UNESCO-IWRA ONLINE CONFERENCE

17-19 JANUARY 2023

3RD IN THE IWRA ONLINE CONFERENCE SERIES

Emerging Pollutants: Protecting Water Quality for the Health of People and the Environment

Circular Economy Systems Engineering

Styliani Avraamidou

18th of January 2023

unesco

Programme hydrologique intergouvernemental

IWRA International Water Resources Association

Overview

1. Circular Economy – Why? What? How?

- 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.

2. Coffee Supply chain

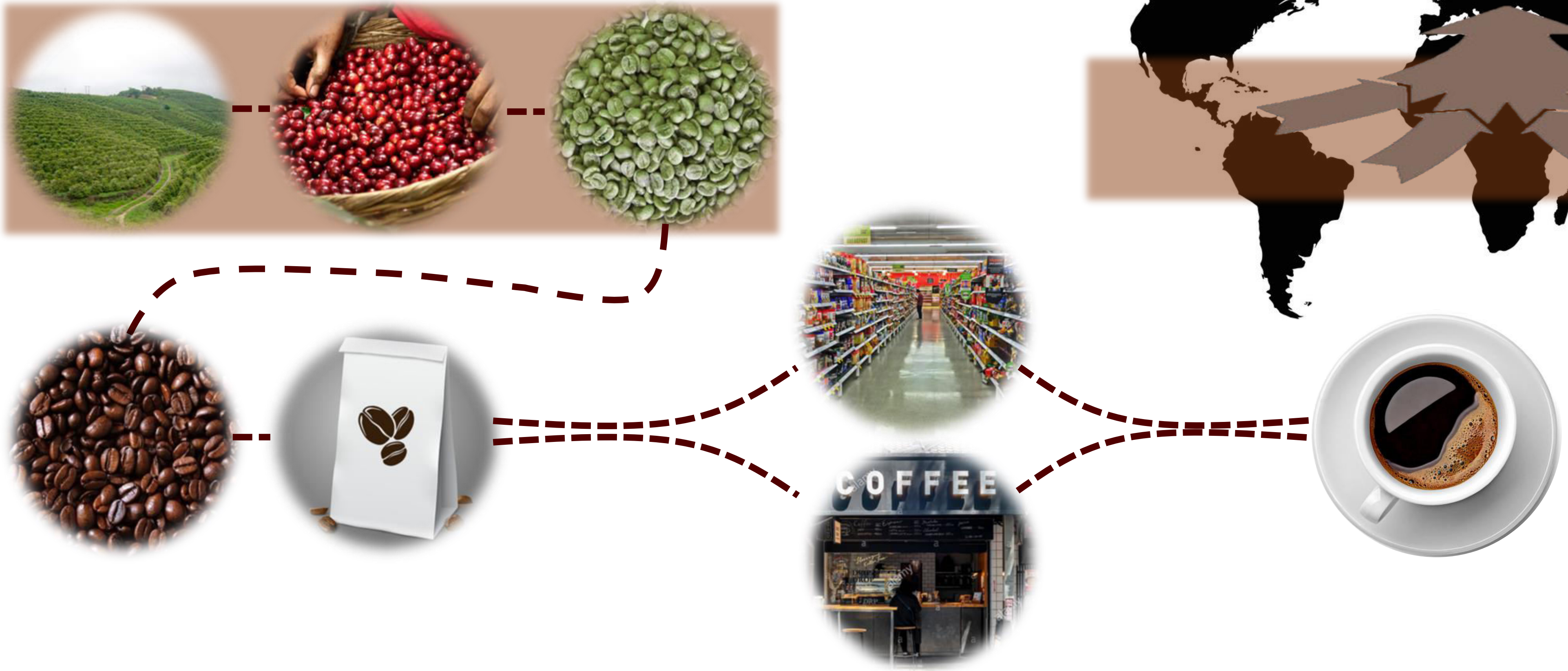
- Baratsas, S. G.; Pistikopoulos, E. N; Avraamidou, S. Circular Economy Systems Engineering: A case study on the Coffee Supply Chain. 31st European Symposium on Computer Aided Process Engineering (ESCAPE-31); 2021.

3. Circular Economy Systems Engineering Framework

- 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)



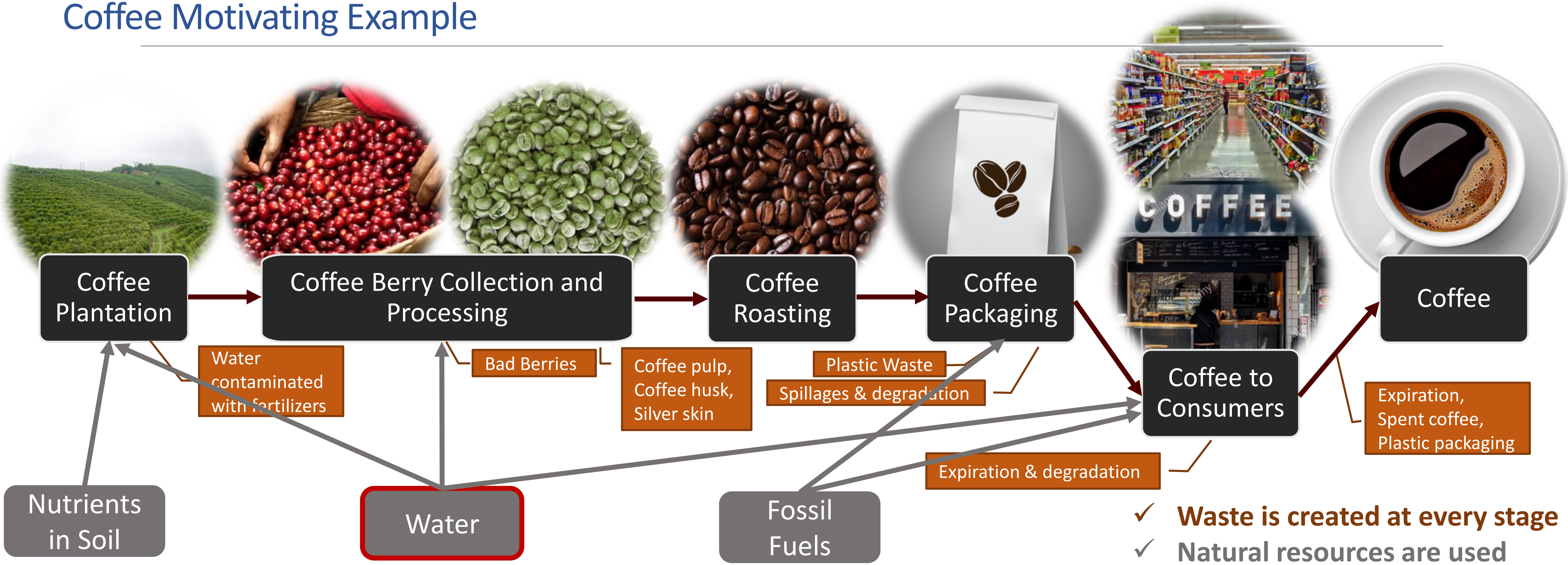
Circular Economy – Why? What? How?
Coffee Motivating Example

1 cup of Coffee (10g dry)

<u>Food industry</u>

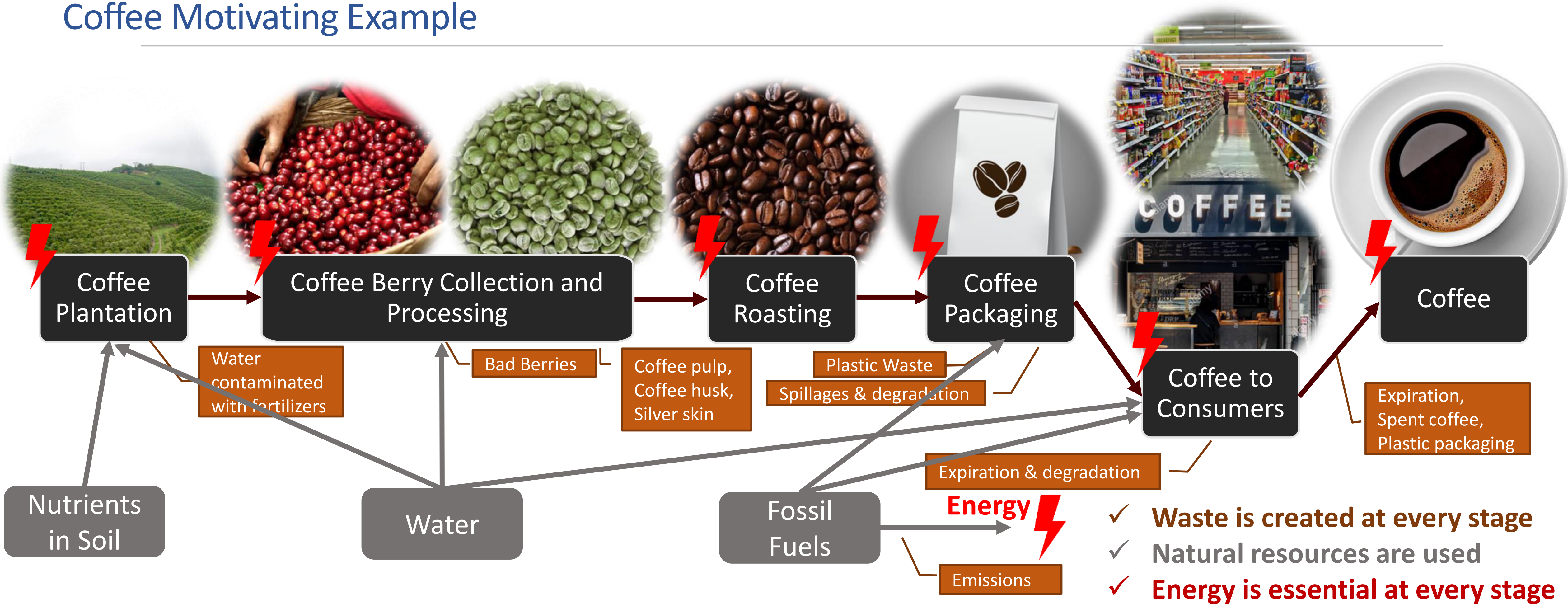
- 30% of the world's **energy**
- 80% of all **water** consumed
- 17% of food is wasted globally (30-40% in the US)
- Plastic waste

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



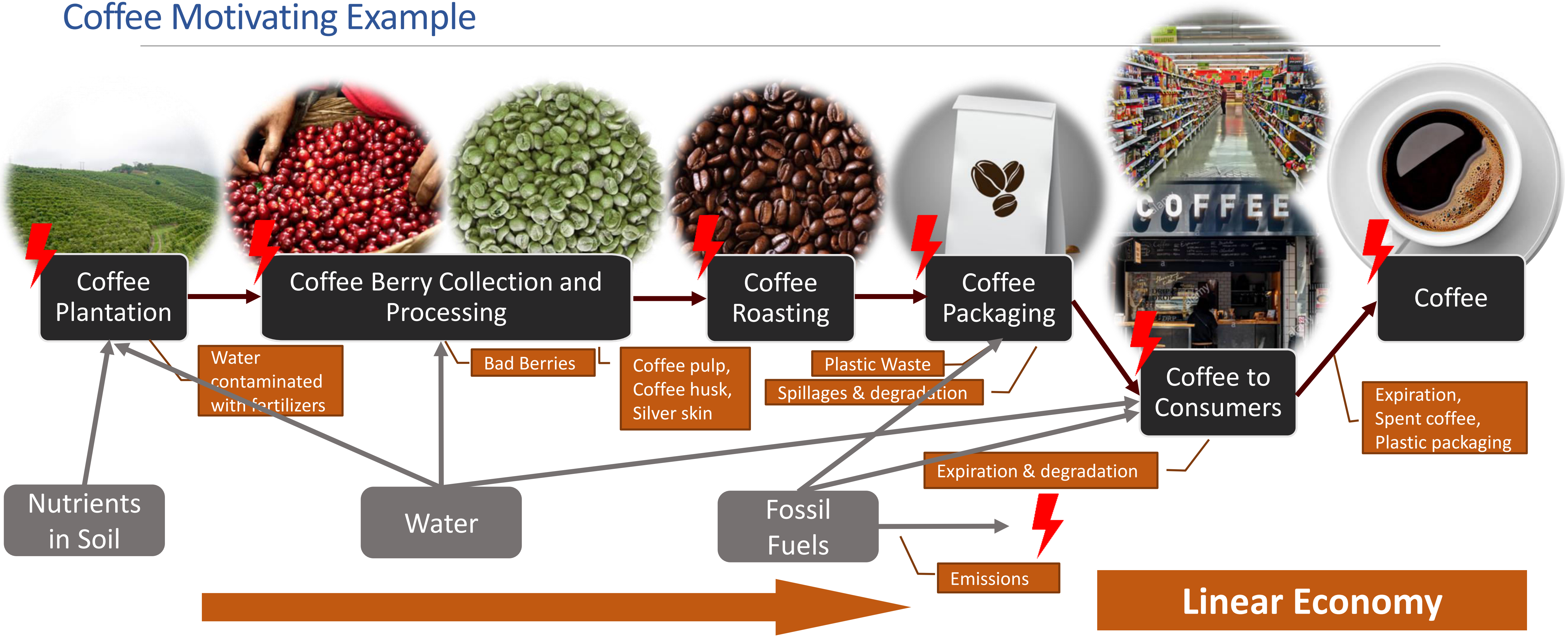
- ✓ **Waste is created at every stage**
- ✓ **Natural resources are used**

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



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

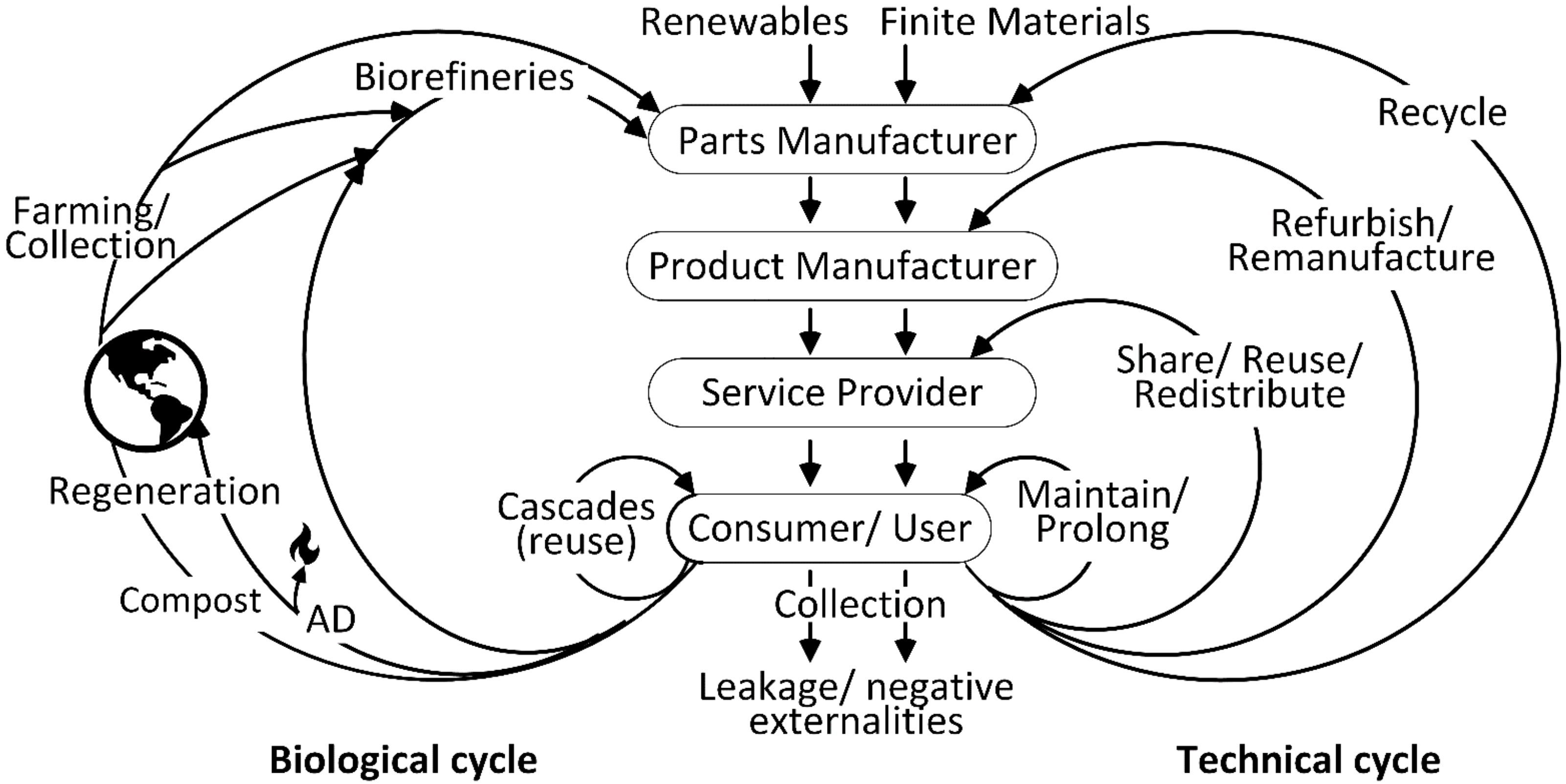
Circular Economy – Why? What? How?
Coffee Motivating Example



What is Circular Economy?

Linear Economy

Circular Economy



How is Circular Economy Defined?

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

Conceptualizing the circular economy: An analysis of 114 definitions

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

1. Reduction of material losses/residuals
2. Reduction of input and use of natural resources
3. Increase in the share of renewable resources and energy
4. Reduction of emission levels
5. Increase the value durability of products

Circular economy throughout the world

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

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

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

CIRCULAR GLASGOW

EPA
BUILDING A CIRCULAR ECONOMY FOR ALL:

Uruguay Circular 2020
HACIA UNA ECONOMÍA CIRCULAR EN URUGUAY

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

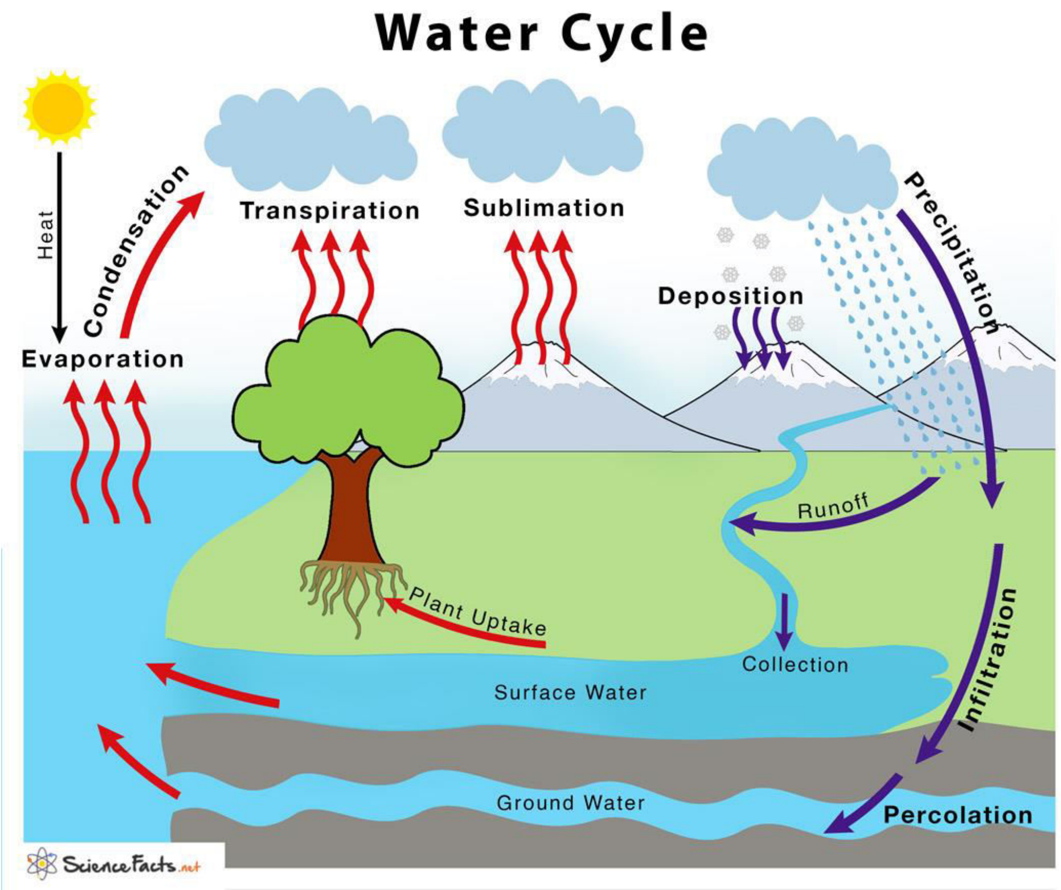
Why Circular Economy?

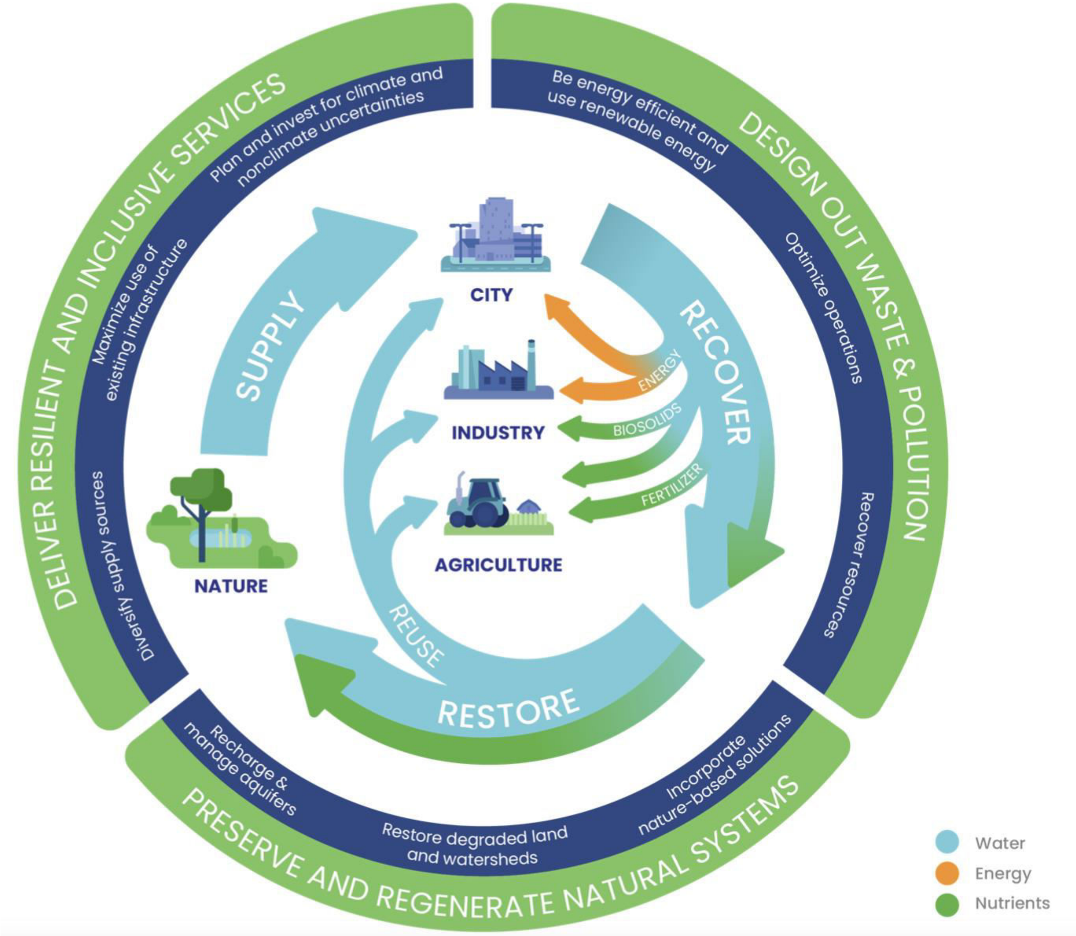
- Rising populations put huge stresses on the natural resources
- Wastes have a negative impact on the environment
- The current **water crisis** is one of the greatest challenges of our time
- Successful Circular Economy would contribute to all dimensions of sustainable development:
  - Economic
  - Environmental
  - Social

"Rethinking urban water through the circular economy and resilience lenses offers an opportunity to tackle all these challenges by providing a systemic and transformative approach to delivering water supply and sanitation services in a more sustainable, inclusive, efficient, and resilient way."

Water in Circular Economy and Resilience (WICER) Report – The World

Circular Economy Systems Engineering





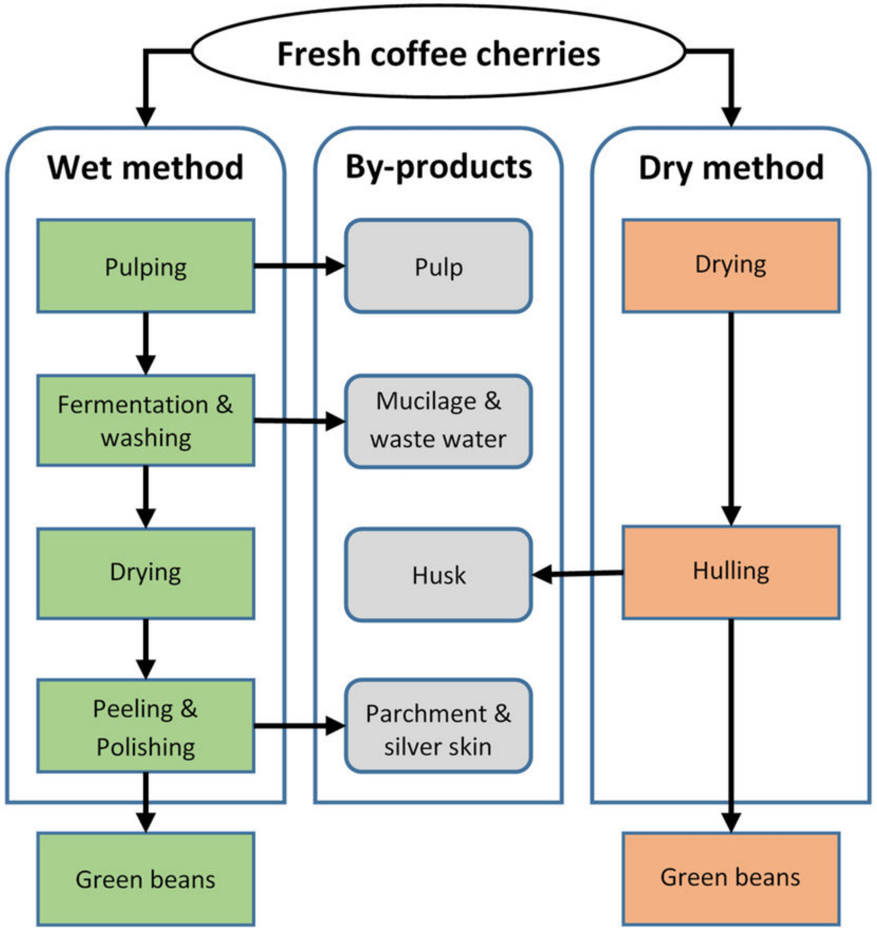
Towards a Circular Economy Systems Engineering Framework

Coffee Case Study

Towards a Circular Economy Systems Engineering Framework

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 Resource-Task-Network (RTN) 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

Towards a Circular Economy Systems Engineering Framework
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.

Towards a Circular Economy Systems Engineering Framework

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 Resource-Task-Network (RTN) 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

Towards a Circular Economy Systems Engineering Framework

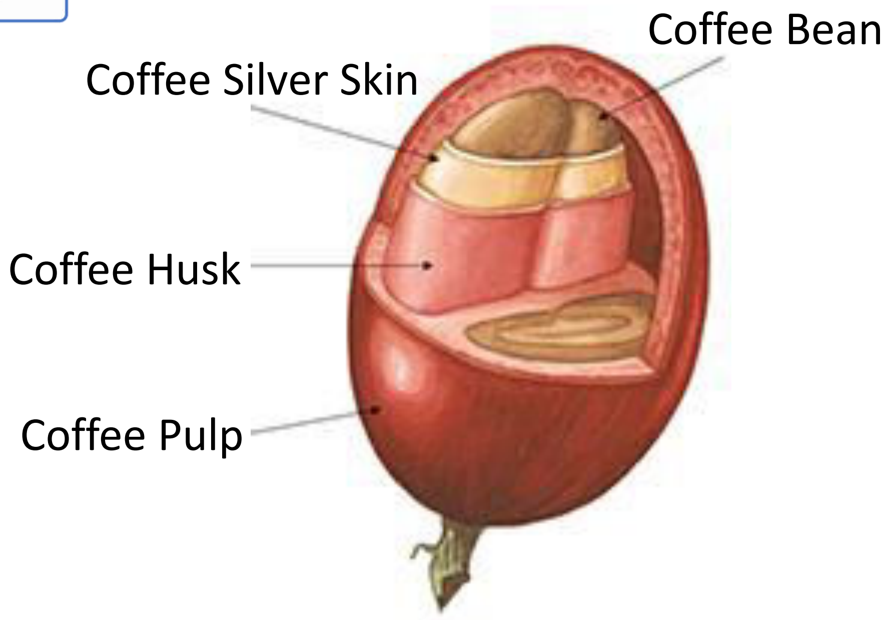
Alternative Products from Coffee Waste

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

Towards a Circular Economy Systems Engineering Framework

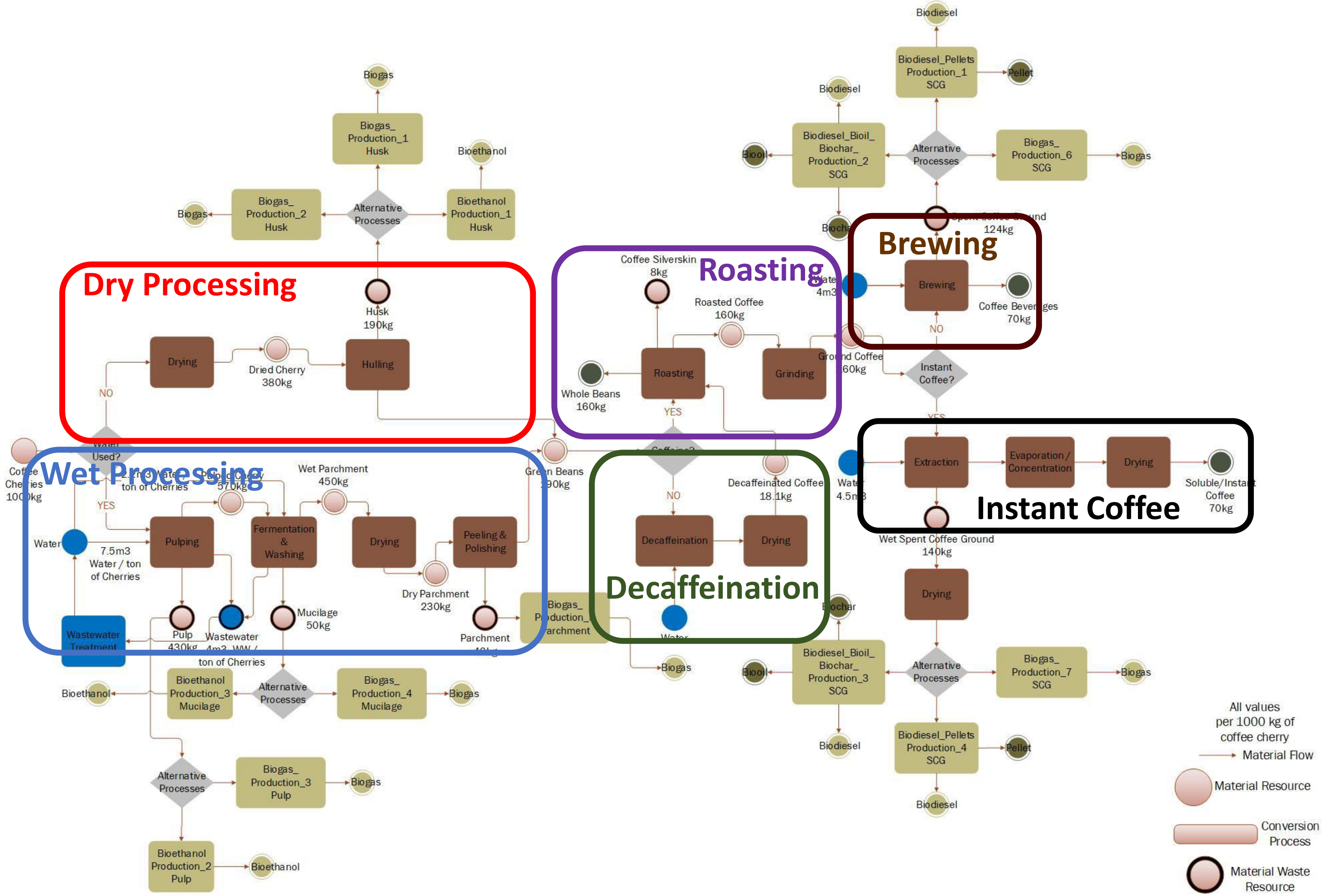
Valorization of coffee by-products for the production of bio-energy

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) Chala et al. (2018) Murthy and Naidu (2012b) Ulsido et al. (2016)			Blinová et al. (2017)	
Coffee Pulp		Blinová et al. (2017) Gurram et al. (2016)	Blinová et al. (2017) Chala et al. (2018) 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) Figueroa et al. (2016)					
Spent Coffee Grounds	Blinová et al. (2017) Campos-Vega et al. (2015) Banu et al. (2020) Karmee (2018) Murthy and Naidu (2012b) Kwon et al. (2013) Tongcumpou et al. (2019) Berhe et al. (2013) Haile (2014) Vardon et al. (2013) McNutt et al. (2019)	Blinová et al. (2017) Banu et al. (2020) Karmee (2018) Figueroa et al. (2016) Murthy and Naidu (2012b) Kwon et al. (2013) McNutt et al. (2019)	Banu et al. (2020) Karmee (2018) Figueroa et al. (2016) Li et al. (2014) Lee et al. (2019) Vítěz et al. (2016)	Banu et al. (2020) Karmee (2018) Figueroa et al. (2016) Li et al. (2014) Vardon et al. (2013)	Banu et al. (2020) Karmee (2018) Lee et al. (2019)	Blinová et al. (2017) Banu et al. (2020) Karmee (2018) Figueroa et al. (2016) Stylianou et al. (2018) Haile (2014)	Banu et al. (2020) Karmee (2018)

Towards a Circular Economy Systems Engineering Framework

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 Resource-Task-Network (RTN) 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

Superstructure Network of the coffee supply chain



Towards a Circular Economy Systems Engineering Framework

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 Resource-Task-Network (RTN) 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

Towards a Circular Economy Systems Engineering Framework
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

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

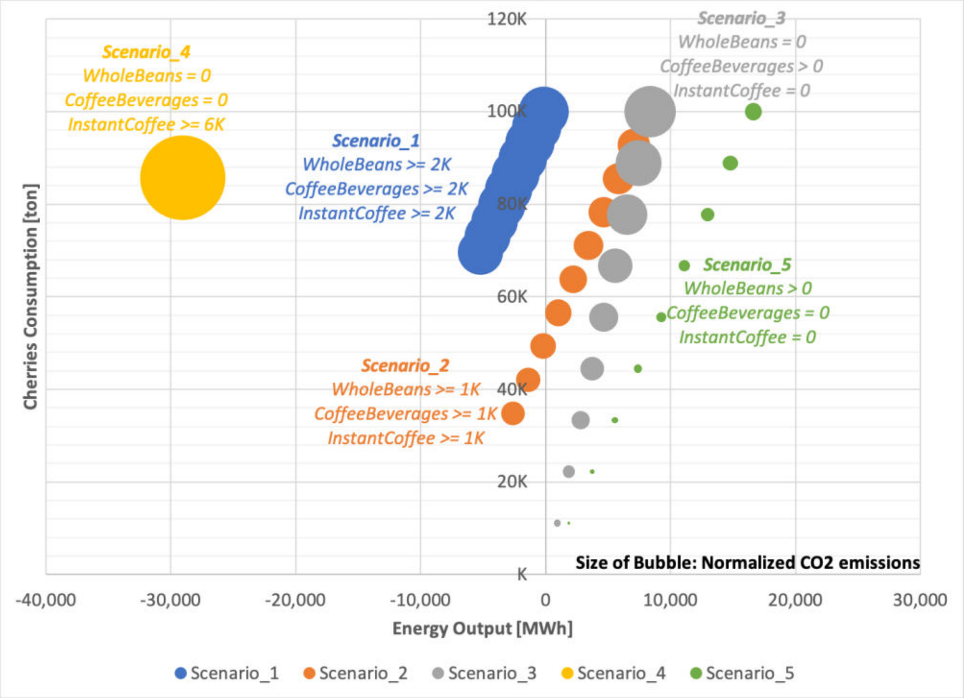
- Objective Functions
  - Maximize profit
  - Minimize waste
  - Minimize natural resource use
  - Minimize GHG emissions
  - Maximize energy efficiency
  - Etc.

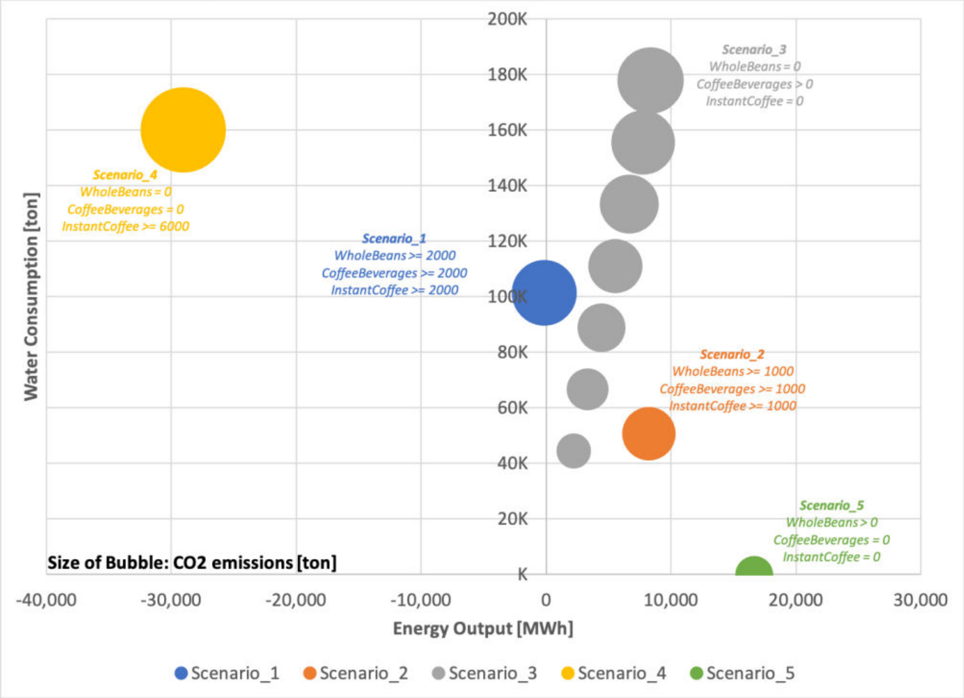
Coffee model statistics:
138 equations
58 continuous variables
18 binary variables

Towards a Circular Economy Systems Engineering Framework

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 Resource-Task-Network (RTN) 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

Towards a Circular Economy Systems Engineering Framework
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

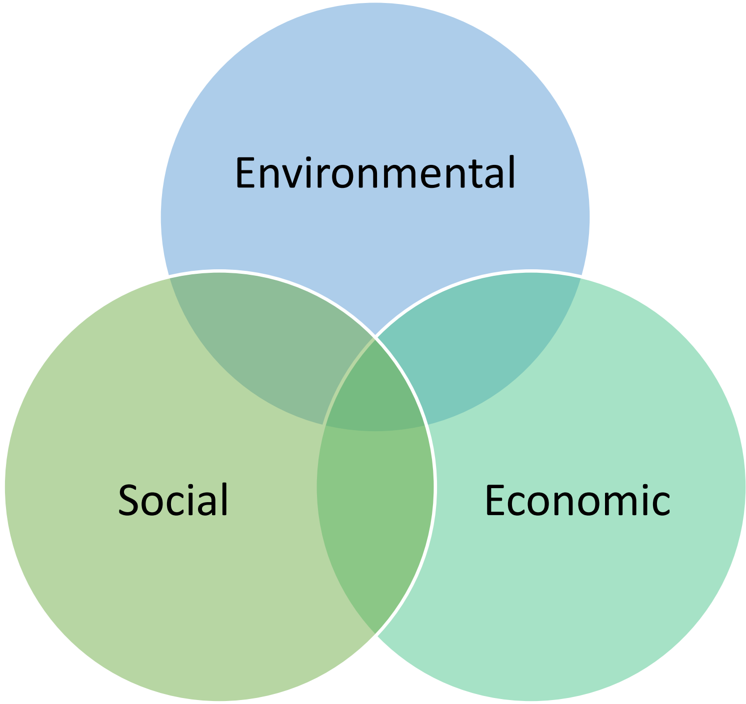
Baratsas, S. G; Pistikopoulos, E. N; Avraamidou, S. **A systems engineering framework for the optimization of food supply chains under circular economy considerations.** Science of The Total Environment 2021, 794, 148726.

Circular Economy Assessment Criteria

- How do we choose between the different optimal points in the Pareto fronts?

- Is Life Cycle Assessment possible/enough?

#	CE Goals & Key Characteristics
1	Reduction of material losses/residuals: Waste and pollutants minimization through the recovery and recycle of materials and products.
2	Reduction of input and use of natural resources: The reduction of the stresses posed on natural resources through the efficient use of natural resources.
3	Increase in the share of renewable resources and energy: Replacement of non-renewable resources with renewable ones, limiting the use of virgin materials.
4	Reduction of emission levels: The reduction in direct and indirect emissions / pollutants.
5	Increase the value durability of products: Extension of product lifetime through the redesign of products and high-quality recycling.



MICRON: CE Assessment Framework

CE Goals & Key Characteristics
Definition of CE goals & identification of principal categories

Economic Sectors
Classification to the economic sector that companies / products belong to

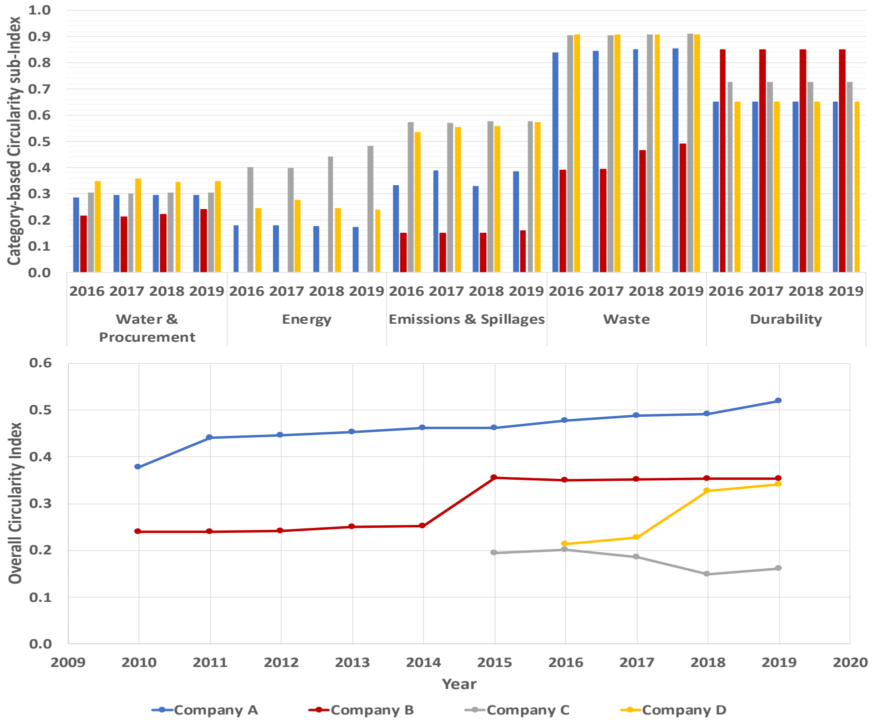
Principal Category Indicators
Selection of GRI-based indicators for each principal category and economic sector

Principal Category Metrics
Standardization and normalization of the metrics of each principal category

Category-based Circularity Sub-Indices
Weighted average of metrics for accessing circularity at principal category level

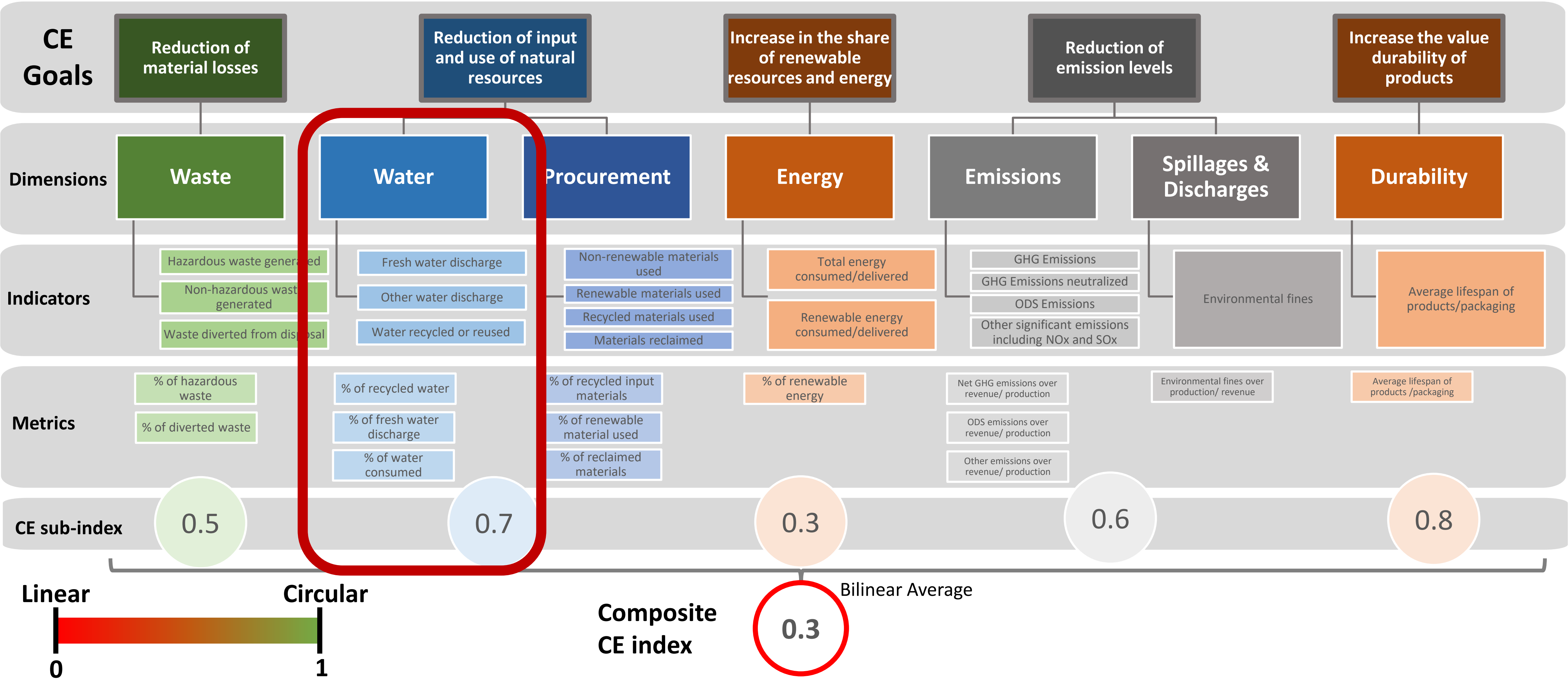
Overall Circularity Index
Linear average of the category-based sub-indices
0 reflects perfect linearity / 1 reflects perfect circularity

Data Visualization, Benchmarking & Comparisons
Temporal analysis, periodic circularity assessment, benchmarking against peers and industry's standards

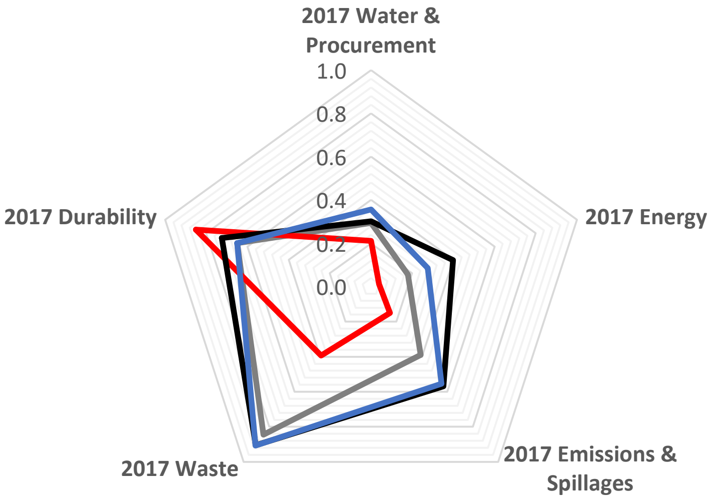


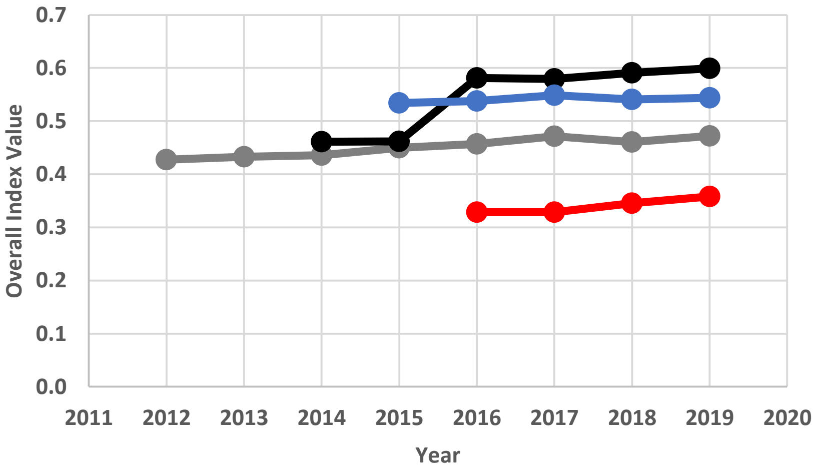
Baratsas, S.; Pistikopoulos, E. N.; Avraamidou, S. A quantitative, holistic and robust circular economy assessment framework at the micro level. *Computers & Chemical Engineering*, **2022**, 160, 107697

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



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





- 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.
- Chialdikas, E.; Munguia-Lopez, A.C.; Aguirre-Villegas, H.; Avraamidou, S. **A framework for the evaluation of the circularity of plastic waste management systems: A case study on mechanical recycling of HDPE**. Foundations of Computer Aided Process Operations / Chemical Process Control; 2023.

- ✓ 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

Towards a Circular Economy Systems Engineering Framework
Remarks

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

A 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

Circular Economy Systems Engineering:

- Offers a holistic integrated approach to assist quantitative decision making

Future Work:

1. Food-Energy-Water Nexus
2. Economics
3. Time dimension
4. Uncertainty/Resilience studies

Acknowledgements

TEXAS A&M ENERGY INSTITUTE

CENTER FOR COFFEE RESEARCH & EDUCATION

CUWP
Chemical Upcycling of Waste Plastics

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

UNESCO-IWRA ONLINE CONFERENCE

17-19 JANUARY 2023

3RD IN THE IWRA ONLINE CONFERENCE SERIES

Emerging Pollutants: Protecting Water Quality for the Health of People and the Environment

Circular Economy Systems Engineering

Styliani Avraamidou

18th of January 2023

unesco

Programme hydrologique intergouvernemental

International Water Resources Association

IWRA