# A Systems Engineering Framework for the Optimization of Circular Economy Supply Chains

**Styliani Avraamidou**

University of Wisconsin-Madison

# Overview

1. Circular Economy – Why? What? How?

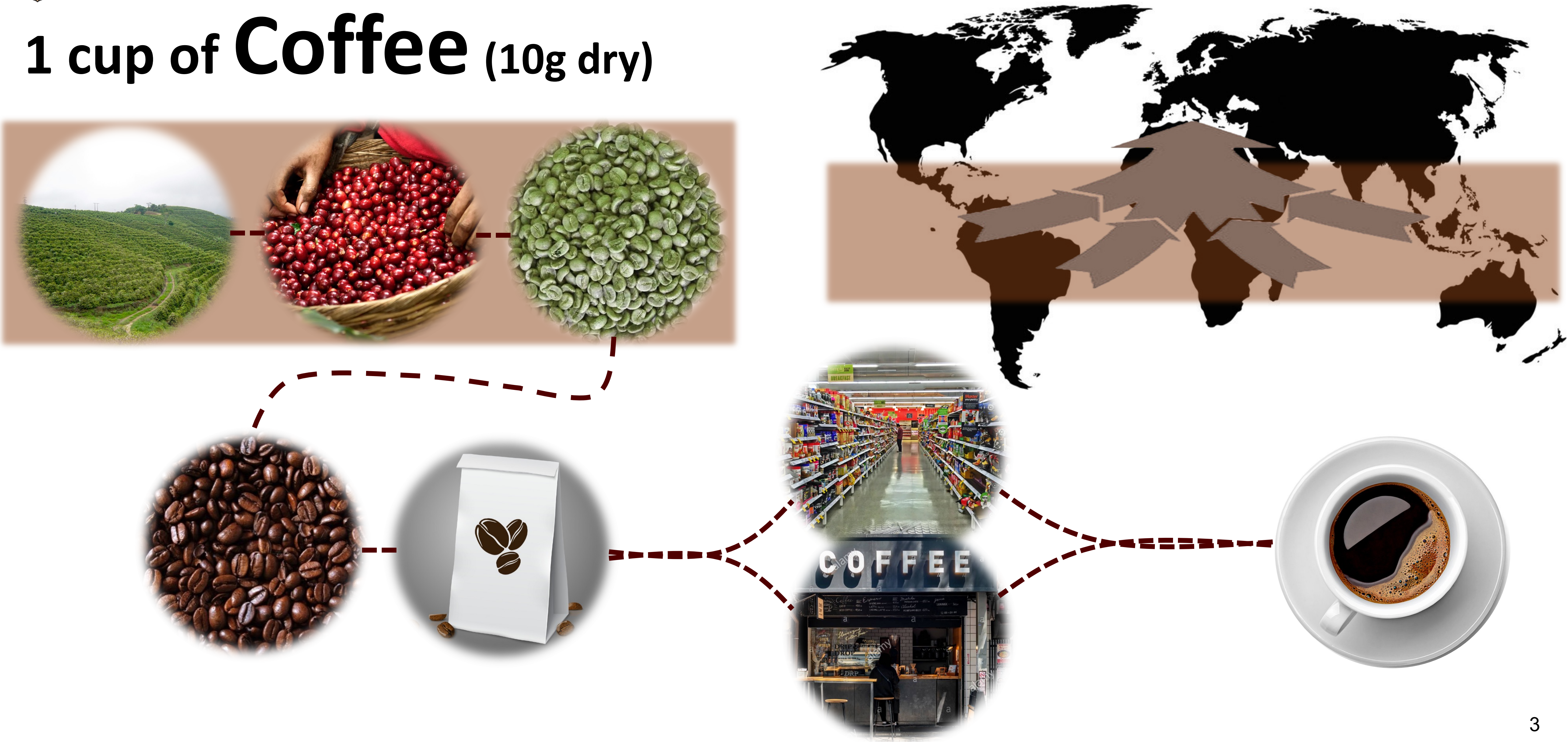
2. Links to Process Systems & Chemical Engineering

3. Circular Economy Systems Engineering Framework

- Baratsas, S. G; Pistikopoulos, E. N; Avraamidou, S. **A quantitative and holistic circular economy assessment framework at the micro level.** Computers & Chemical Engineering 2022, 160, 107697.
- Baratsas, S. G; Pistikopoulos, E. N; Avraamidou, S. **A systems engineering framework for the optimization of food supply chains under circular economy considerations.** Science of The Total Environment 2021, 794, 148726.
- Avraamidou, S.; Baratsas, S.; Tian, Y.; Pistikopoulos, E. N. **Circular Economy - a challenge and an opportunity for Process Systems Engineering.** Computers & Chemical Engineering 2020, 133,106629.

# Circular Economy – Why? What? How?
## *Coffee Motivating Example*

**1 cup of Coffee (10g dry)**



# 1 cup of Coffee (10g dry)


## Food industry

- 30% of the world's energy
- 80% of all water consumed
- 17% of food is wasted globally (30-40% in the US)
- Plastic waste

# Beer motivating example

# Circular Economy – Why? What? How?
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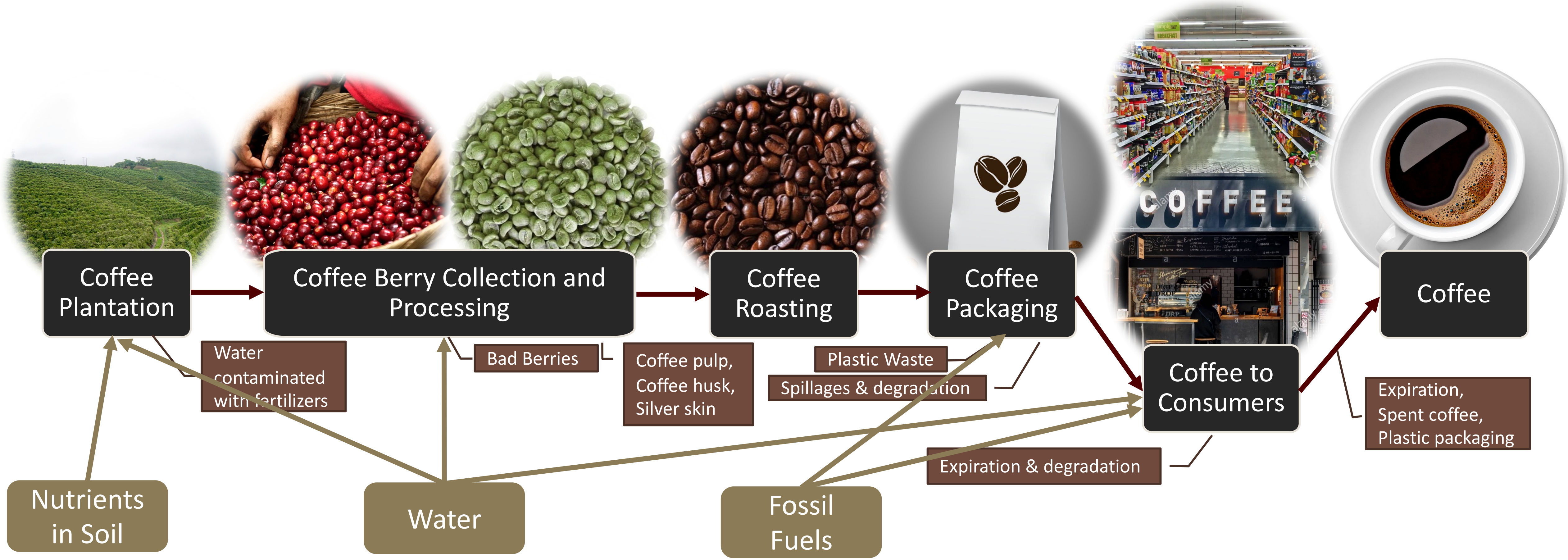


- ✓ **Waste is created at every stage**
- ✓ **Natural resources are used**

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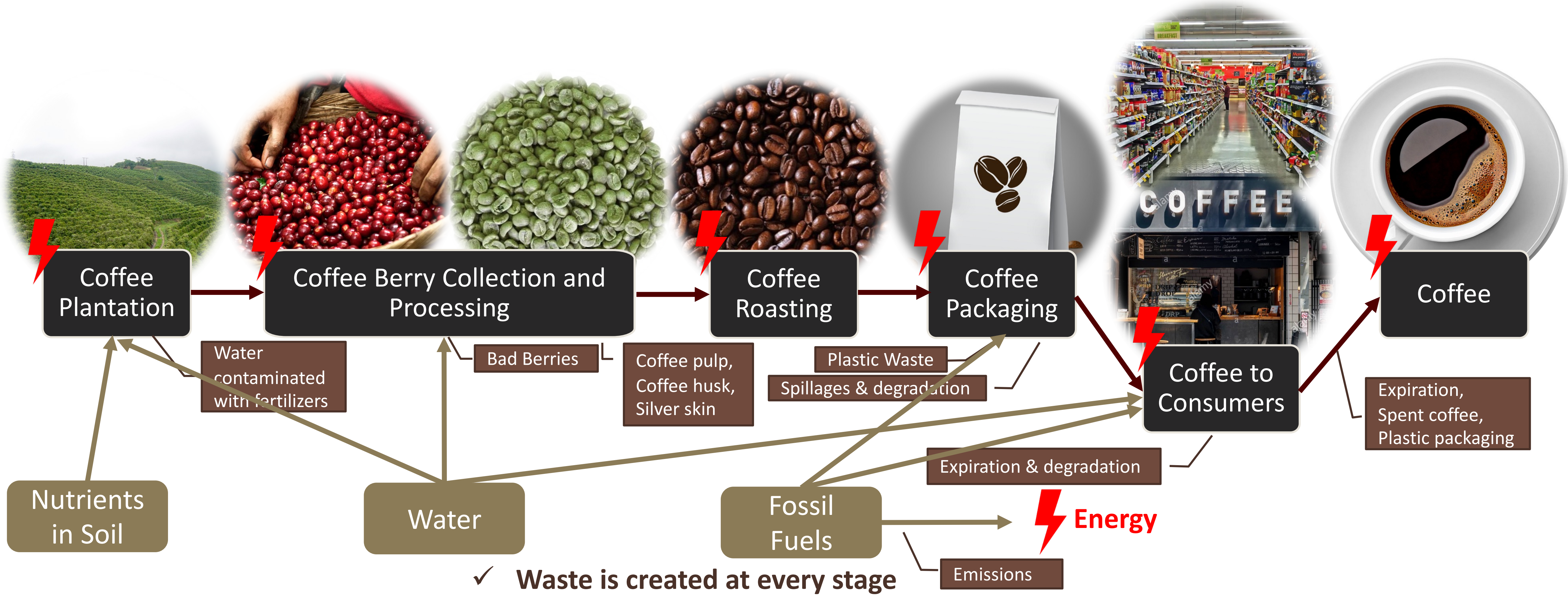


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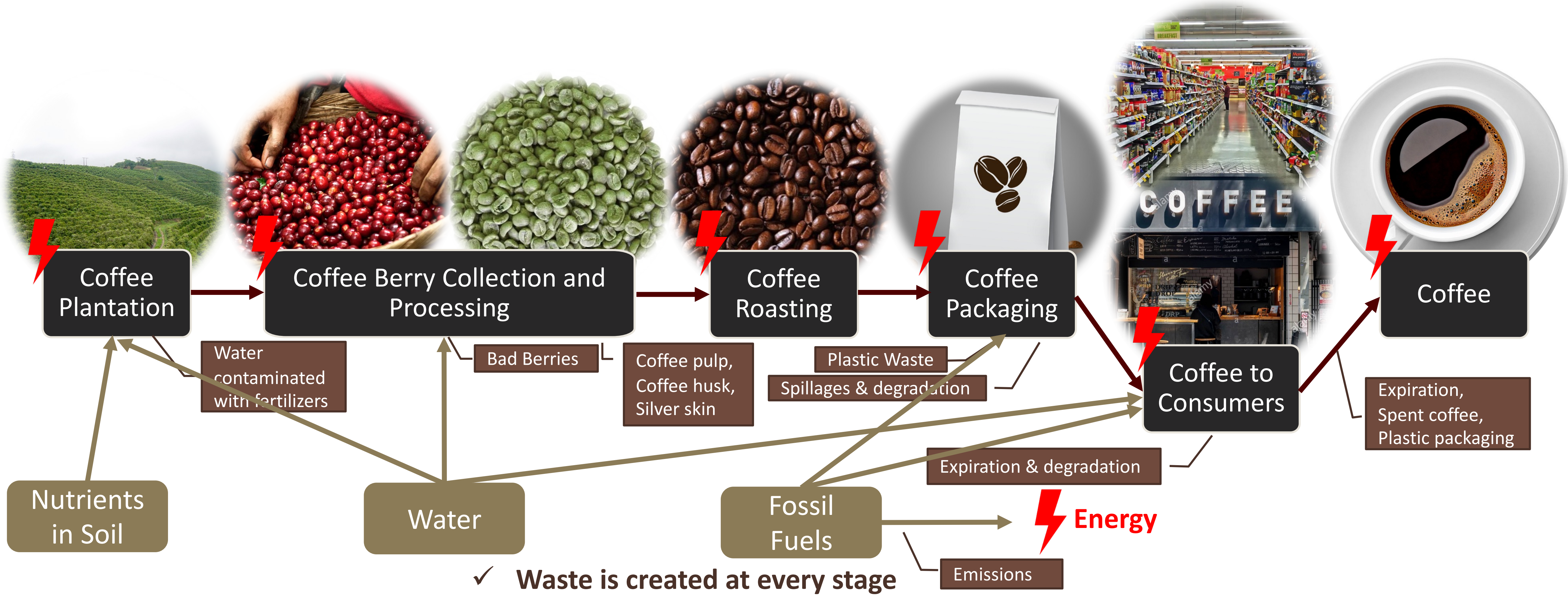


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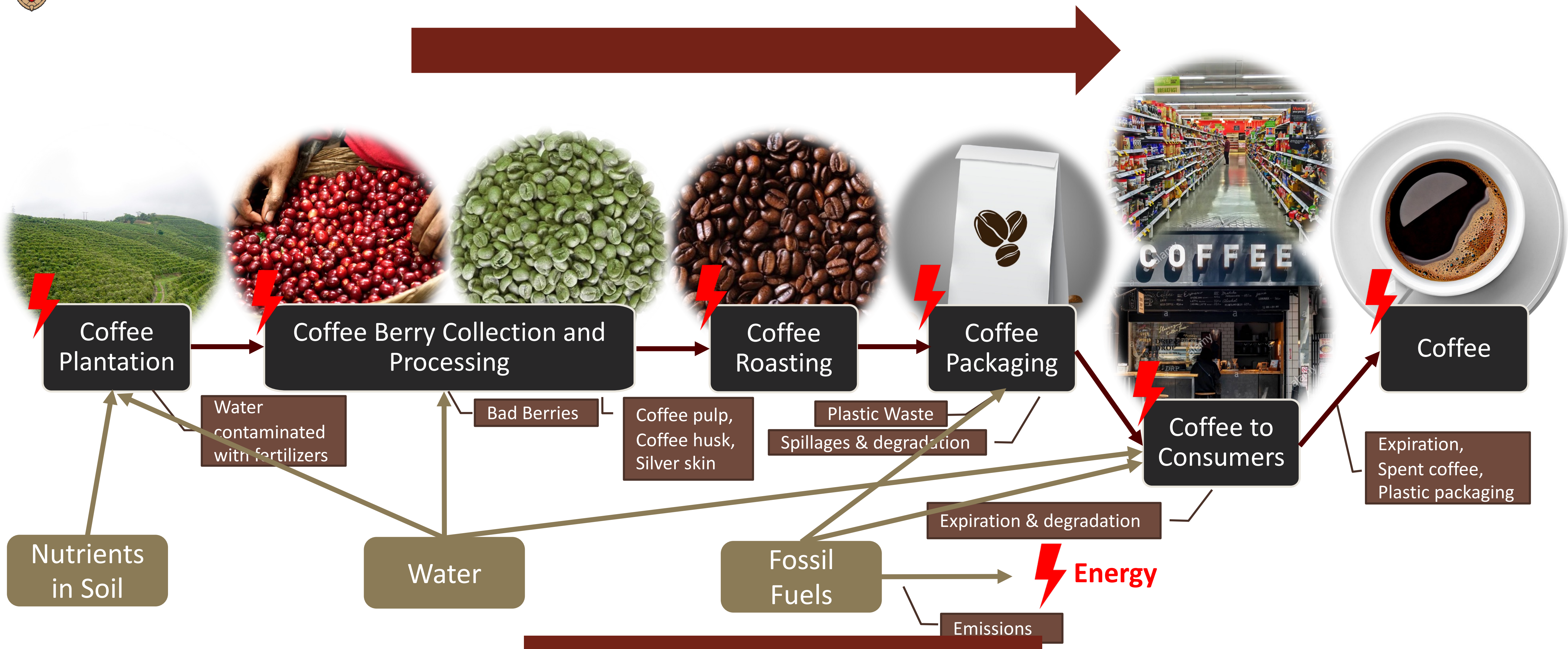
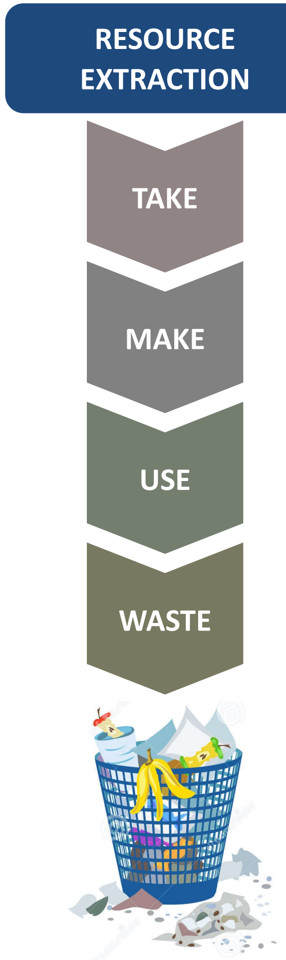



**Linear Economy**

# What is a Circular Economy?

## Linear Economy




## Circular Economy

# What is a Circular Economy?

## Definitions:

- Maintain products as long as possible
- Minimize waste and resource use

**(EC 2015, 1)**

- Conserve resources and the environment
- Recycle resources
- Low consumption of energy
- Low emission of pollutants
- High efficiency

**(UNEP)**

- Restorative and regenerative by design
- Keep materials in use
- Transition to renewable energy and materials

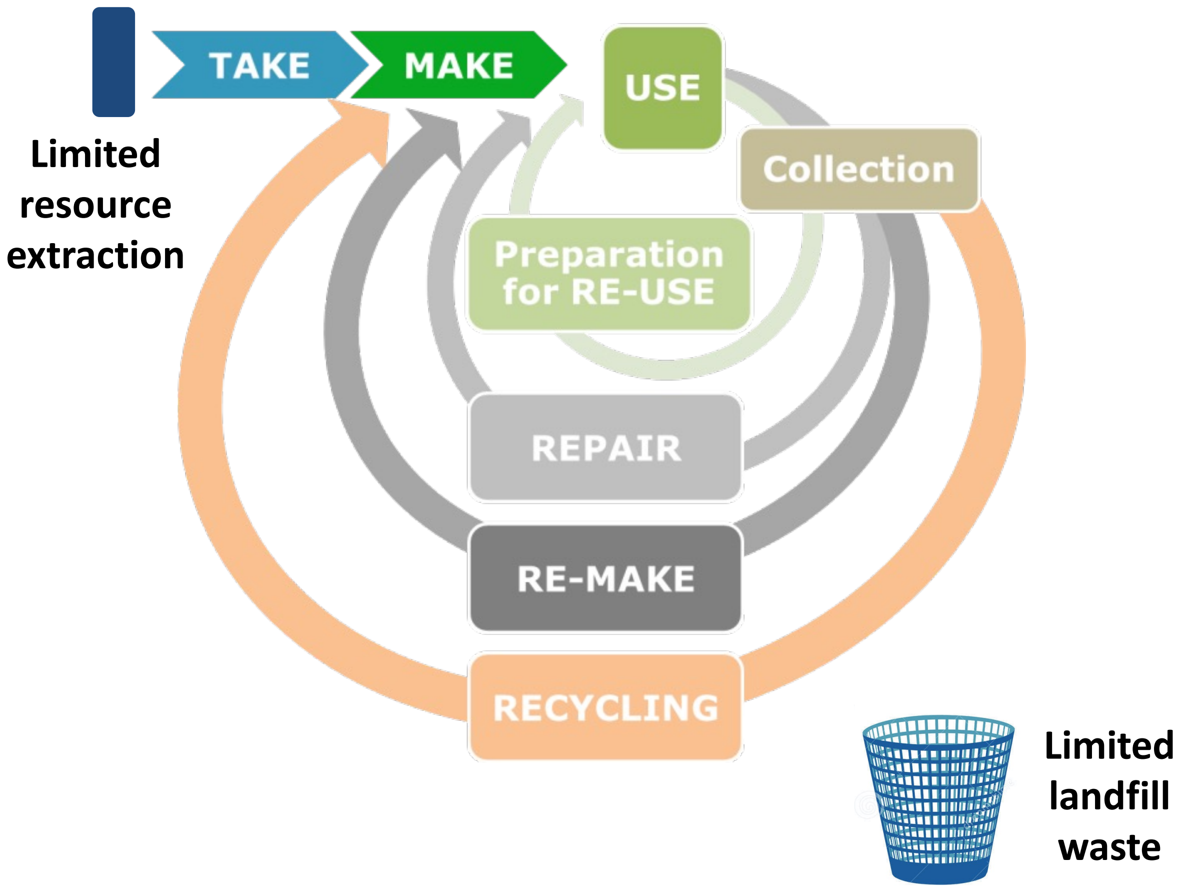
**(Ellen McArthur Foundation)**

Kirchherr, J.; Reike, D.; Hekkert, M.

Conceptualizing the circular economy: An analysis of 114 definitions

*Resources, Conservation & Recycling, 2017, 127, 221-232*

## Circular Economy



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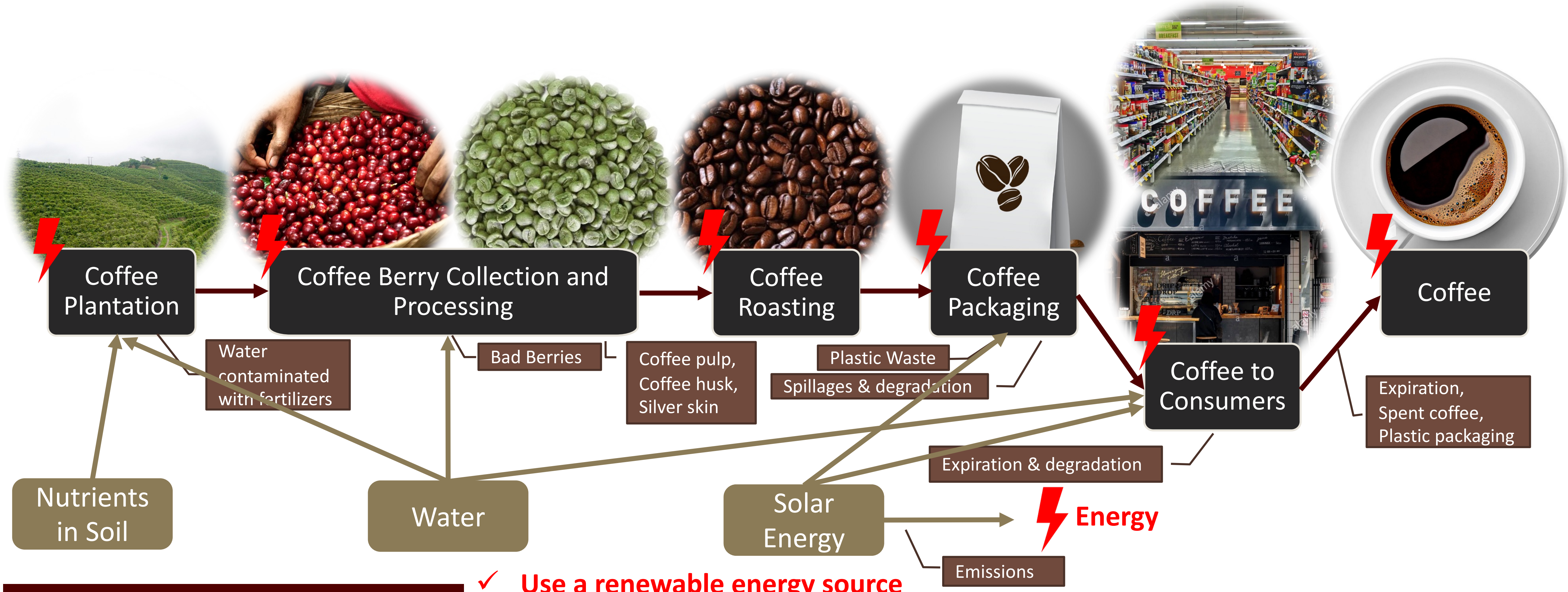


✓ Use a renewable energy source

**Circular Economy**

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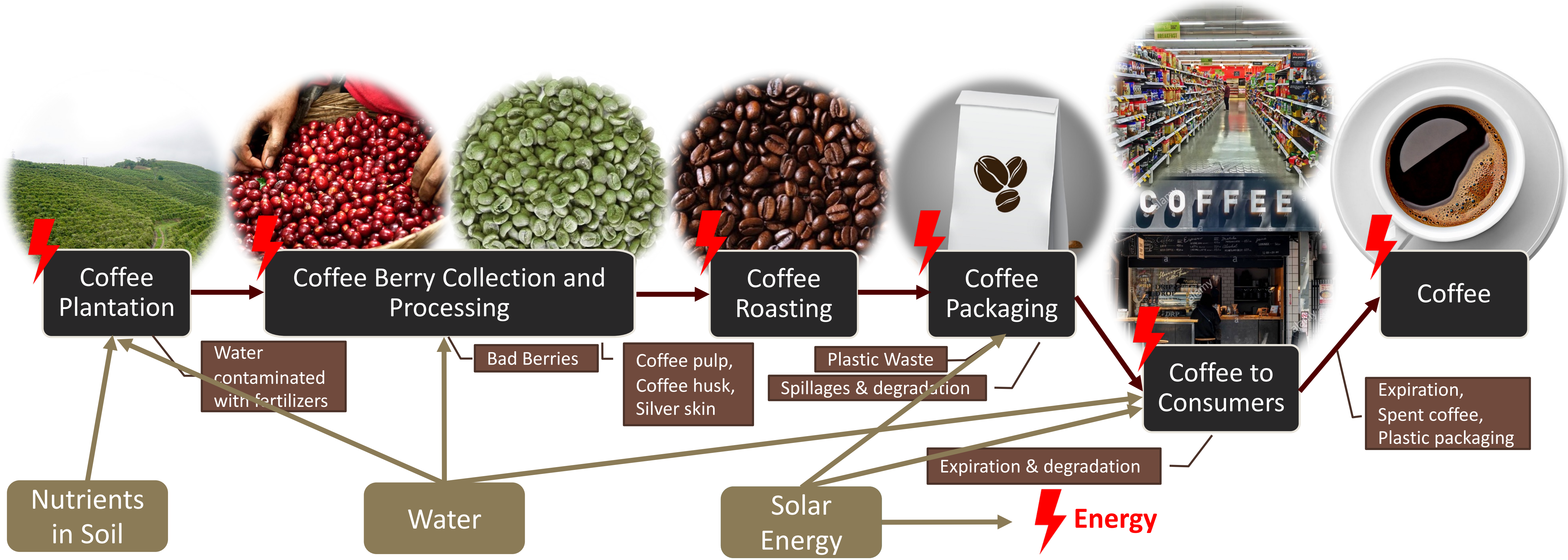


**Circular Economy**

- ✓ **Use a renewable energy source**
- ✓ **Use reusable packaging**

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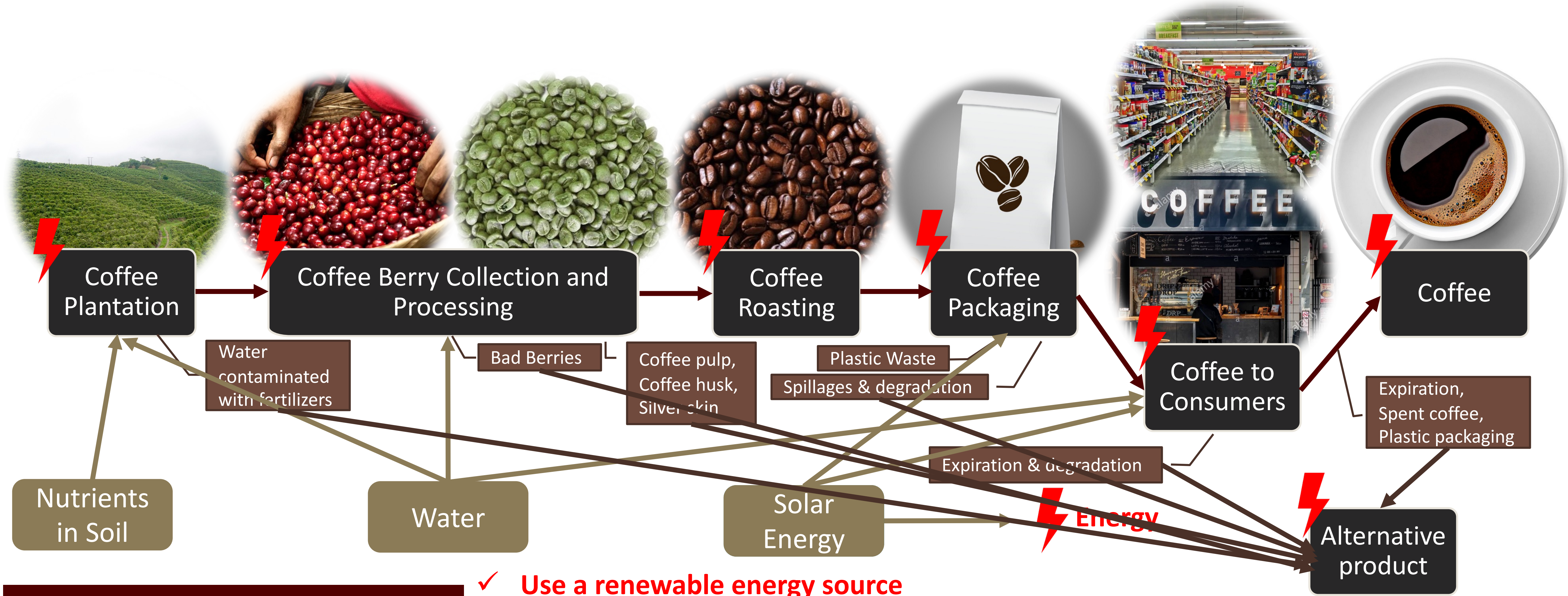


**Circular Economy**

- ✓ **Use a renewable energy source**
- ✓ **Use reusable packaging**
- ✓ **Collect waste and produce alternative products**

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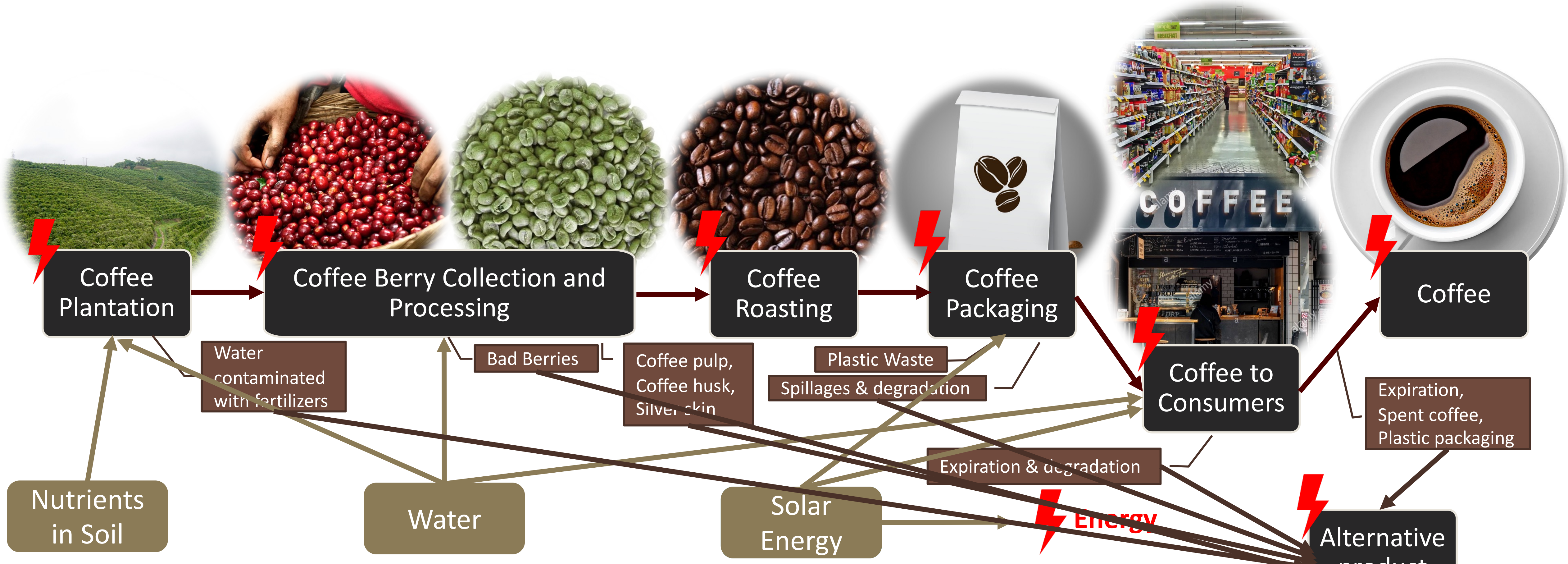



**Circular Economy**

- ✓ **Use a renewable energy source**
- ✓ **Use reusable packaging**
- ✓ **Collect waste and produce alternative products**
- ✓ **Return natural resources to the source**

# Circular economy throughout the world

中华人民共和国
循环经济促进法
解读

China Circular Economy Promotion Law

Benefits of a Circular Economy in South Australia

Government of South Australia
Green Industries SA

Roadmap for the Circular Economy
Let's be in the loop, let's change model

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

European Commission
CIRCULAR ECONOMY
Closing the loop
AN AMBITIOUS EU CIRCULAR ECONOMY PACKAGE

TORONTO
GM28.29
REPORT FOR ACTION
Implementation Plan and Framework for Integrating Circular Economy Approaches into City Procurement Processes to Support Waste Reduction and Diversion

Unilever

U.S. CHAMBER OF COMMERCE FOUNDATION
Sustainability and Circular Economy Program

A Circular Economy in the Netherlands by 2050
Government-wide Programme for a Circular Economy

DANONE

THE Coca-Cola COMPANY

Nestlé

LUXEMBOURG AS A KNOWLEDGE CAPITAL AND TESTING GROUND FOR THE CIRCULAR ECONOMY

CIRCULAR GLASGOW

PEPSICO

**CE is currently promoted by several national governments and businesses around the world**

# Why Circular Economy?

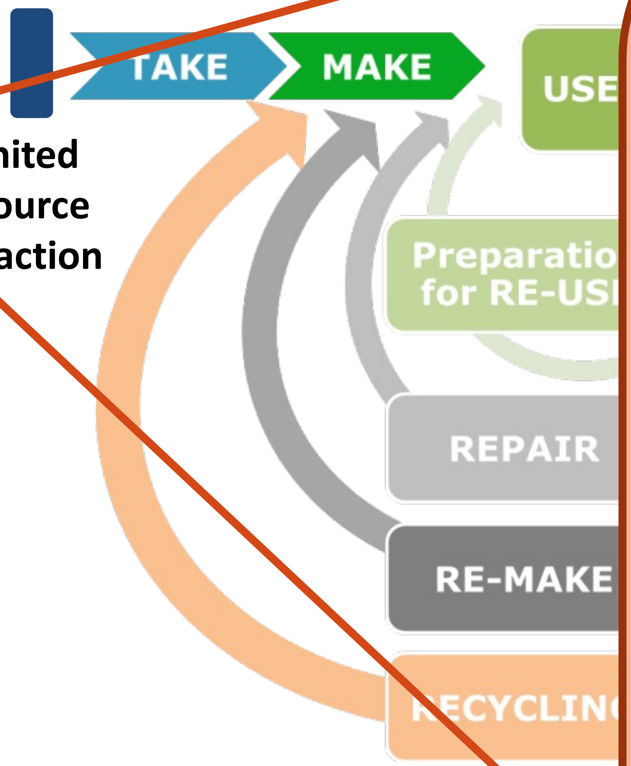
- Rising populations put huge stresses on the natural resources
- Wastes from food industry have a negative impact on the environment
- Successful Circular Economy would contribute to all dimensions of sustainable development:
  - Economic
  - Environmental
  - Social

# Links to Process Systems & Chemical Engineering

# What are the links of Circular Economy to Chemical Engineering?

Green Chemistry

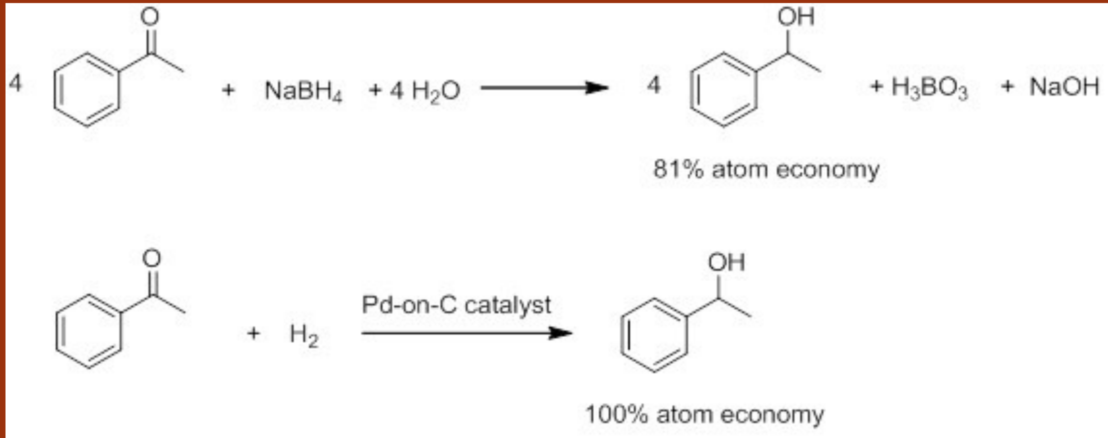
Atom Economy




## Atom Economy

**Example:**

The reduction of a ketone to the corresponding secondary alcohol using sodium borohydride or molecular hydrogen as the reductant.




*Roger A. Sheldon,* Green Chemistry Principle #9, *American Chemical Society*

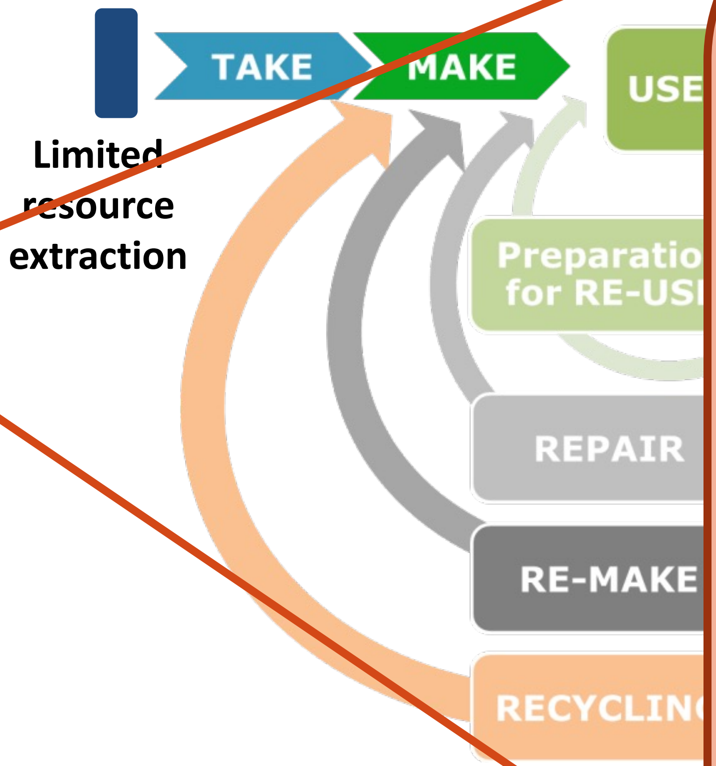
- Minimize resource use
- Minimize waste at the production stage

# What are the links of Circular Economy to Chemical Engineering?

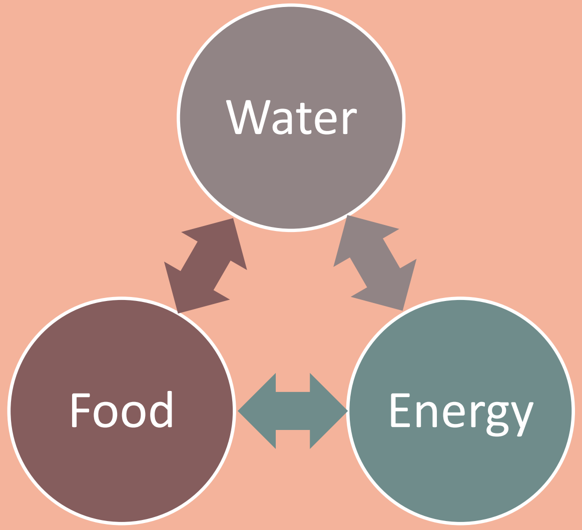
Green Chemistry

Atom Economy

Food-Energy-Water Nexus




## Food-Energy-Water Nexus (FEW-N)




**FEW-N in PSE:** Holistic approaches to minimize the stresses between the nexus elements

# What are the links of Circular Economy to Chemical Engineering?

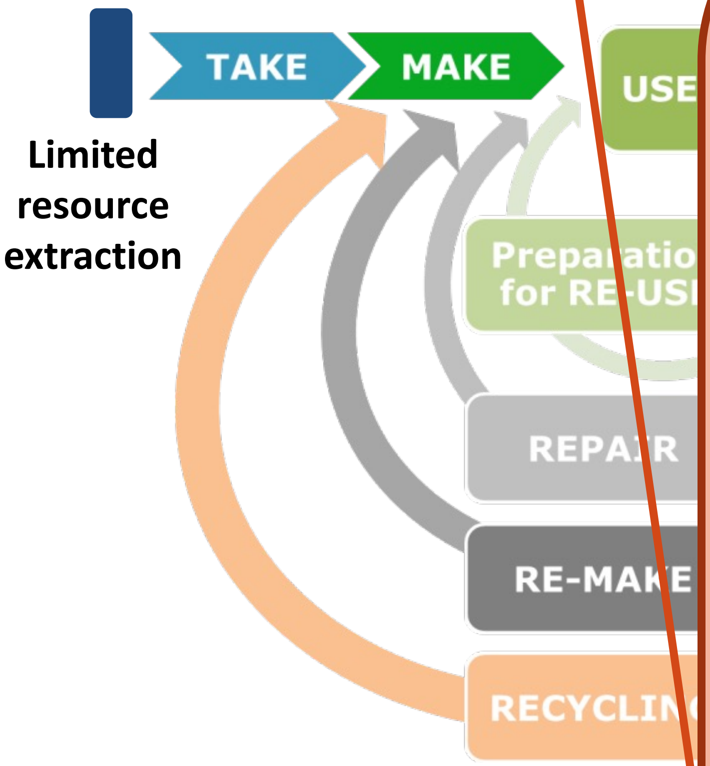
Process Intensification

Green Chemistry

Atom Economy

Food-Energy-Water Nexus

Resource management




## Process Intensification

"Any chemical engineering development that leads to a substantially smaller, cleaner, safer, and more energy-efficient technology"[1]

1. A.J. Stankiewicz and J.A. Moulijn, Process Intensification: Transforming Chemical Engineering. Chem. Eng. Prog. 96 (2000) 22

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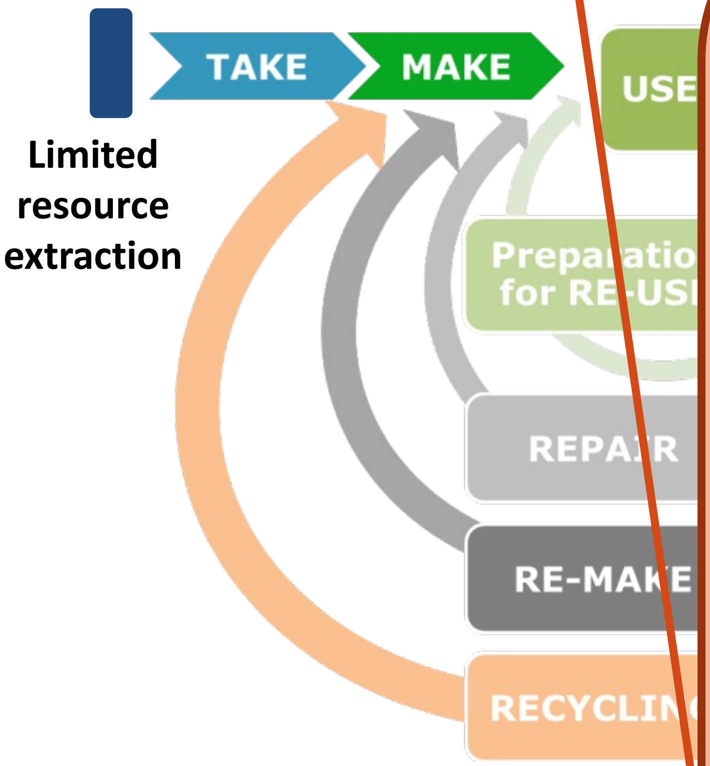
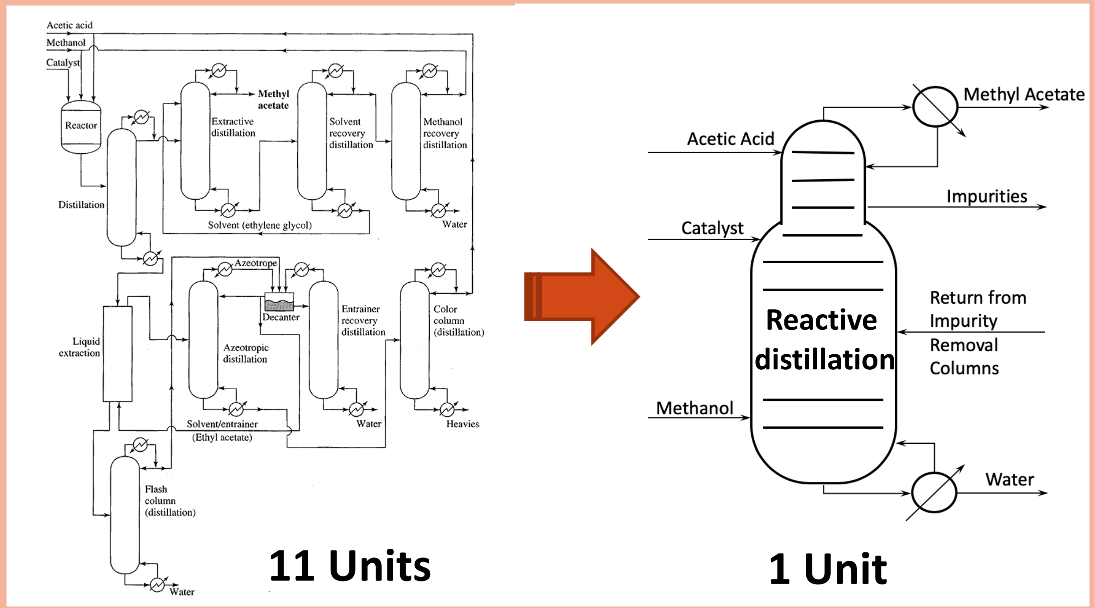



## Process Intensification

**Example:**

Production of Methyl Acetate

Acetic Acid + Methanol ↔ Water + Methyl Acetate

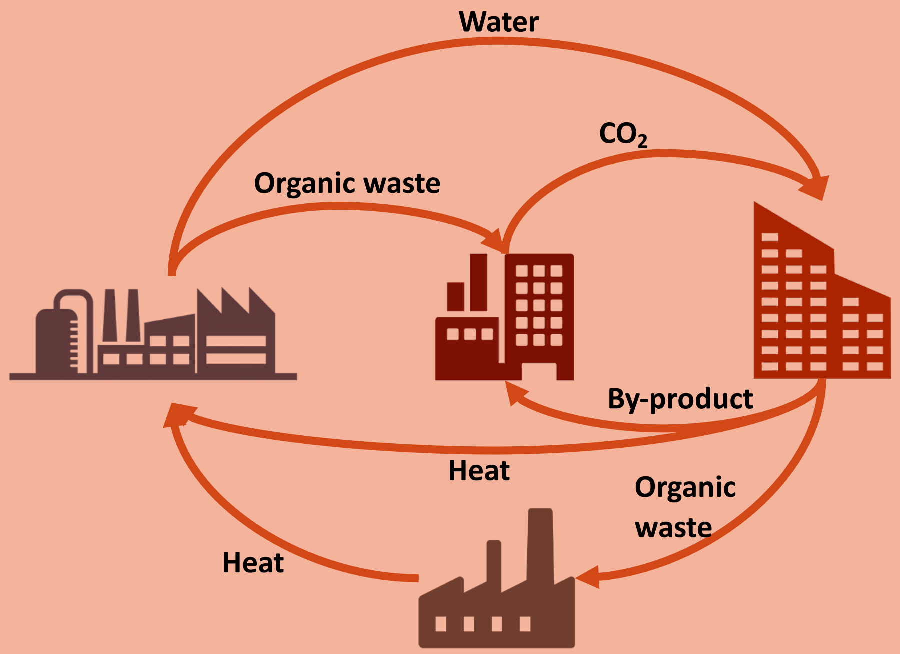



75 % Reduction in *Cost, Energy & Pollution*

1. A.J. Stankiewicz and J.A. Moulijn, Process Intensification: Transforming Chemical Engineering. Chem. Eng. Prog. 96 (2000) 22

# What are the links of Circular Economy to Chemical Engineering?

## Industrial Symbiosis




**Wastes from one company can be used as resources for the other**

- Waste heat recovery
- Cogeneration
- By-product exchange

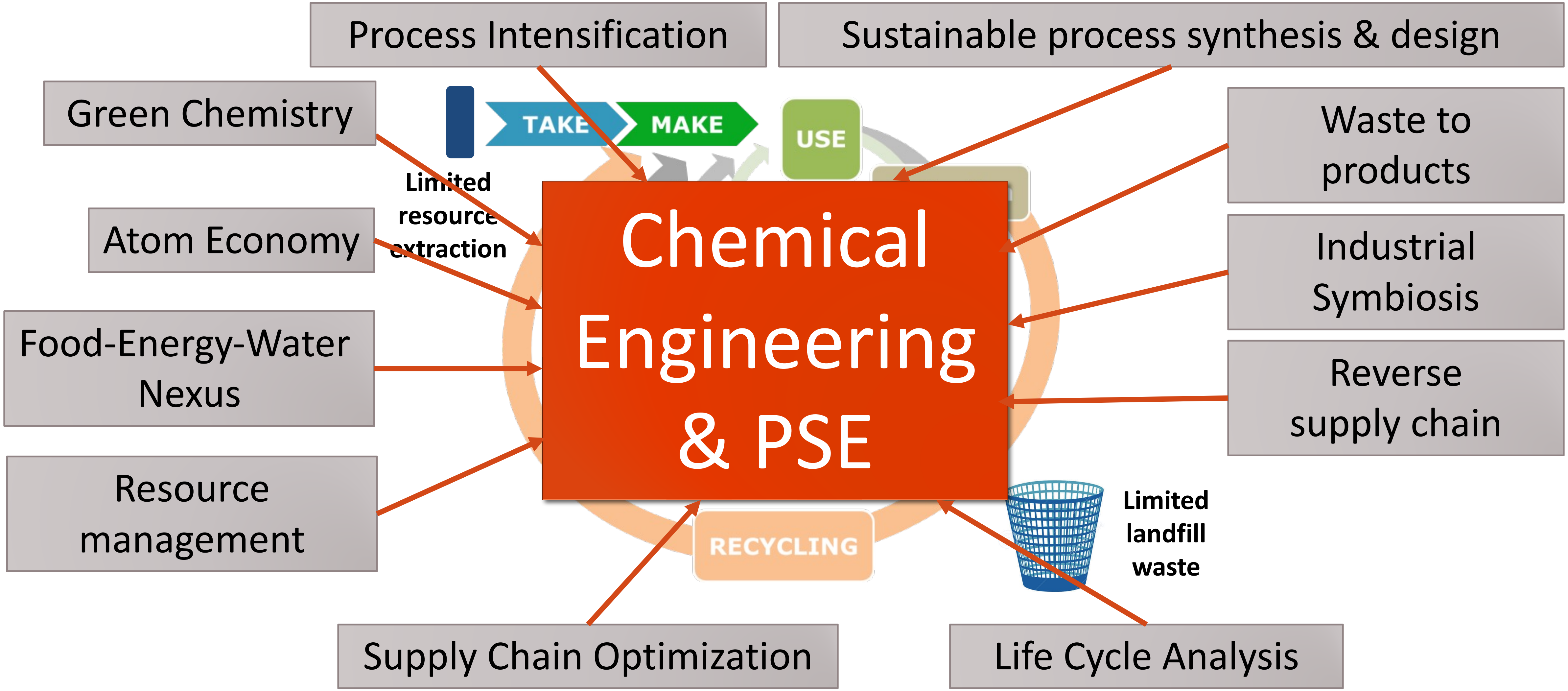

**Limited landfill waste**

Waste to products

Industrial Symbiosis

Reverse supply chain

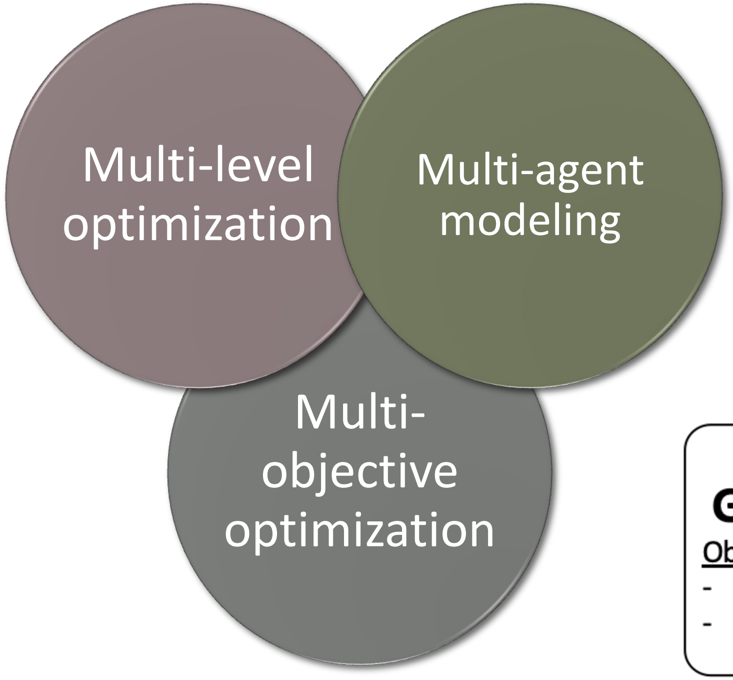
# What are the links of Circular Economy to Chemical Engineering?

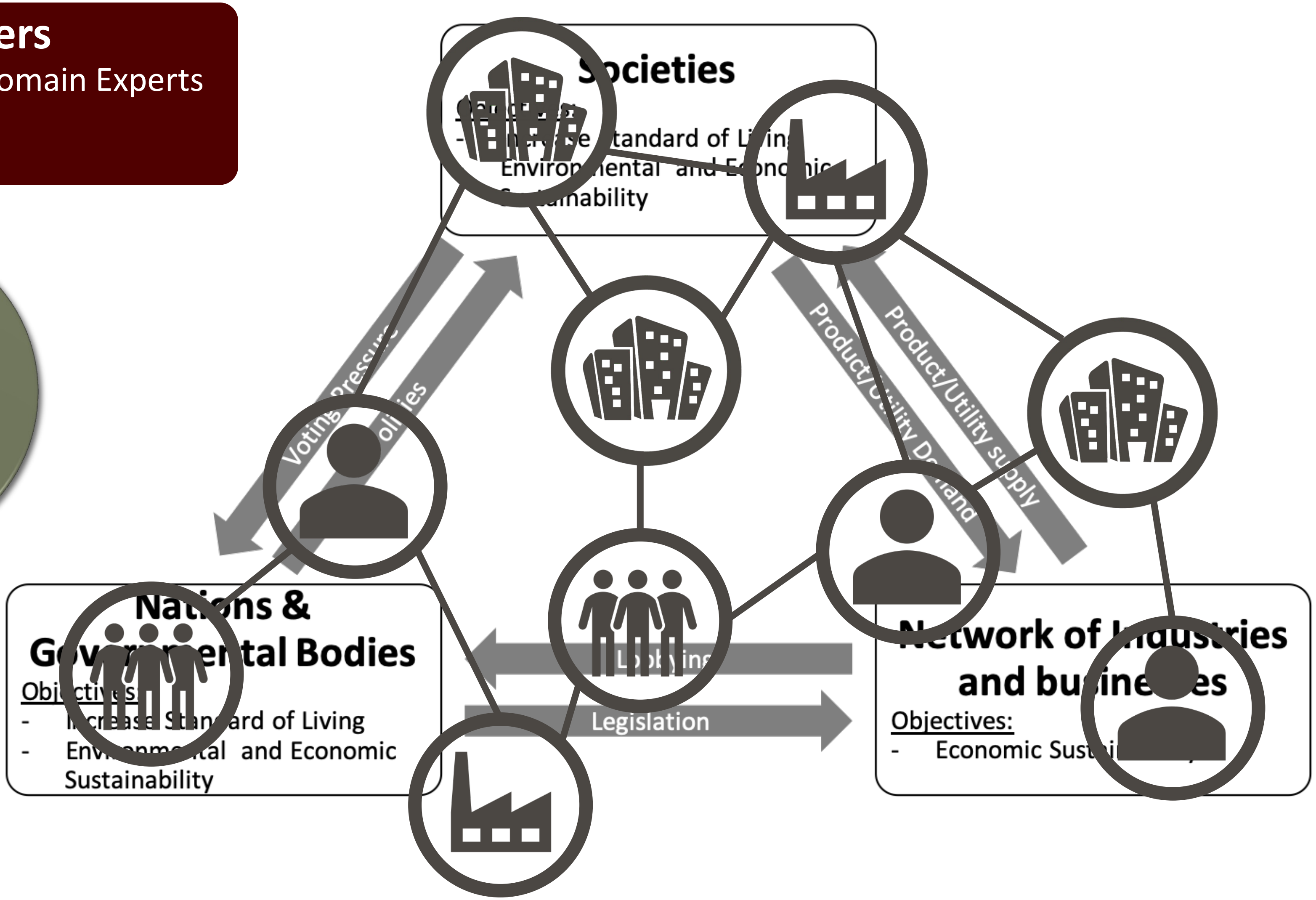


# What are the scientific needs and challenges in Circular Economy research?

## 1. Interconnected Players

- Multiple Stakeholders & Domain Experts
- Legislation
- Role of Policy



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## 1. Interconnected Players
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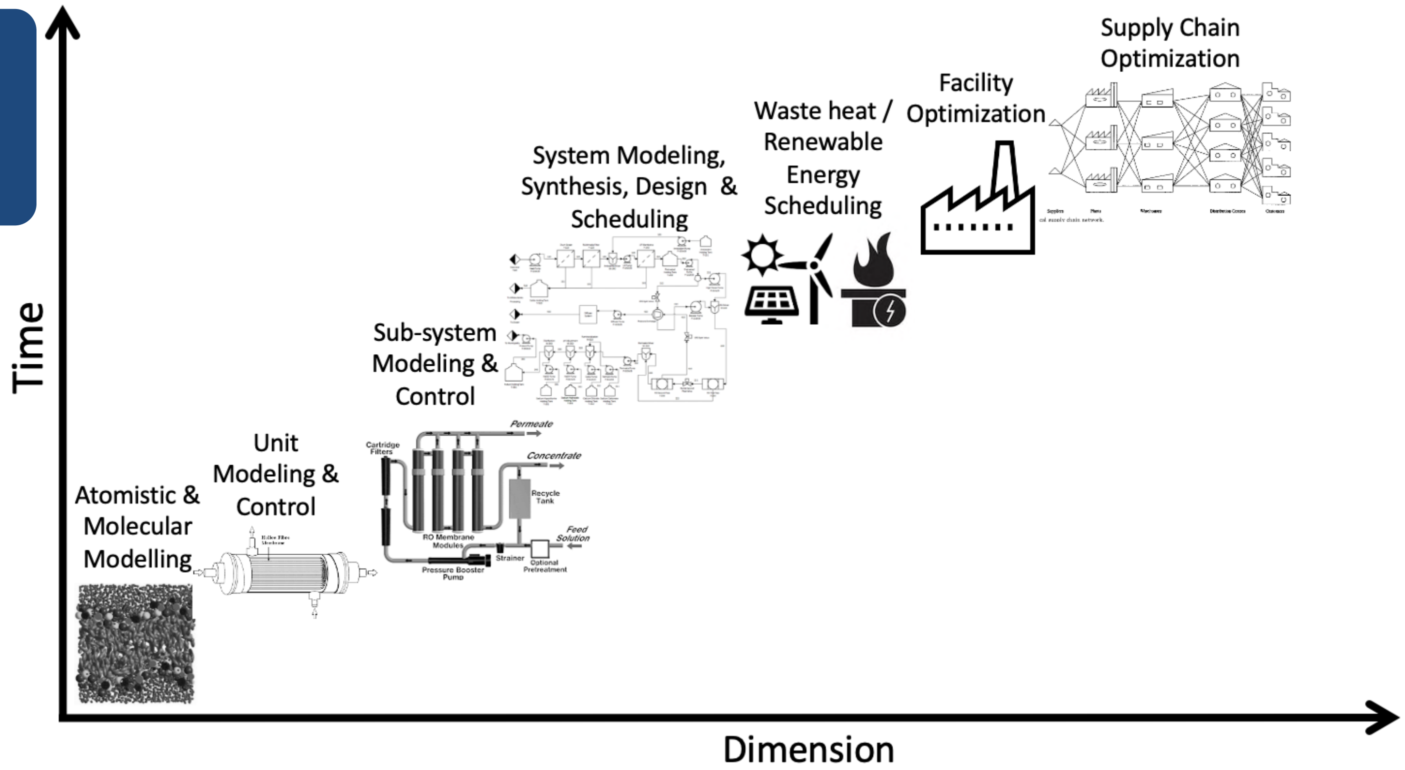
## 2. Multi-scale issues
- Data & Model integration
- Novel pathways
- Spatial & Temporal System Boundaries

Multi-level optimization

Design, Planning, Scheduling & Control Integration

Multi-scale modeling & optimization



# What are the scientific needs and challenges in Circular Economy research?

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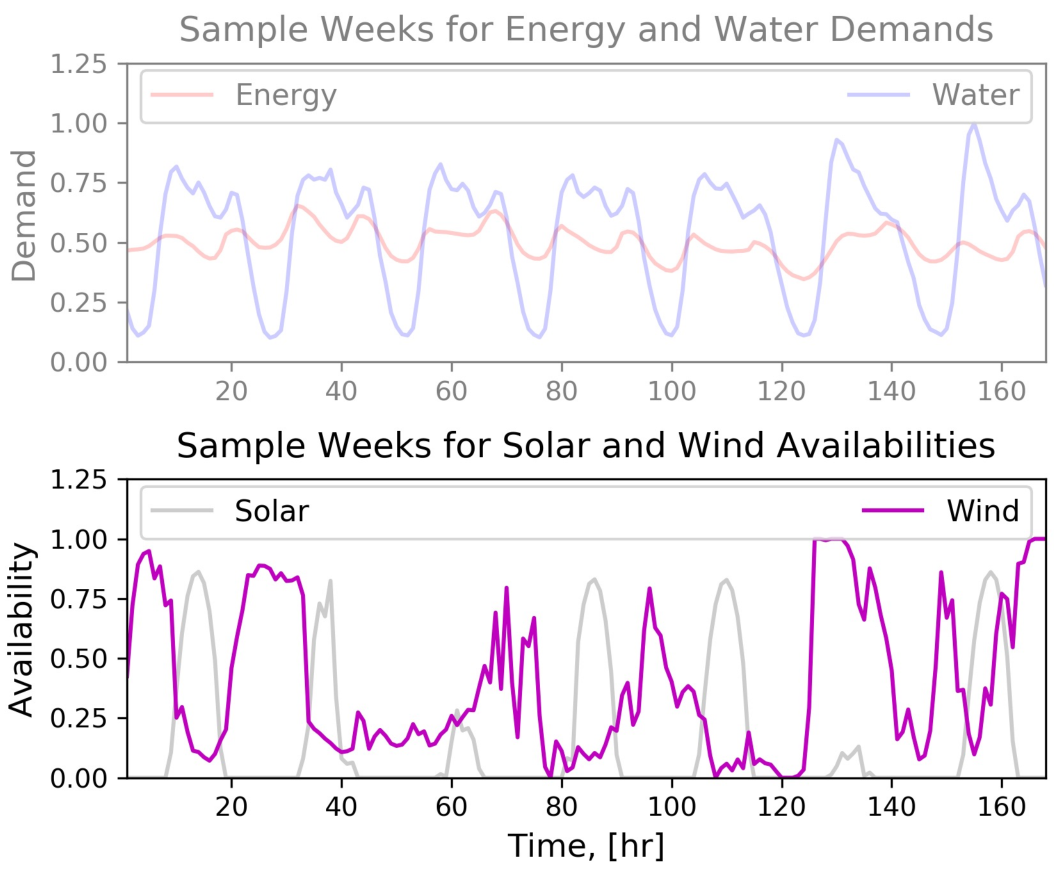
## 3. Dynamic/Uncertain Conditions
- Demand variability
- Cost variability
- Resource availability

Data analytics

Scenario reduction

Multi-stage stochastic optimization



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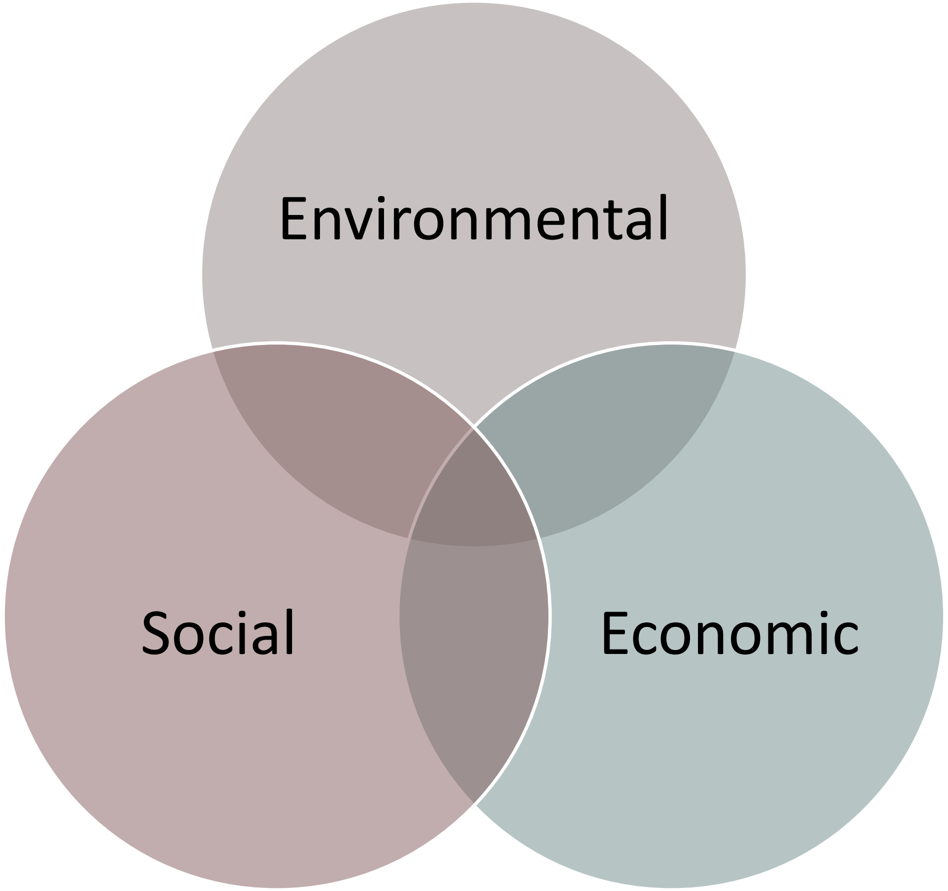
## 4. Assessment Criteria
- Metric to compare ‘circular’ alternatives
- Global net sustainability?



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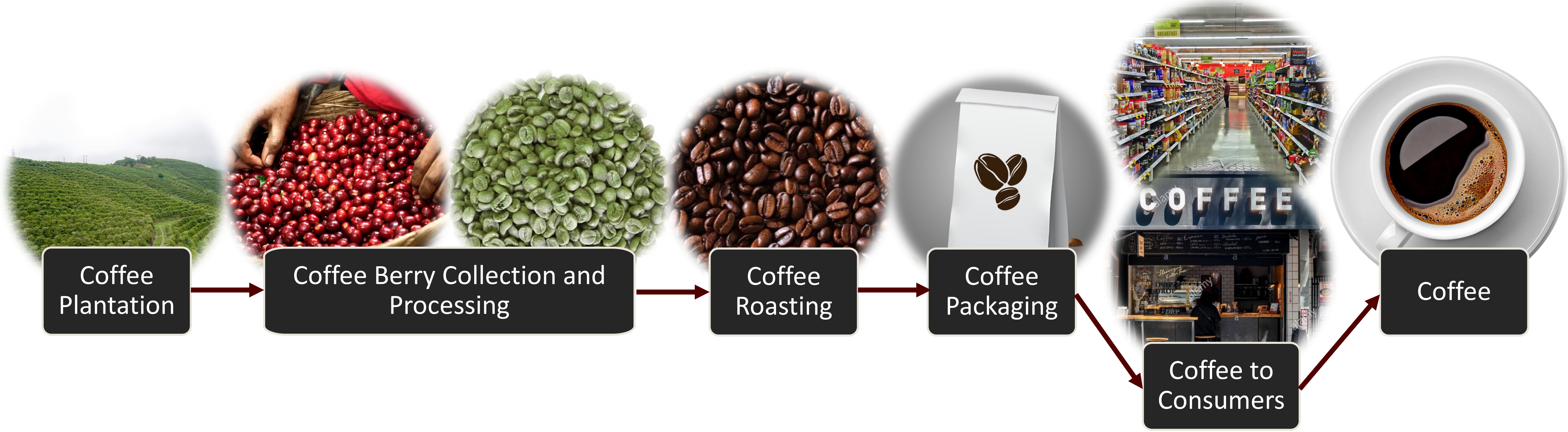
Styliani Avraamidou, Ana I. Torres. **Circular Economy: Definitions, Challenges, and Opportunities.** FOCAPO-CPC 2023

# Towards a Circular Economy Systems Engineering Framework

## Coffee Case Study

## A Circular Coffee Supply Chain



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| | |
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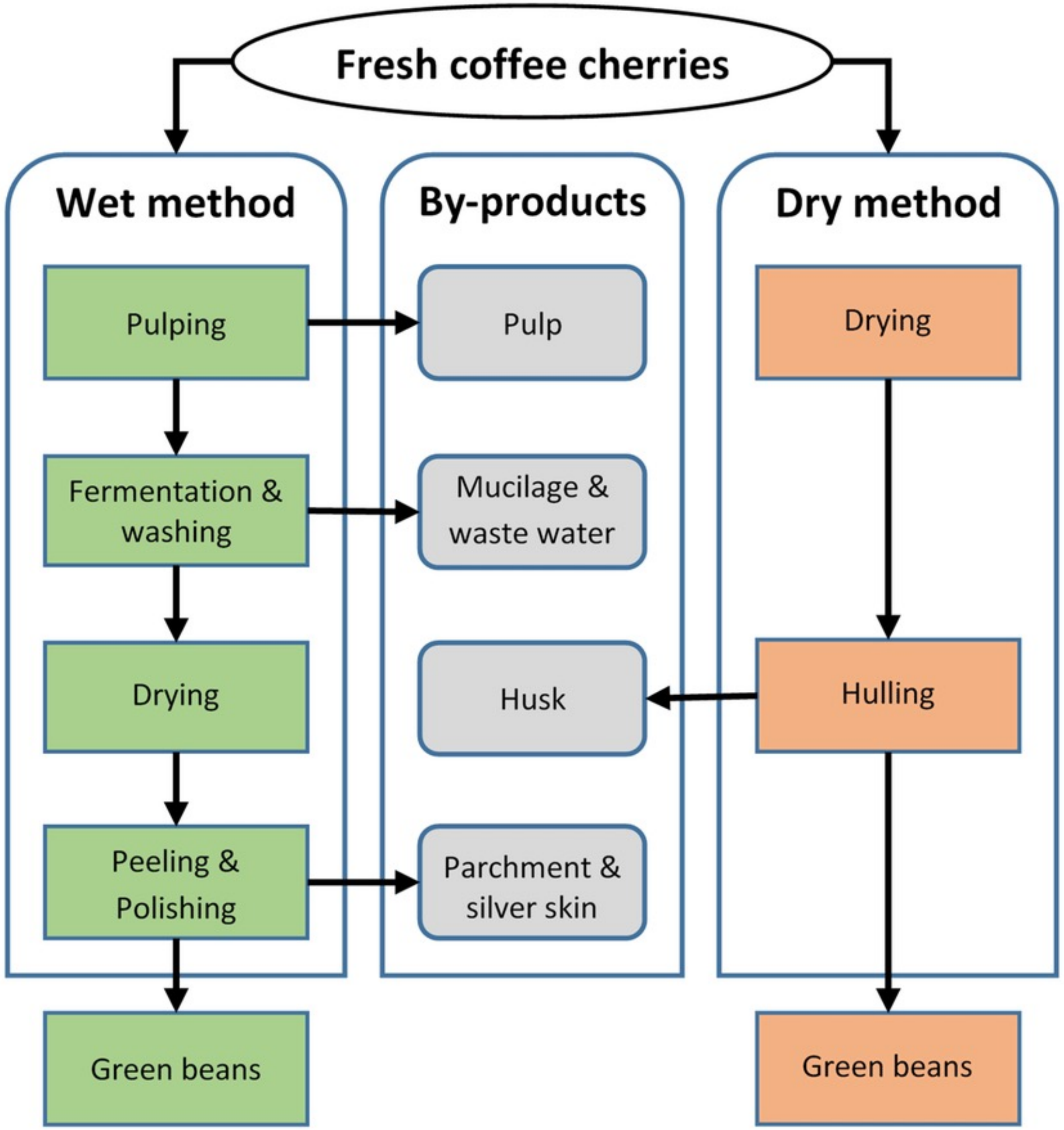
| **1.** Production paths | • Identify and characterize alternative paths to produce the desired product |
| **2.** Waste utilization paths | • Identify and characterize alternative paths to utilize waste streams |
| **3.** Network representation | • Built a network representation that includes all alternative paths |
| **4.** MILP Model | • Derive the Mixed Integer Linear Programing (MILP) model to represent the supply chain with the alternative paths |
| **5.** Optimization | • Solve the model through multi-objective optimization to consider all CE objectives |

# Coffee alternative production paths




Chala, Bilhat & Oechsner, Hans & Latif, Sajid & Müller, Joachim. (2018). Biogas Potential of Coffee Processing Waste in Ethiopia. Sustainability. 10. 2678. 10.3390/su10082678.

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# Towards a Circular Economy Systems Engineering Framework

# **Alternative Products from Coffee Waste**

CENTER FOR COFFEE RESEARCH & EDUCATION

## Spent Coffee

- Animal feed
- Biodiesel, Biooil Biochar
- Biogas
- Coffee oil
- Adsorbent
- Activated Carbon
- Pellets
- Antioxidants
- Spent coffee extracts
- Soil Amendment

## Coffee Pulp

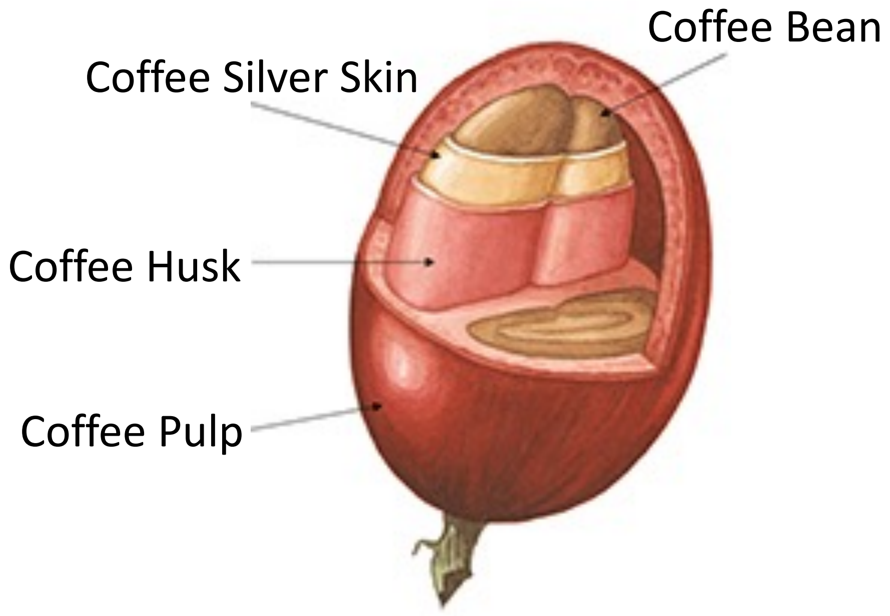
- Mushroom production
- Composting
- Food commodities
- Polyphenol extraction
- Anthocyanins
- Animal feed
- Biosorbents
- Biogas
- Bioethanol

## Coffee Husk

- Citric Acid
- Gibberellic
- Vermicompost
- Flavor
- Particle board
- Biosorbents
- Tannase
- Biogas
- Bioethanol

## Coffee silver skin

- Phenolic compounds
- Dietary fiber
- Biogas




Murthy S. P., Naidu M. M.; Sustainable management of coffee industry by-products and value addition – A review. *Resources, Conservation and Recycling* 66 (2012) 45-58

# Valorization of coffee by-products for the production of bio-energy

| Coffee By-Products & Wastes | Bio-Energy Production | | | | | | |
|---|---|---|---|---|---|---|---|
| | Biodiesel | Bioethanol | Biogas | Bio-oil | Fatty Acid Methyl Ester (FAME) | Fuel Pellet | Hydrogen |
| Coffee Husk | | Gouvea et al. (2009) | Blinová et al. (2017)<br>Chala et al. (2018)<br>Murthy and Naidu (2012b)<br>Ulsido et al. (2016) | | | Blinová et al. (2017) | |
| Coffee Pulp | | Blinová et al. (2017)<br>Gurram et al. (2016) | Blinová et al. (2017)<br>Chala et al. (2018)<br>Figueroa et al. (2016) | | | Blinová et al. (2017) | |
| Coffee Mucilage | | Orrego et al. (2018) | Chala et al. (2018) | | | | Hernández et al. (2014) |
| Coffee Parchment | | | Chala et al. (2018) | | | | |
| Coffee Silverskin | | Blinová et al. (2017)<br>Figueroa et al. (2016) | | | | | |
| Spent Coffee Grounds | Blinová et al. (2017)<br>Campos-Vega et al. (2015)<br>Banu et al. (2020)<br>Karmee (2018)<br>Murthy and Naidu (2012b)<br>Kwon et al. (2013)<br>Tongcumpou et al. (2019)<br>Berhe et al. (2013)<br>Haile (2014)<br>Vardon et al. (2013)<br>McNutt et al. (2019) | Blinová et al. (2017)<br>Banu et al. (2020)<br>Karmee (2018)<br>Figueroa et al. (2016)<br>Murthy and Naidu (2012b)<br>Kwon et al. (2013)<br>McNutt et al. (2019) | Banu et al. (2020)<br>Karmee (2018)<br>Figueroa et al. (2016)<br>Li et al. (2014)<br>Lee et al. (2019)<br>Vítěz et al. (2016) | Banu et al. (2020)<br>Karmee (2018)<br>Figueroa et al. (2016)<br>Li et al. (2014)<br>Vardon et al. (2013) | Banu et al. (2020)<br>Karmee (2018)<br>Lee et al. (2019) | Blinová et al. (2017)<br>Banu et al. (2020)<br>Karmee (2018)<br>Figueroa et al. (2016)<br>Stylianou et al. (2018)<br>Haile (2014) | Banu et al. (2020)<br>Karmee (2018) |

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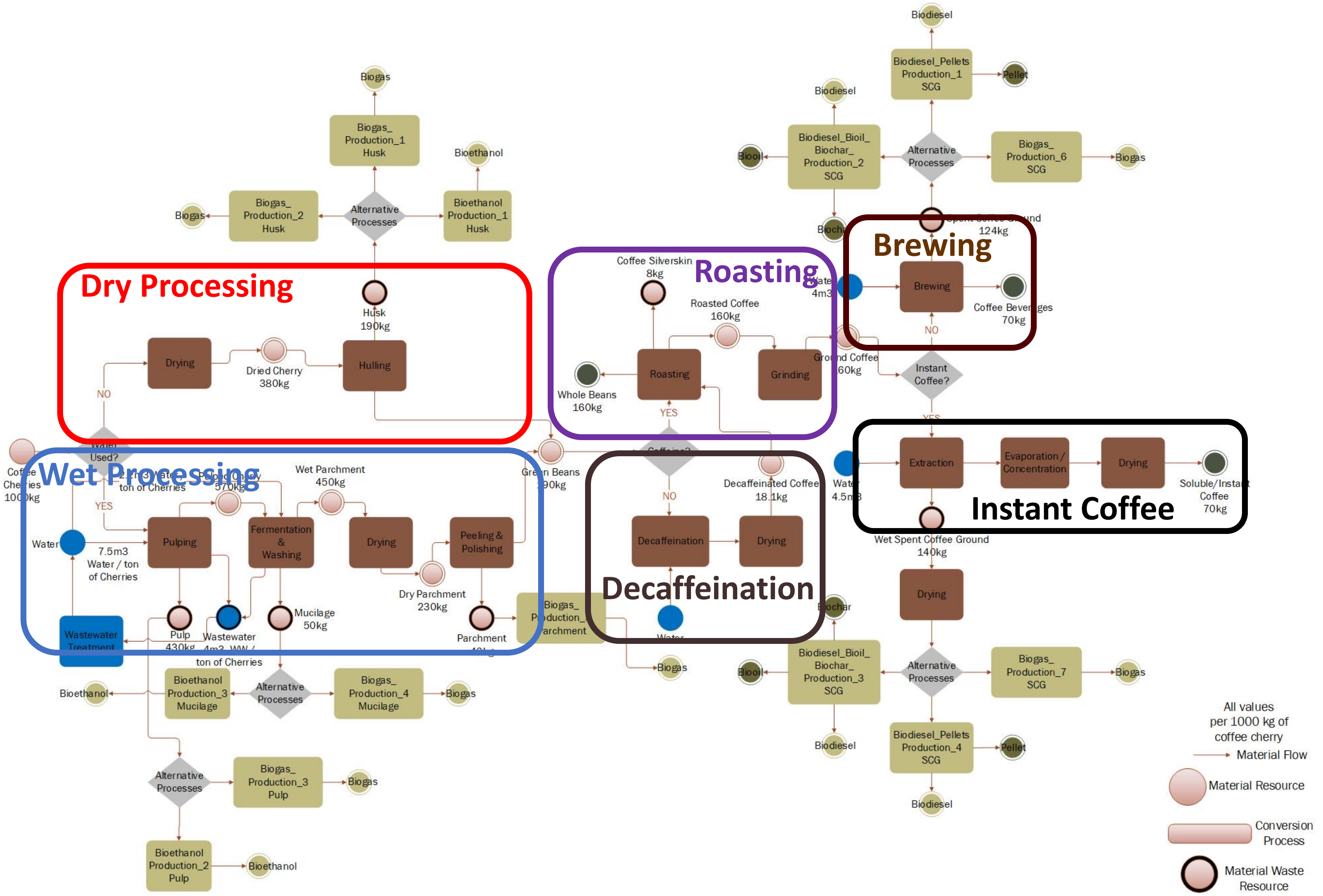
Towards a Circular Economy Systems Engineering Framework

# Superstructure Network of the coffee supply chain



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# MILP model for the coffee supply chain

- Binary Variables:
  - Choice of process (e.g. wet or dry)
  - Choice of waste utilization processes

- Continuous Variables
  - Amount of material going in and out of each process

- Constraints
  - Mass balances and conversion equations

$$p_i + \sum_{j \in \mathcal{P}} pc_{i,j} \cdot x_j = s_i \ \forall\ i \in \mathcal{M}$$

  - Big-M constraints

$$x_j \le M \cdot y_j \ \forall\ j \in \mathcal{P}$$

- Objective Functions
  - Maximize profit
  - Minimize waste
  - Minimize natural resource use
  - Minimize GHG emissions
  - Maximize energy efficiency
  - Etc.

**Coffee model statistics:**
138 equations
58 continuous variables
18 binary variables

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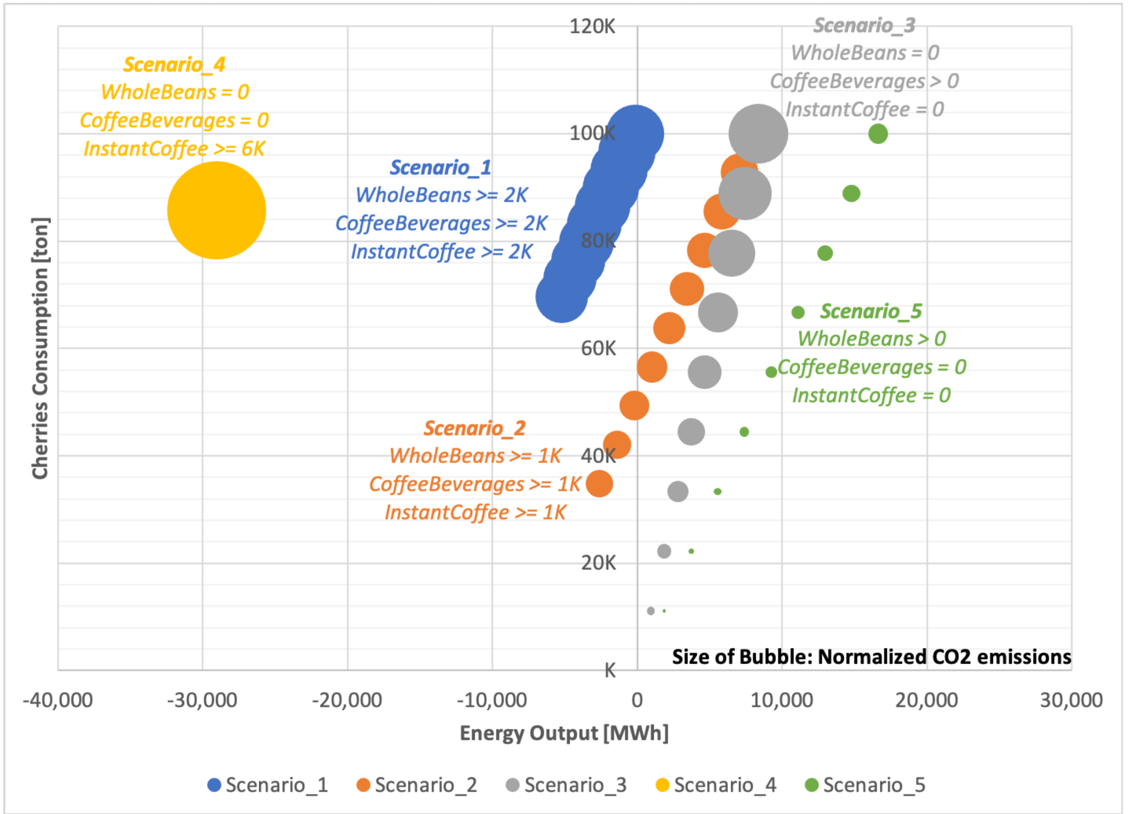
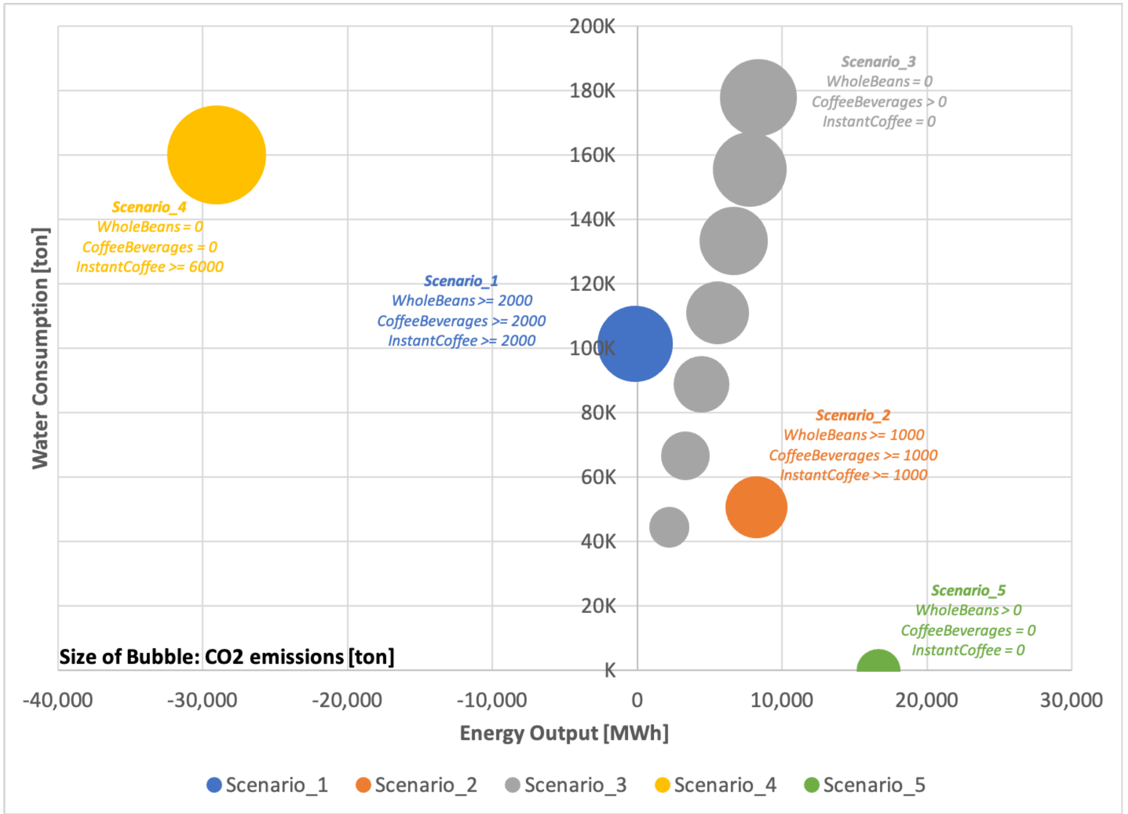
## **Pareto fronts – Analysis of different demand scenarios**




| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|
| Whole Beans (ton) | ≥ 2,000 | ≥ 1,000 | = 0 | = 0 | > 0 |
| Coffee Beverages (ton) | ≥ 2,000 | ≥ 1,000 | > 0 | = 0 | = 0 |
| Instant Coffee (ton) | ≥ 2,000 | ≥ 1,000 | = 0 | ≥ 6,000 | = 0 |

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# CE Coffee Supply Chain – Remarks

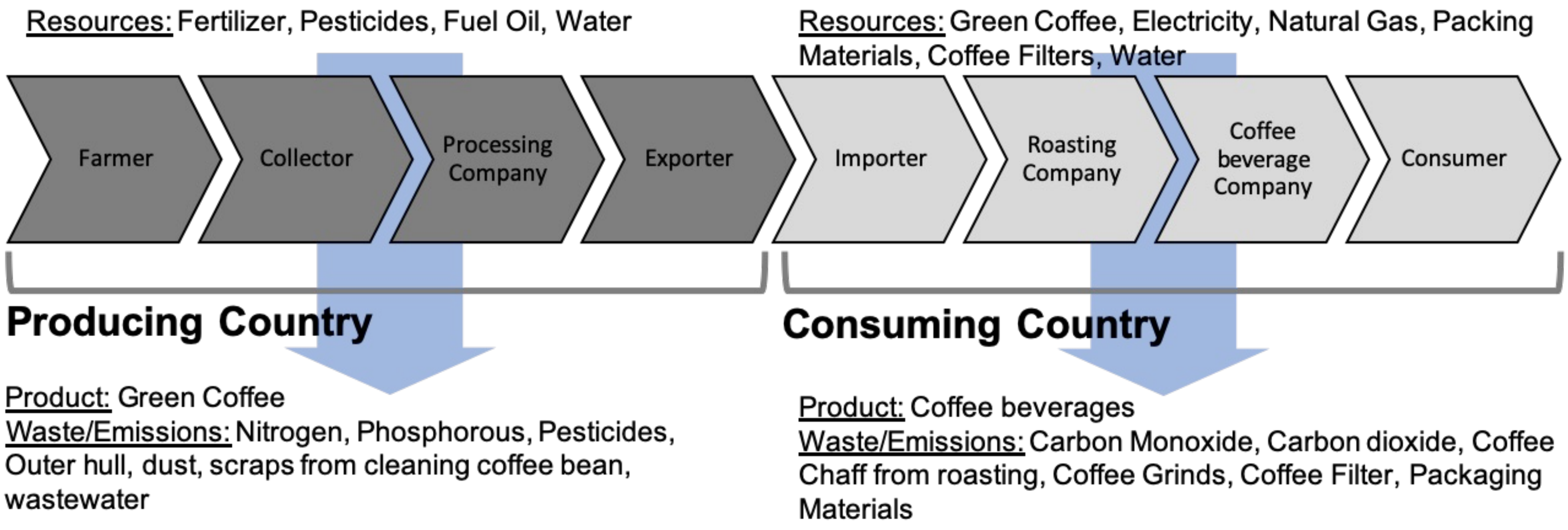
- Presented a framework for the **modeling** and **optimization** of CE food supply chains
- Can aid in the **understanding, analysis** and **optimization** of more general Circular Economy Supply Chains

Future Work:

1. Economics!
2. Time dimension
3. Uncertainty/Resilience studies
4. Modeling simplifications

# CE Coffee Supply Chain – Future work/Open Questions

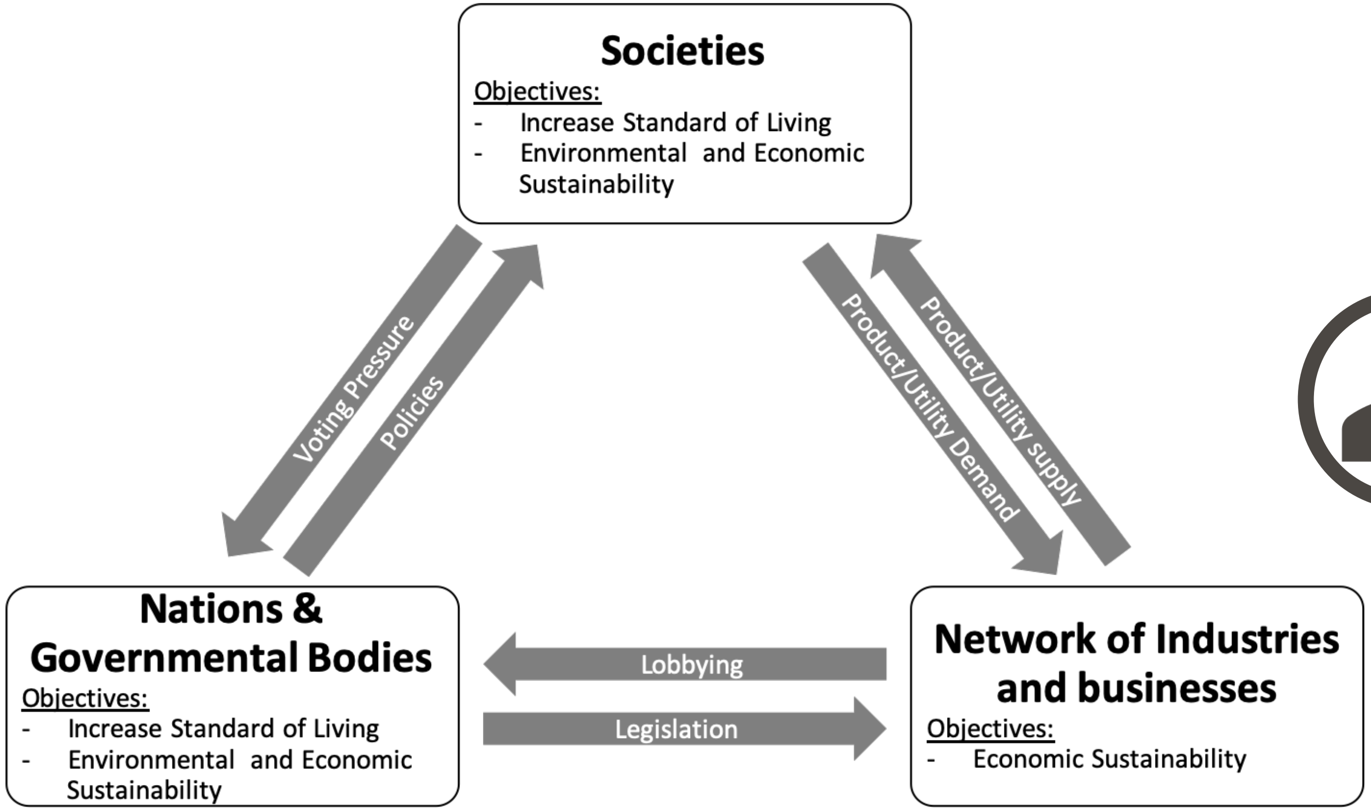
1. How do we model different decision makers?

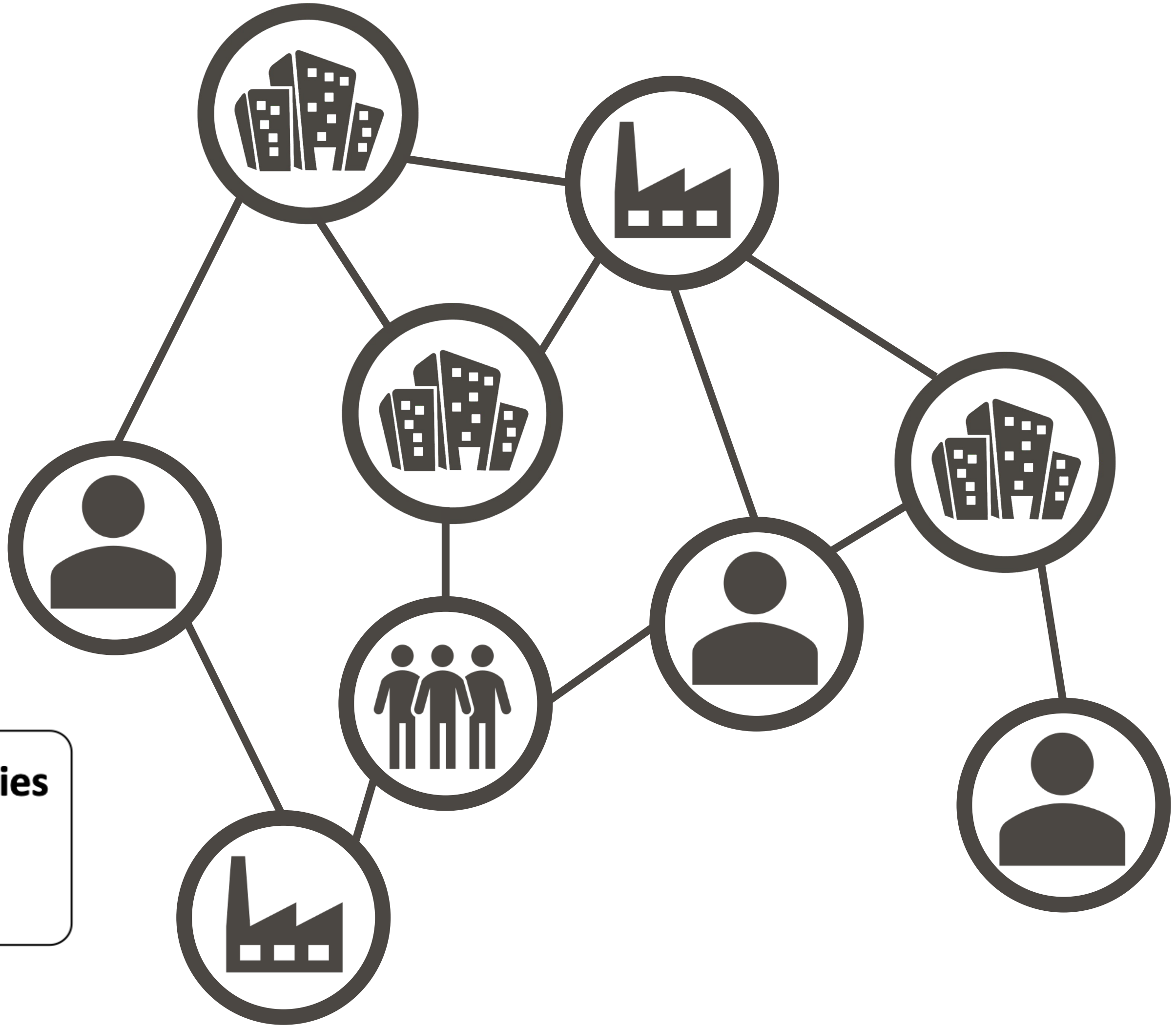



Avraamidou, S.; Baratsas, S.; Tian, Y.; Pistikopoulos, E. N. Circular Economy - a challenge and an opportunity for Process Systems Engineering. *Computers & Chemical Engineering* **2020,** *133,* 106629.

# CE Coffee Supply Chain – Future work/Open Questions

1. How do we model different decision makers?
2. Policy & regulation issues?



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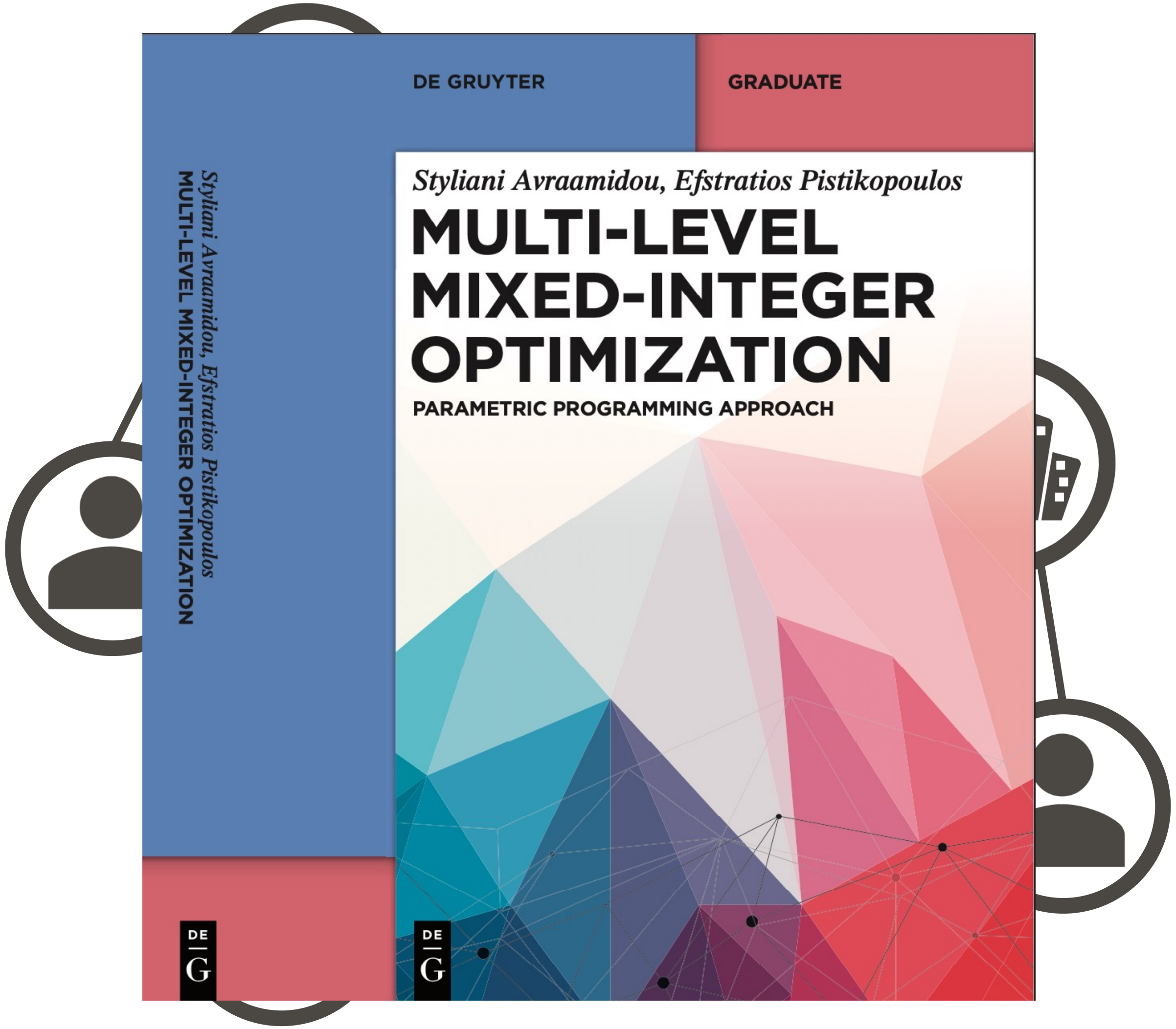
## Interconnected Players

- Role of policy
- Multiple Stakeholders and Domain Experts
- Legislation

**Observations:**

1. Multiple decision makers
2. Different objectives
3. Control different variables
4. Take decisions sequentially

**Multi-level optimization**



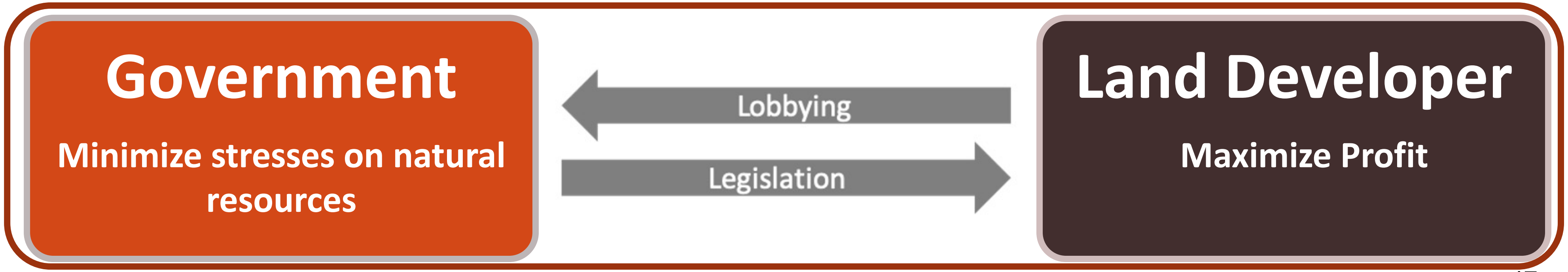
# Towards a Circular Economy Systems Engineering Framework

## Challenge 1: Interconnected Players

| | | | |
|---|---|---|---|
| **Wind Energy** | **Solar Energy** | **Fruit** | **Livestock** |
| **Wind Energy** | **Solar Energy** | **Vegetables** | **Livestock** |

We have a fictional piece of land owned by an organization

- Invest on this land to **maximize profit**
- Considering important characteristics of
  - Each land process
  - Land itself
  - Subsidies given by the government
- **Climate:** Texas climate (4 – seasons)
- **Land Properties:** 8 equal-sized sections



## Challenge 1: Interconnected Players

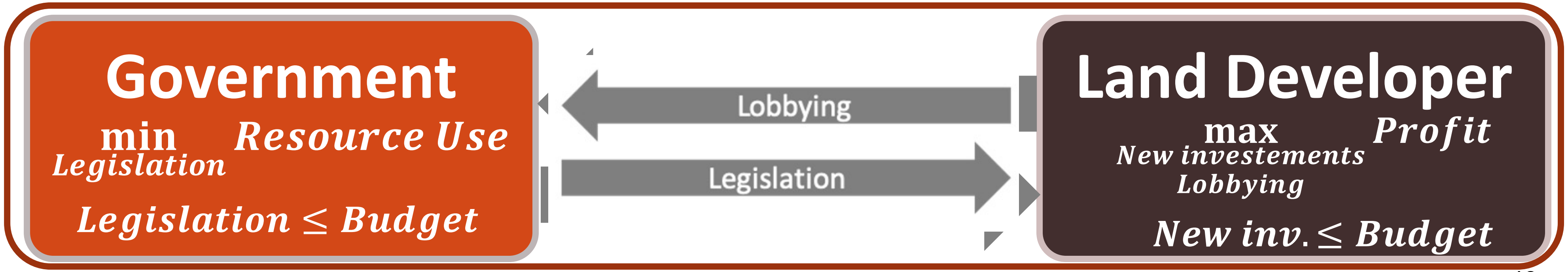
| | | | |
|---|---|---|---|
| Wind Energy | Solar Energy | Fruit | Livestock |
| Wind Energy | Solar Energy | Vegetables | Livestock |

**Observations:**

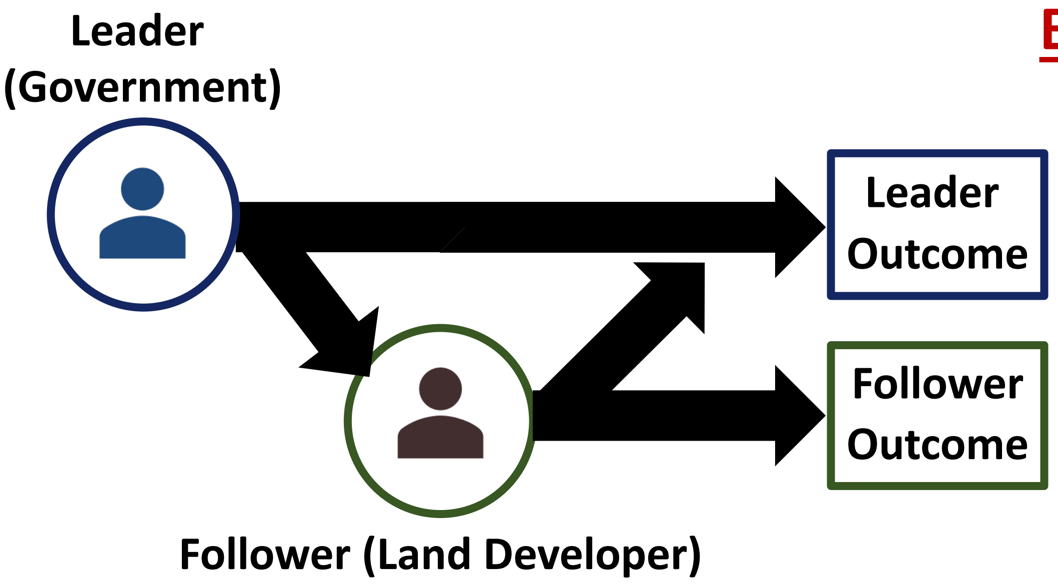
1. Two decision makers
2. Different objectives
3. Control different variables
4. Take decisions sequentially

**Bi-level optimization of Land Use Allocation:**

$$\min \; \textit{Stresses on Natural Resources}$$
$$s.t. \; \textit{Government Budget}$$
$$\max \; \textit{Developer's Profit}$$
$$s.t. \; \textit{Land Properties, Developers Budget, Land Process Models}$$



## Challenge 1: Interconnected Players




**Bi-level optimization of Land Use Allocation:**

$$\min \quad \textit{Stresses on Natural Resources}$$
$$s.t. \quad \textit{Government Budget}$$
$$\max \quad \textit{Developer's Profit}$$
$$s.t. \quad \textit{Land Properties}, \textit{Developers Budget}, \textit{Land Process Models}$$

# Multi-level Programming – An overview

Very difficult (NP-hard) even in the bi-level linear case (without integer variables at any level)

- **Need for Global optimization**

*Integer variables* in the follower's optimization problem

- **Even more challenging!! Only sporadic attempts**

Both **continuous** and **integer** variables in the **lower level**

$$\begin{aligned} \min_{x_1, y_1} \quad & F(x,y) = {c_1}^T x + {d_1}^T y \\ s.t. \quad & A_1 x + B_1 y \leq b_1 \\ & \min_{x_2, y_2} \quad f(x,y) = {c_2}^T x + {d_2}^T y \\ & s.t. \quad A_2 x + B_2 y \leq b_2 \end{aligned}$$

$$x = [{x_1}^T {x_2}^T]^T \in \Re$$

$$y = [{y_1}^T {y_2}^T]^T \in Z$$

# Multi-level Programming – An overview

Very difficult (NP-hard) even in the bi-level linear case (without integer variables at any level)

- ➢**Need for Global optimization**

*Integer variables* in the follower's optimization problem

- ➢**Even more challenging!! Only sporadic attempts**

*Multiple followers and/or levels*

- ➢**Even more challenging!!**

➡ **Multi-parametric programming based algorithms for the solution of mixed-integer multi-level problems**

# Mixed-Integer Multi-level Programming
# via
# Multi-Parametric Programming

- **Main ideas:**

  - *The feasible sets of the lower level problems are multi-parametric in terms of the decision variables of the higher level problems.*

  - *Using multi-parametric programming the linearity of the problem is conserved.*

# *Multi-level Mixed-Integer Programming*-The algorithms

Global optimization algorithms for the *global* solution of different classes of multi-level programming problems:

1. Bi-level mixed-integer linear programming problems (**B-MILP**)
2. Bi-level mixed-integer quadratic programming problems (**B-MIQP**)
3. Extensions to problems with **RHS uncertainty.**
4. Tri-level mixed-integer programming problems (**T-MILP** and **T-MIQP**)
5. Multi-level mixed-integer programming problems (**M-MILP** and **M-MIQP**)
6. Bi-level multi-follower programming problems (**BMF-MILP** and **BMF-MIQP**)

containing both integer and continuous variables at all optimization levels.

**Government's Opt. Problem**

$$\min_{x_1,y_1} \quad F(x,y) = {c_1}^T x + {d_1}^T y$$
$$s.t. \quad A_1 x + B_1 y \leq b_1$$

**Investor's Opt. Problem**

$$\min_{x_2,y_2} \quad f(x,y) = {c_2}^T x + {d_2}^T y$$
$$s.t. \quad A_2 x + B_2 y \leq b_2$$

**B-MILP**

$$x = [{x_1}^T {x_2}^T]^T \in \Re$$
$$y = [{y_1}^T {y_2}^T]^T \in Z$$

# B-POP toolbox

**B-MILP**

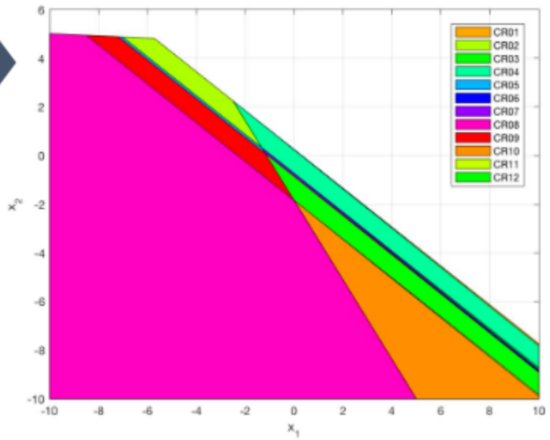
$$\min_{x_1,y_1} \quad F(x,y) = {c_1}^T x + {d_1}^T y$$
$$s.t. \quad A_1 x + B_1 y \le b_1$$
$$\quad \min_{x_2,y_2} \quad f(x,y) = {c_2}^T x + {d_2}^T y$$
$$\quad s.t. \quad A_2 x + B_2 y \le b_2$$
$$x = [{x_1}^T {x_2}^T]^T \in \Re$$
$$y = [{y_1}^T {y_2}^T]^T \in Z$$

**1 Recast as a mp-MILP**

$$\min_{x_2,y_2} \quad f(x,y) = {c_2}^T x + {d_2}^T y$$
$$s.t. \quad A_2 x + B_2 y \le b_2$$
$${x_1}^L \le x_1 \le {x_1}^U$$

Parameters: $x_1, y_1$

**2 Solve the mp-MILP using POP®**




$$[x_2, y_2] = \begin{cases} \xi_1 = p_1 + q_1 x_1, \psi_1 & \text{if } H_1 x_1 \le h_1 \\ \xi_2 = p_2 + q_2 x_1, \psi_2 & \text{if } H_2 x_1 \le h_2 \\ \vdots & \vdots \\ \xi_k = p_k + q_k x_1, \psi_k & \text{if } H_k x_1 \le h_k \end{cases}$$

**3 Substitute mp solution in the upper level**

$$z_1 = \min_{x_1,y_1} \quad {c_1}^T x + {d_1}^T y$$
$$s.t. \quad A_1 x + B_1 y \le b_1, \quad H_1 x_1 \le h_1, \quad x = [{x_1}^T \ \xi_1(x_1)^T]^T, \quad y = [{y_1}^T \ {\psi_1}^T]^T$$

$$z_2 = \min_{x_1,y_1} \quad {c_1}^T x + {d_1}^T y$$
$$s.t. \quad A_1 x + B_1 y \le b_1, \quad H_2 x_1 \le h_2, \quad x = [{x_1}^T \ \xi_2(x_1)^T]^T, \quad y = [{y_1}^T \ {\psi_2}^T]^T$$

$$\vdots$$

$$z_k = \min_{x_1,y_1} \quad {c_1}^T x + {d_1}^T y$$
$$s.t. \quad A_1 x + B_1 y \le b_1, \quad H_k x_1 \le h_k, \quad x = [{x_1}^T \ \xi_k(x_1)^T]^T, \quad y = [{y_1}^T \ {\psi_k}^T]^T$$

**4 Solve single-level MILP**

| CR | Objective |
|---|---|
| 1 | $z_1$ |
| 2 | $z_2$ |
| … | … |
| k | $z_k$ |

**5 Compare and choose optimum**

- ✓ Bi-level
- ✓ Tri-level
- ✓ Multi-level
- ✓ Integer & Continuous Variables for all decision makers
- ✓ Linear
- ✓ Quadradic

## Challenge 1: Interconnected Players

**Government's Opt. Problem** — **LP**

$$\begin{aligned} \min_{x_1,y_1} \quad & F(x,y) = {c_1}^T x + {d_1}^T y \\ s.t. \quad & A_1 x + B_1 y \leq b_1 \end{aligned}$$

**Investor's Opt. Problem** — **MILP**

$$\begin{aligned} \min_{x_2,y_2} \quad & f(x,y) = {c_2}^T x + {d_2}^T y \\ s.t. \quad & A_2 x + B_2 y \leq b_2 \end{aligned}$$

$$x = [{x_1}^T {x_2}^T]^T \in \Re$$

$$y = [{y_1}^T {y_2}^T]^T \in Z$$

| | | | |
|---|---|---|---|
| Wind Energy | Solar Energy | Fruit | Livestock |
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Avraamidou, S.; Beykal, B.; Pistikopoulos, I. P. E.; Pistikopoulos, E. N. A hierarchical Food-Energy-Water Nexus (FEW-N) Decision-making Approach for Land Use Optimization. 13th International Symposium on Process Systems Engineering (PSE 2018); Elsevier, **2018**; pp 1885-1890.

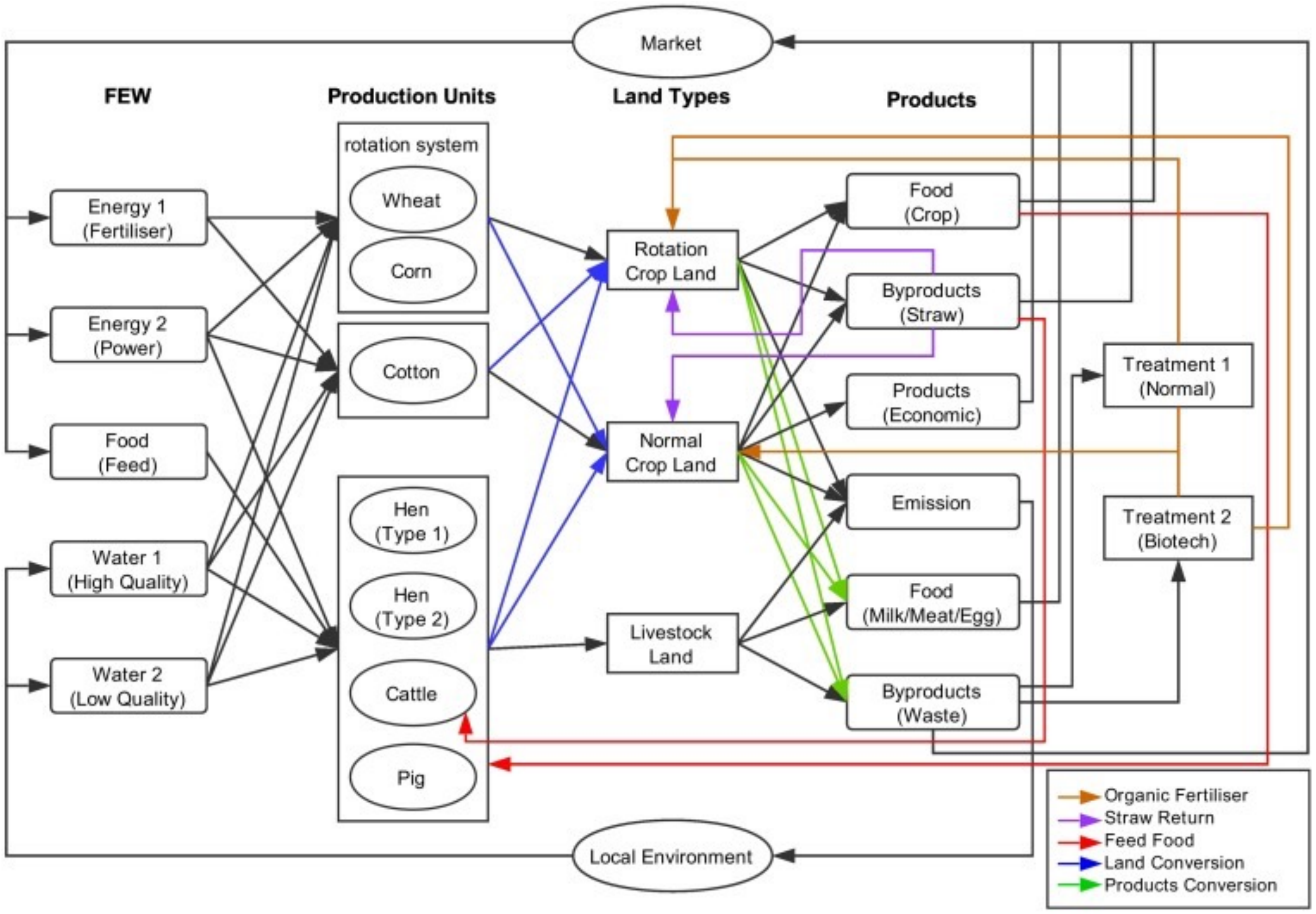
## Land Use Allocation - Extensions

### Yucheng County, Shandong Province of China:

Nie, Y.; Avraamidou, S.; Xiao, X.; Pistikopoulos, E. N.; Li, J.; Zeng, Y.; Song, F.; Yu, J.; Zhu, M. A Food-Energy-Water Nexus approach for **land use optimization**. Science of the Total Environment **2019**, 659, 7-19.

### Texas Edwards region:

Nie, Y.; Avraamidou, S.; Xiao, X.; Pistikopoulos, E. N.; Li, J. **Two-stage Land use optimization** for a **Food-Energy-Water nexus** system: a case study in Texas Edwards region. Foundations of Computer-Aided Process Design (FOCAPD 2019); **2019**

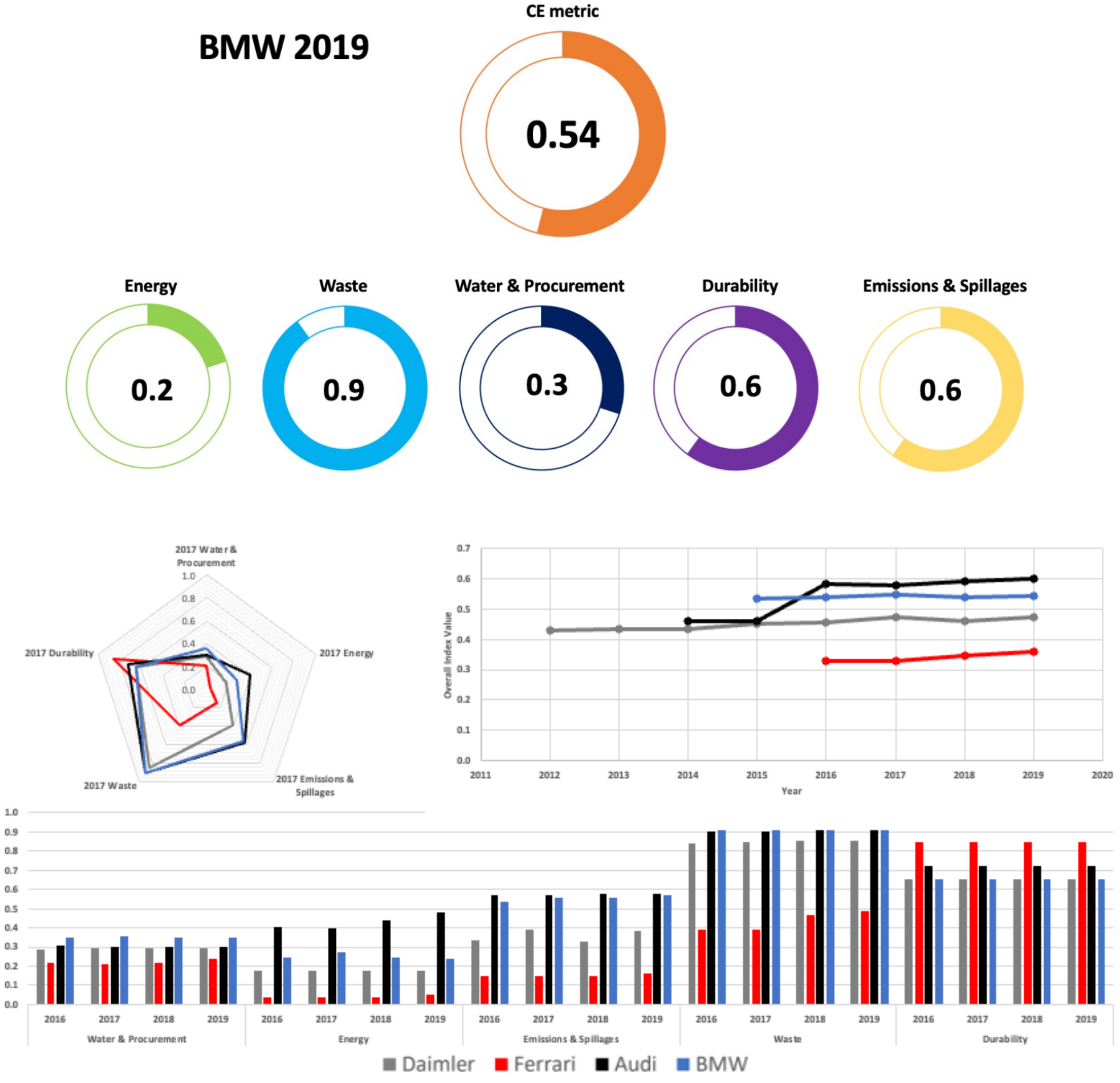


# CE Coffee Supply Chain – Future work/Open Questions

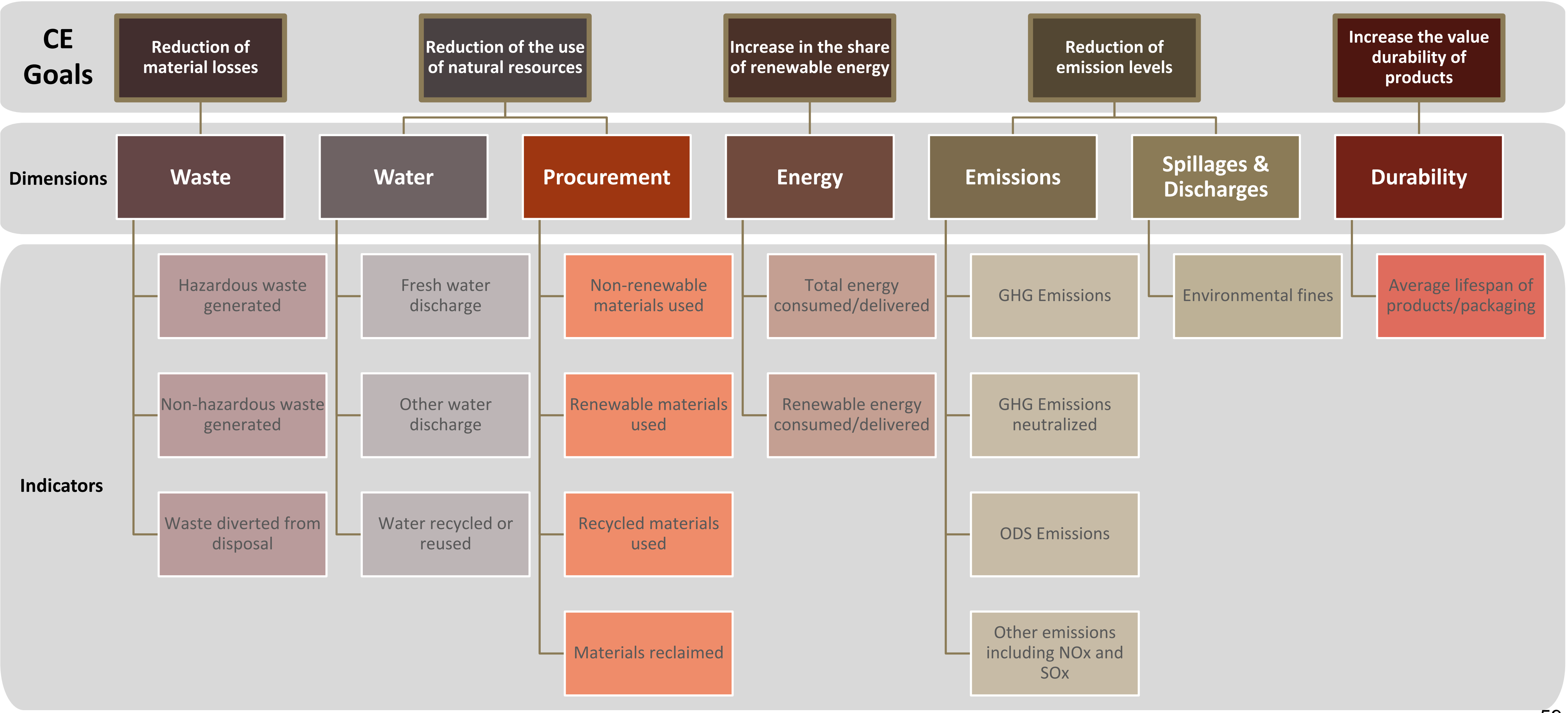
1. How do we choose between the different optimal points in the Pareto fronts?
2. How do we optimize Circularity?

# Towards a Circular Economy Calculator

- A tool to evaluate the ‘circularity’ of companies
- Considers a set of specific indicators and metrics based on the CE goals
- Metrics are mostly GRI based with some LCA
- A set of indicators and metrics with sector-specific dimensions
- Media for data visualization and analysis of CE indicators
- Towards an analytical tool to assess the multi-scale, multi-faceted and interconnected CE supply chains.



# Towards a CE Calculator



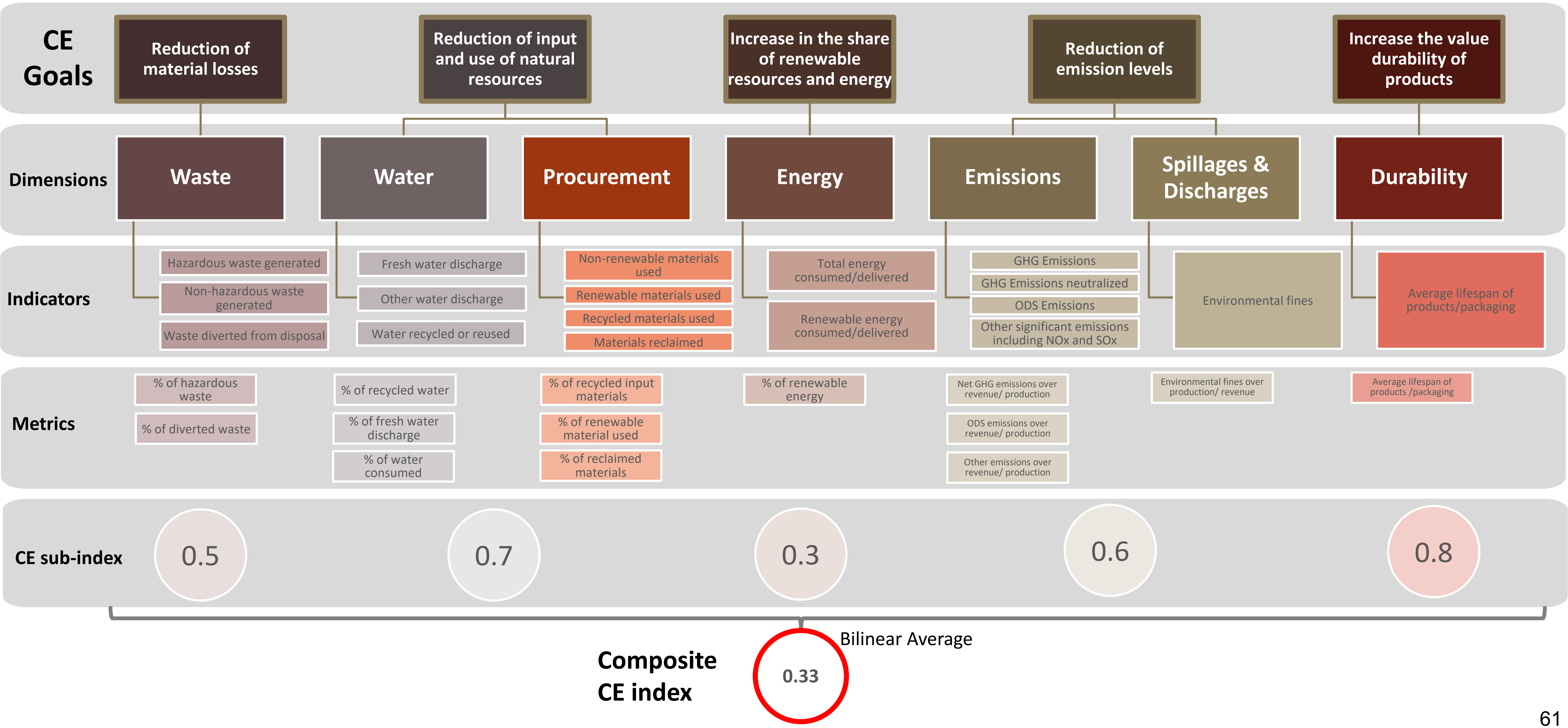
# Towards a CE Calculator

**CE Goals**

- Reduction of material losses → Waste
- Reduction of the use of natural resources → Water, Procurement
- Increase in the share of renewable energy → Energy
- Reduction of emission levels → Emissions, Spillages & Discharges
- Increase the value durability of products → Durability

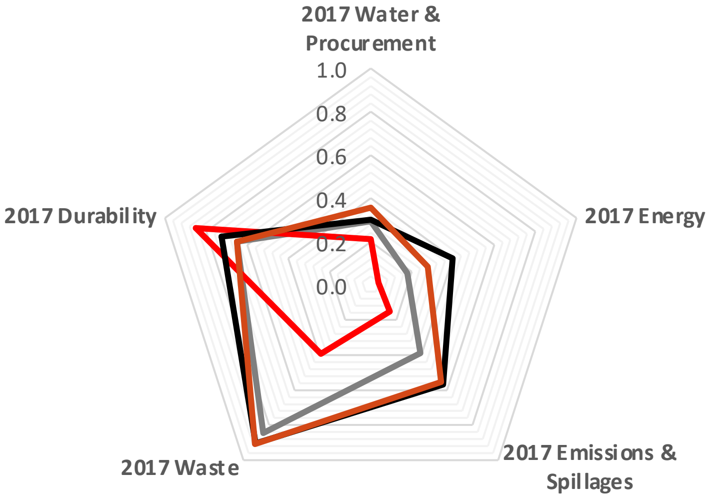
| Dimensions | Indicators | Metrics |
|---|---|---|
| Waste | Hazardous waste generated<br>Non-hazardous waste generated<br>Waste diverted from disposal | % of hazardous waste<br>% of diverted waste |
| Water | Fresh water discharge<br>Other water discharge<br>Water recycled or reused | % of recycled water<br>% of fresh water discharge<br>% of water consumed |
| Procurement | Non-renewable materials used<br>Renewable materials used<br>Recycled materials used<br>Materials reclaimed | % of recycled input materials<br>% of renewable material used<br>% of reclaimed materials |
| Energy | Total energy consumed/delivered<br>Renewable energy consumed/delivered | % of renewable energy |
| Emissions | GHG Emissions<br>GHG Emissions neutralized<br>ODS Emissions<br>Other significant emissions including NOx and SOx | Net GHG emissions over revenue/ production<br>ODS emissions over revenue/ production<br>Other emissions over revenue/ production |
| Spillages & Discharges | Environmental fines | Environmental fines over production/ revenue |
| Durability | Average lifespan of products/packaging | Average lifespan of products /packaging |

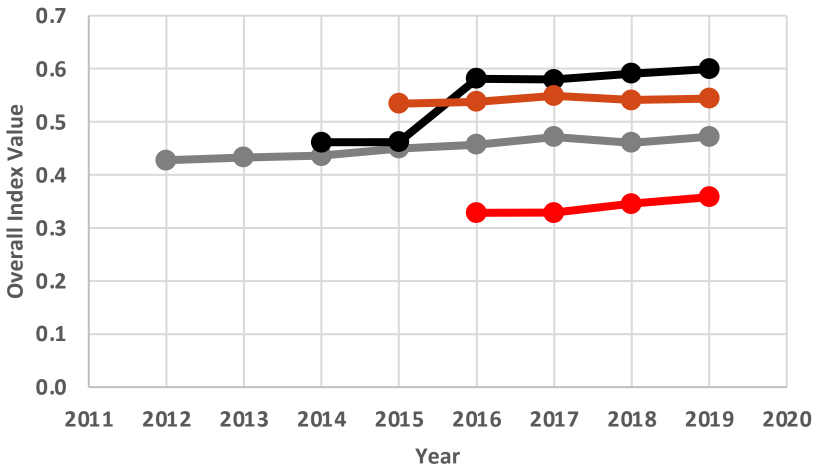
# Towards a CE Calculator



# Towards a Circular Economy Systems Engineering Framework

## Towards a Circular Economy Calculator for Measuring the "Circularity" of Companies





- Chialdikas, Elizabeth, Aurora del C. Munguia-Lopez, Horacio Aguirre-Villegas, Styliani Avraamidou. **A framework for the evaluation of the circularity of plastic waste management systems.** FOCAPO-CPC (2023)
- Baratsas, Stefanos G., Efstratios N. Pistikopoulos, and Styliani Avraamidou. **A quantitative and holistic circular economy assessment framework at the micro level**. Computers & Chemical Engineering (2022), 107697.
- Baratsas, S. G., Masoud, N., Pappa, V. A., Pistikopoulos, E. N., & Avraamidou, S. **Towards a Circular Economy Calculator for Measuring the "Circularity" of Companies.** In Computer Aided Chemical Engineering (2021), Vol. 50, pp. 1547-1552. Elsevier.


- ✓ Companies are able to track their transition towards CE
- ✓ Identify areas that need improvement
- ✓ Conduct temporal analysis
- ✓ Compare their performance against their peers

**A step towards predictive metrics to be used in supply chain optimization**

# Circular Economy Systems Engineering - Concluding remarks

- Circular Economy relies on system-wide innovation
- The concept has been created mainly by practitioners, the business community and policy-makers
  - **Building a scientific basis for Circular Economy is important**

A Process Systems Engineering approach can have a big impact on:

- The **understanding, analysis and optimization** of Circular Economy Supply Chains, and
- The **convergence of different disciplines** towards a common vision of Circular Economy

**Open Research Questions:**

1. Uniqueness of a circular system?
2. Robustness?
3. At which scale? 'Centralized'? Decentralized?
4. Policy & regulation issues?
5. Resource utilization & novel pathway analysis

# Acknowledgements

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Chemical Upcycling of Waste Plastics

NSF

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Dr. Stefanos Baratsas

Department of Chemical and Biological Engineering
UNIVERSITY OF WISCONSIN–MADISON

**CE supply chain of Beer**

Ryan Peters

Ethan Saye

**CE Calculator**

Saanvi Malhotra

**CE of plastics**

Elizabeth Chialdikas

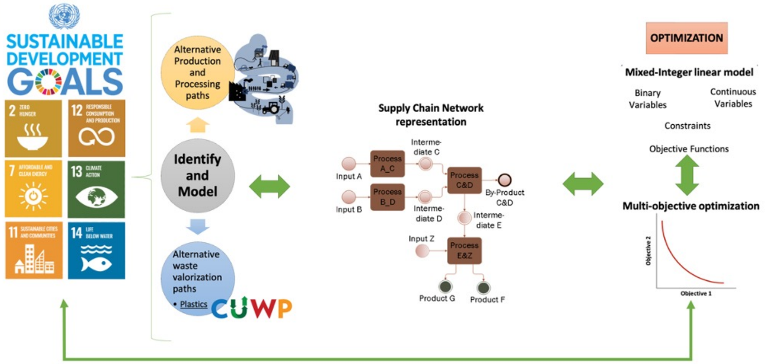
# **Avraamidou Group:** Circular Economy Systems Engineering

Department of Chemical and Biological Engineering
UNIVERSITY OF WISCONSIN–MADISON

## Modeling and Optimization of Food Supply Chains


Developing CE systems engineering framework and decision-making tool for the modeling and optimization of food supply chains.

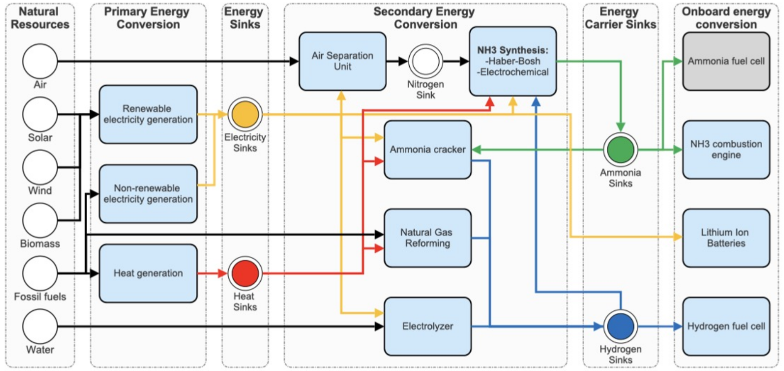
- A superstructure representation will be used to model and capture all identified pathways, based on which an optimization model will be developed and solved.
- Current case studies include supply chain of coffee, dairy and plastics.




## Modeling and Optimization of Chemical Supply Chains

Developing decision-making tools for the design of sustainable chemical supply chains by:
i) Modeling the critical components in the supply chain of chemicals
ii) Mathematical optimization under uncertainty
iii) Infrastructure expansion planning optimization

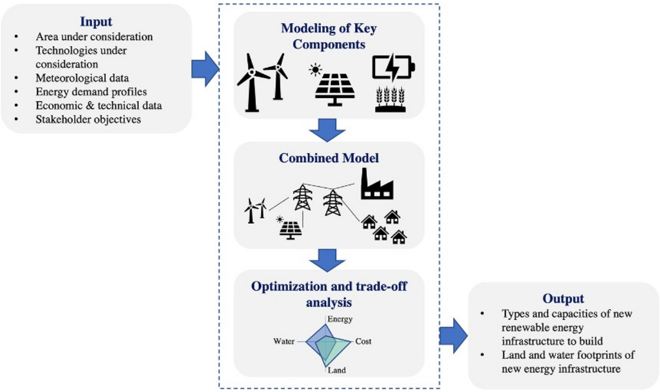
Example case study on the supply chain of ammonia and hydrogen for transportation fuels:




## Energy Systems Engineering

Developing a systems engineering decision-making framework for the trade-off analysis and optimization of renewable energy systems.

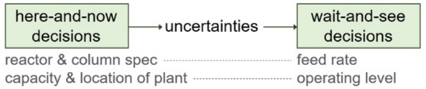
- Combine mathematical modeling, optimization, and data analytics to capture the interdependencies of the different elements (energy, water, land) and therefore facilitate informed decision making.




## Multistage Optimization under Uncertainty

Developing an algorithm for two-stage mixed-integer quadratic adjustable robust optimization (ARO) to find the exact and global solution.

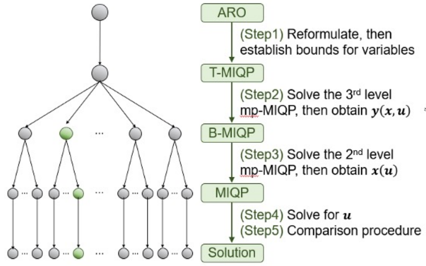
- Several algorithms have been proposed and studied, but most methods are limited to continuous linear ARO problems. Solving the mixed-integer quadratic ARO problems still remains a challenge.
- Application area: scheduling & control, facility location & transportation ...

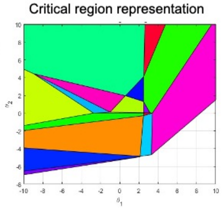


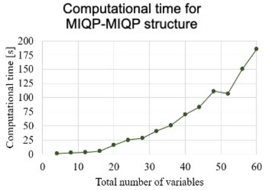

$$\min_x (Q_x x + c_x)^T x + \max_u \min_y (Q_y y + c_y)^T y \quad \text{(1st stage) here-and-now} \quad \text{(2nd stage) wait-and-see}$$

$$\text{s.t. } A_x x + A_y y + A_u u \le b$$

$$x \in X \coloneqq \mathbb{R}^{p_c} \times \{0,1\}^{p_b},\ y \in Y \coloneqq \mathbb{R}^{q_c} \times \{0,1\}^{q_b},\ u \in U \coloneqq \mathbb{R}^{r_o}$$



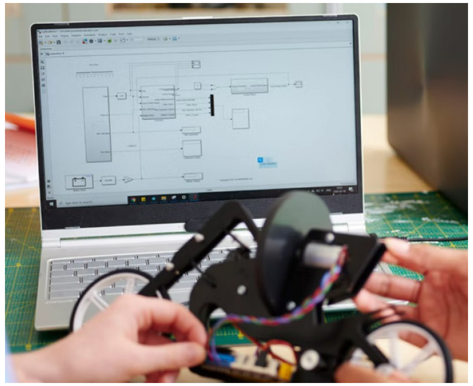



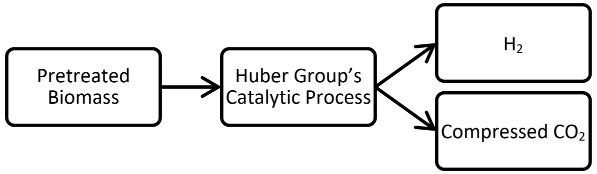
# **Avraamidou Group:** Circular Economy Systems Engineering

## Undergraduate Student Projects:

### ➢ Control systems

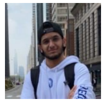


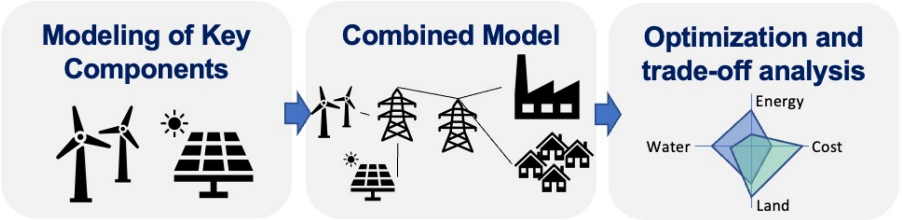
### ➢ LCA and TEA of $H_2$ Supply Chain



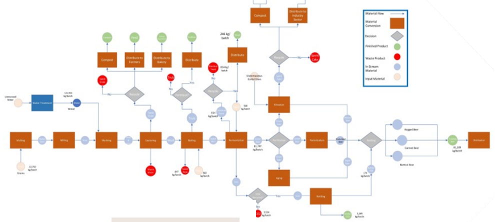

*Collaboration with the Huber Group*

### ➢ Energy Systems Engineering

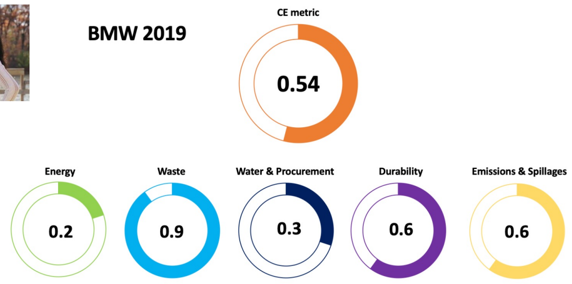




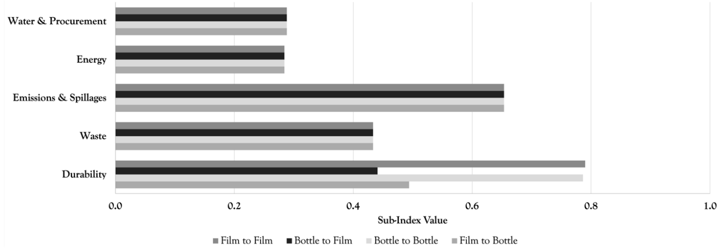

### ➢ Designing a CE Beer Supply Chain




### ➢ Measuring CE: The CE Calculator




- Web-based tool for measuring circularity at the company level




- Tool for measuring and comparing circularity of different plastic waste management processes

*Collaboration with the Zavala Group*

**Group Website:** https://avraamidougroup.che.wisc.edu

# A Systems Engineering Framework for the Optimization of Circular Economy Supply Chains

**Styliani Avraamidou**

University of Wisconsin-Madison