
</tr>
<tr>
<td>m9</td>
<td>Chemical production, inorganic</td>
</tr>
<tr>
<td>m10</td>
<td>Chemical production, organic</td>
</tr>
<tr>
<td>m11</td>
<td>Lignite mine operation</td>
</tr>
<tr>
<td>m12</td>
<td>Treatment of inert waste, inert material landfill</td>
</tr>
<tr>
<td>m13</td>
<td>Treatment of drilling waste, landfarming</td>
</tr>
<tr>
<td>m14</td>
<td>Silica sand production</td>
</tr>
<tr>
<td>m15</td>
<td>Petroleum refinery operation</td>
</tr>
<tr>
<td>m16</td>
<td>Isopropanol production</td>
</tr>
<tr>
<td>m17</td>
<td>Hydrochloric acid production, from the reaction of hydrogen with chlorine</td>
</tr>
<tr>
<td>m18</td>
<td>Ethylene glycol production</td>
</tr>
<tr>
<td>m19</td>
<td>Potassium chloride production</td>
</tr>
<tr>
<td>m20</td>
<td>Carboxymethyl cellulose production, powder</td>
</tr>
<tr>
<td>m21</td>
<td>Soda ash, dense, to generic market for neutralizing agent</td>
</tr>
<tr>
<td>m22</td>
<td>Sodium persulfate production</td>
</tr>
<tr>
<td>m23</td>
<td>Sodium borates production</td>
</tr>
<tr>
<td>m24</td>
<td>Citric acid production</td>
</tr>
<tr>
<td>m25</td>
<td>Pesticide production, unspecified</td>
</tr>
<tr>
<td>m26</td>
<td>N, N-dimethylformamide production</td>
</tr>
<tr>
<td>m27</td>
<td>UK electricity generation, with mixed energy inputs</td>
</tr>
<tr>
<td>m28</td>
<td>Transport, freight, lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified</td>
</tr>
<tr>
<td>m29</td>
<td>Injection in disposal well</td>
</tr>
<tr>
<td>m30</td>
<td>Wastewater treatment by CWT</td>
</tr>
<tr>
<td>m31</td>
<td>Onsite treatment with MSF</td>
</tr>
<tr>
<td>m32</td>
<td>Onsite treatment with MED</td>
</tr>
<tr>
<td>m33</td>
<td>Onsite treatment- with RO</td>
</tr>
<tr>
<td>m34</td>
<td>Steam production, in chemical industry</td>
</tr>
<tr>
<td>m35</td>
<td>Tap water production, direct filtration treatment</td>
</tr>
<tr>
<td>m36</td>
<td>Transporting gas through pipelines</td>
</tr>
<tr>
<td>m37</td>
<td>Ethanolamine production</td>
</tr>
<tr>
<td>m38</td>
<td>Ethylene glycol production</td>
</tr>
<tr>
<td>m39</td>
<td>Fugitive emissions of CO2</td>
</tr>
<tr>
<td>m40</td>
<td>Fugitive emissions of CH₄</td>
</tr>
</tbody>
</table>
Hybrid LCI Data Structure

**IO System** (896 × 896 matrix)
- Multi-region: UK and ROW (rest of world)
- Supply-Use Table (SUT): each containing 224 industrial sectors/products
LCA Results

- Electricity generation
- Transportation

- Drilling
- EIO system

- Electricity generation
- Processing

CO₂
Comparison with Existing Hybrid LCA Studies

- GHG emissions of shale gas are comparable to those of natural gas
- Less GHG emissions than Coal and Oil
Definition: *Activity* is a flexible process that involves decision making.

Hybrid LCO Model for Shale Gas

Economic objective:
\[
\min LCOE = \frac{TC_{cap} + \sum_{t \in T} \frac{TC_{oper}}{(1 + dr)^t}}{TGE}
\]

Environmental objective:
\[
\min UE = \frac{TE^{pro} + TE^{IO}}{TGE}
\]

s.t. Economic Constraints

Environmental Constraints
Mass Balance Constraints
Capacity Constraints
Composition Constraints
Bounding Constraints
Logic Constraints

Total GHG emissions:
\[
TE^{pro} = e^{pro}_m Q_m \quad TE^{IO} = e^{IO}_{ns} P_{ns}
\]

Total output of each industrial sector \( P_{ns} \)
\[
P_{ns} - \sum_{ns' \in NS} aio_{ns,ns'} \cdot P_{ns} \geq UP_{ns}
\]

Upstream input from industry sector \( ns \) to process systems
\[
UP_{ns} = \sum_{m \in M} c_{ns,m} \cdot price\_m \cdot Q_m
\]

Mixed-Integer Nonlinear Fractional Program
Case Study of UK Shale Gas Supply Chain

- **15 Shale sites**
  (7 existing, 8 potential ones)

- **4 processing plants**
  (2 existing, 2 potential)

- **6 CCGT power plants**

- **10-year planning horizon**
  (40 time periods)

MINLP problem:
- 414 integer variables
- 11,797 continuous variables
- 15,370 constraints
Pareto-optimal Curve

Cost breakdowns

Emission breakdowns

Drilling
Production
Processing
Transportation
Electricity generation
IO emissions

Life cycle GHG emissions (kg CO₂-eq/MWh)

LCOE (£/MWh)

472 473 474 475 476 477 478 479 480 481 482

35 40 45 50 55 60 65 70 75
Drilling Schedules and Production Profiles

Drilling Schedules

Point A
- Number of wells
- Time periods (quarter)
- Legend: site 4, site 9, site 10, site 14, site 15

Point B
- Number of wells
- Time periods (quarter)
- Legend: site 4, site 9, site 10, site 14

Production Profiles

Point A
- Shale gas production (Bscf)
- Time periods (quarter)
- Legend: site 1, site 2, site 3, site 4, site 5, site 6, site 7, site 8, site 9, site 10, site 11, site 12, site 13, site 14, site 15

Point B
- Shale gas production (Bscf)
- Time periods (quarter)
- Legend: site 1, site 2, site 3, site 4, site 5, site 6, site 7, site 8, site 9, site 10, site 11, site 12, site 13, site 14, site 15
Integrated Hybrid Life Cycle Assessment and Optimization of Shale Gas

Jiayao Gao and Fengqi You*

Robert Frederick Smith School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, New York 14853, United States

ABSTRACT: This paper analyzes the life cycle environmental impacts of shale gas by using an integrated hybrid life cycle analysis (LCA) and optimization approach. Unlike the process-based LCA that suffers system truncation, the integrated hybrid LCA supplements the truncated system with a comprehensive economic input-output system. Compared with the economic input–output-based LCA that loses accuracy from process aggregation, the integrated hybrid LCA retains the precision in modeling major unit processes within the well-to-wire system boundary. Three environmental categories, namely, life cycle greenhouse gas emissions, water consumption, and energy consumption, are considered. Based on this integrated hybrid LCA framework, we further developed an integrated hybrid life cycle optimization model, which enables automatic identification of sustainable alternatives in the design and operations of shale gas supply chains. We applied the model to a well-to-wire shale gas supply chain in the UK to illustrate the applicability. According to the optimization results, the lowest levelized cost of electricity generated from shale gas is £51.8/MWh, and the optimal life cycle GHG emissions, water consumption, and energy consumption are 473.5 kg CO₂-eq/MWh, 2263 kg/MWh, and 1009 MJ/MWh, respectively.

KEYWORDS: Hybrid life cycle assessment, Hybrid life cycle optimization, Shale gas, Supply chain
LCO: Attributional v.s. Consequential

Multiobjective Optimization

Automatic generation of system design decisions

Life Cycle Assessment

- Goal and Scope Definition
- Life Cycle Inventory Analysis
- Life Cycle Impact Assessment

- Attributional LCA
- Consequential LCA
Motivating Example

**Attributional LCA: static and fact-based**

Environmental Impacts of producing A + Environmental Impacts of the conversion + Environmental Impacts of end of life of B

**Consequential LCA: dynamic and change-driven**

Environmental Impacts of the new system - Environmental Impacts of the original system

Or

Environmental Impacts of conversion (2) + Environmental Impacts of end of life of B - Environmental Impacts of conversion (1) - Environmental Impacts of end of life of C
Consequential Life Cycle Optimization

- What upstream and downstream processes are influenced by the target process?
- How does the target process influence the upstream and downstream processes?

How does it work?

Multiobjective Optimization

Consequential LCA

Techno-economic Analysis

Process Models
An Analogy – Spot the Difference

Before

After
Attributional LCA for Process Design Problems

- Environmental impacts in the feedstock production phase
- Environmental impacts from transportation
- Environmental impacts from the process
- Environmental impacts in the use and end-of-life phases

Target Process

- Section 1
- Section 2
- Section 3

Feedstock suppliers' processes

Product consumers' processes

Attributional system boundary

- Applicable to existing systems
- Not suitable for new systems
- Overlook the power of markets and influences in other processes
System Boundary of the Consequential LCO

**Primary**

- Feedstock market $f$
  - Increase
  - Consequential system boundary

**Secondary**

- Feedstock suppliers’ processes
  - Increase
  - Other suppliers’ processes for downstream market $a$
  - Decrease

- Other feedstock customers’ processes
  - Decrease

- Other product suppliers’ processes
  - Increase
  - Other suppliers’ processes for downstream market $b$
  - Decrease

- Product consumers’ processes
  - Increase

- Downstream market $a$
  - Decrease

- Downstream market $b$
  - Increase

- Unchanged
Partial Equilibrium Model

Supply

\[ as0_l = ad0_l, \quad \forall l \]

Demand

Aggregate supply function

\[ AS_l = \sum_{p \in \text{PPC}_l} (asc_{l,p} \cdot XS_{l,p} + bsc_{l,p} \cdot YS_{l,p}) + PS_l, \quad \forall l \]

\[ asc_{l,p} = \frac{ns_{l,p} - ns_{l,p-1}}{ms_{l,p} - ms_{l,p-1}}, \quad \forall l, p \]

\[ bsc_{l,p} = ns_{l,p} - asc_{l,p} \cdot ms_{l,p}, \quad \forall l, p \]

\[ \sum_{p \in \text{PPC}_l} YS_{l,p} = 1, \quad \forall l \]

\[ \sum_{p \in \text{PPC}_l} XS_{l,p} = PR_l, \quad \forall l \]

\[ ms_{l,p} \cdot YS_{l,p-1} \leq XS_{l,p} \leq ms_{l,p} \cdot YS_{l,p}, \quad \forall l, p \]

Price elasticity of demand

\[ AD_l = \frac{ed_l \cdot \alpha_l}{\beta_l} \cdot PR_l + \alpha_l \cdot (1 - ed_l) + PD_l, \quad \forall l \]

Quantities by the target process

Equilibrium

\[ AS_l = AD_l, \quad \forall l \]

Life Cycle Inventory

\[ LCI_{Supplier}^{l} = (AS_l - PS)_{l} - as0_l, \quad \forall l \]

\[ LCI_{Customer}^{l} = (AD_l - PD_l) - ad0_l, \quad \forall l \]
### Consequential LCO framework

<table>
<thead>
<tr>
<th>Objective</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Objective</td>
<td>e.g. maximize net present value</td>
</tr>
<tr>
<td>Environmental Objective</td>
<td>e.g. minimizing ReCiPe points</td>
</tr>
</tbody>
</table>

#### Maximize

\[
\max \sum_{k,l} h_{k,l} \left( P_l, Q_l, X_k, YC_k \right)
\]

#### Minimize

\[
\min \sum_{l,r,s} \left[ c_{l,r,s} \cdot v_{l,r,s} \left( Q_l, AS_l, AD_l \right) \right]
\]

#### Subject to

\[
Q_l = \sum_k f_{k,l} \left( X_k, YP_k \right), \ \forall l
\]

\[
AS_l = m_l \left( Q_l, P_l, YS_l \right), \ \forall l
\]

\[
AD_l = n_l \left( Q_l, P_l, YD_l \right), \ \forall l
\]

\[
AS_l = AD_l, \ \forall l
\]

#### Process Model

Integer variables for technology selection; Mass and energy balance

#### Market Model

Partial equilibrium models
Application to Algae-based Biofuel Production

Scenedesmus sp. with 27.4 wt % lipid

Functional Unit:
1 GJ of renewable diesel
Detailed superstructure

6 markets in the U.S.
Optimization Results for ReCiPe

Production Rate: 3.5 MMGal/year
## Environmental Impact Breakdown

### Attributional

<table>
<thead>
<tr>
<th>Market</th>
<th>Impact Score (kPt./year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Markets</td>
<td>Attributional</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>Increase fertilizer production</td>
</tr>
<tr>
<td>Hexane</td>
<td>Positive characterization factors*</td>
</tr>
<tr>
<td>Diesel</td>
<td>Combustion in end of life</td>
</tr>
</tbody>
</table>

*Data for “rest of the world” from Ecoinvent 3.3*
Consequential Environmental Profile

The chart illustrates the environmental impact across various categories, with each bar representing a different impact area. The chart uses different colors to distinguish between various sources and impacts:

- **Urea production**
- **DAP production**
- **Hexane production**
- **Electricity production**
- **Diesel production**
- **Fertilizer consumption**
- **Diesel consumption**
- **Direct emissions**
- **Transportation**

The categories include:
- Agricultural land occupation
- Climate change, ecosystems
- Freshwater eutrophication
- Marine ecotoxicity
- Natural land transformation
- Terrestrial acidification
- Terrestrial ecotoxicity
- Urban land occupation
- Climate change, human health
- Human toxicity
- Ionising radiation
- Ozone depletion
- Particulate matter formation
- Photochemical oxidant formation
- Fossil depletion
- Metal depletion

The x-axis represents the environmental impact categories, while the y-axis shows the percentage impact range from -100% to 80%. The bars illustrate the contribution of different sources to each impact category.
Consequential Life Cycle Optimization: General Conceptual Framework and Application to Algal Renewable Diesel Production

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Supporting Information

ABSTRACT: Life cycle optimization (LCO) enables static life cycle analysis (LCA) and techno-economic analysis to be performed dynamically for automatic generation and optimization of process alternatives. Existing LCO models are developed following an attributional LCA approach, which overlooks the environmental consequences in response to the changes in the market. In this study, we develop a consequential LCO framework that simultaneously optimizes consequential environmental impacts and economic performance. We propose a general system boundary that encloses processes linked by markets. On the basis of the general system boundary, we develop a multiobjective optimization model, which integrates process models and market models with the tenets of consequential LCA and techno-economic analysis methodologies. To efficiently solve the resulting nonconvex mixed-integer nonlinear programming problem, a global optimization algorithm is proposed to integrate the inexact parametric algorithm and the branch-and-refine algorithm. The application of the proposed framework is illustrated through a case study of producing renewable diesel from microalgae. We conduct detailed market analysis to identify the consequences associated with the renewable diesel production process. The environmental impacts of the optimal process designs based on the proposed consequential LCO framework are significantly lower than those based on the existing attributional LCO framework.

KEYWORDS: Life cycle optimization, Consequential life cycle analysis, Superstructure optimization, Sustainability, Algal biofuel
Conclusion

• **Life cycle analysis and life cycle optimization**
  • Process-level LCA and life cycle design/optimization
    • Systems boundary
    • Functional unit
  • **Integrated hybrid** LCA and LCO
    • Process systems to supply chain, and to macroeconomics scales
  • **Consequential** LCA and LCO
    • Dynamic and change-driven
    • Suitable for new product systems to account for influences of other processes through the market

• **Applications to energy systems**
  • Algal biorefinery
  • Shale gas
  • ……
Thank you for your attention
Questions?

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