TEQIP-III Short Course on Systems Analysis of Biofuels and Bioproducts

Module 4: Life Cycle Assessment

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Goals of this Lecture

Introduce the Life Cycle Assessment(LCA)

Learning Objectives

By the end of this lecture, you must be able to:

1. Understand the importance of systems analysis.
2. Understand the LCA Process
3. Describe how environmental impacts are calculated using life cycle impact assessment method

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Life Cycle Analysis

LCA is not Risk Assessment! LCA is not a cost/performance analysis model. LCA is a model to assess environmental impact of the products, processes and services.

Two versions: Attributional LCA and Consequential LCA.

Other variants:

- Cradle to grave: Involves LCA for production, manufacturing, use and disposal
- Cradle to cradle: Involves recycle in addition to all the phases mentioned above.
- Cradle to gate: This is a partial LCA assessing impact from cradle to factory gate. Used to declare environmental friendliness of process.
- Well to wheel: A specific LCA for transportation sector.

Ref:
1. Life Cycle Analysis: Principles and Practice. EPA/600/R-06/060 (2006)

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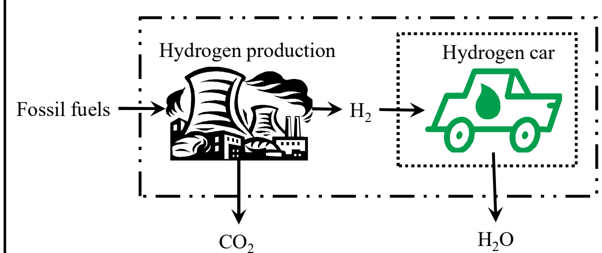
Shifting of Environmental Burden



Elementary flows are defined as flows to/from the environment which will not be subject to any further human interventions.
Intermediate flows occur between the unit processes within the system boundary. ***Product flows*** are products of some other product system.

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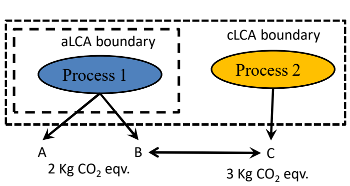
Variants of LCA

The two types of Life Cycle Assessments which answer different questions:

• Attributional Life Cycle Assessment (aLCA): What are the ***total*** emissions from the process during the life cycle of the product?

• Consequential Life Cycle Assessment (cLCA): What is the ***change*** in total emissions from the process during the life cycle of the product?



B replaces C
aLCA: 2 = 2 Kg CO2 eq.
cLCA: 2-3= -1 Kg CO2 eq.

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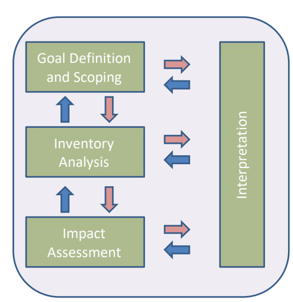
Life Cycle Analysis

LCA is divided into four distinct stages:

1. Goal Definition and Scoping
2. Life Cycle Inventory
3. Life Cycle Impact Assessment
4. Life Cycle Interpretation



Ref: Life Cycle Analysis: Principles and Practice. EPA/600/R-06/060 (2006)

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Life Cycle Analysis: Goal Definition and Scoping

Formulation of goals and the scope of study is the most critical part of LCA. The object of the study is defined in terms of "functional unit".

- Description of the products, processes, and the system boundaries.
- Clear and quantifiable goals will help in arriving at more objective interpretation
- Setting clearly identifiable the boundaries of the system is critical

Factors to be considered

- What is the required specificity?
- What are the resources available for the study?
- What type of information is needed?
- How should the results be displayed?

Ref:
- http://en.wikipedia.org/wiki/Life_cycle_assessment#Energy_production
- Life Cycle Analysis: Principles and Practice. EPA/600/R-06/060 (2006)

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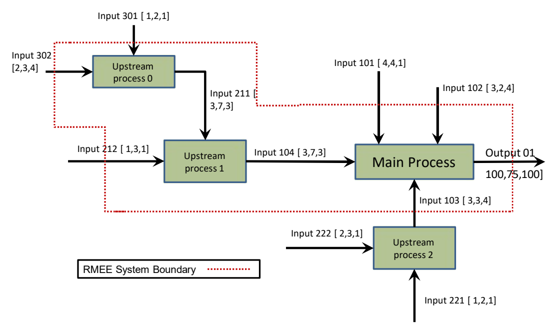
Life Cycle Analysis: Goal Definition and Scoping



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System Boundary Example

RMEE cut-off : 5%						
Input	Absolute values			As a percentage of the output		
	Mass	Energy	Economic value	Mass	Energy	Economic value
101	4	3	1	4%	4%	1%
102	3	2	4	3%	3%	4%
103	3	3	4	3%	4%	4%
104	4	10	4	4%	**13%**	4%
211	3	7	3	3%	**9%**	3%
212	1	3	1	1%	4%	1%
221	1	2	1	1%	3%	1%
222	2	3	1	2%	4%	1%
301	1	2	1	1%	3%	1%
302	2	3	4	2%	4%	4%
Output	100	75	100			

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Steps in LCA: Life Cycle Inventory

Input data collected during the LCI process may be classified as follows (ISO 14044):

- Energy, raw materials and other inputs to the process.
- All products, coproducts and waste streams
- All releases to air, water and soil
- Other environmental aspects

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Steps in LCA: Life Cycle Inventory

LCI databases

- US NREL LCI,
- US Dept. of Agriculture LCA Digital Commons
- European reference Life Cycle Database (ELCD)
- EcoInvent database
- GaBi database
- UNEP/SETAC Life Cycle Initiative Database Registry
- New Energy Externalities Development for Sustainability (NEEDS).
- ProBas
- Okubau.dat

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Steps in LCA: Life Cycle Inventory

Coproduct Allocation

- System partition/ system expansion
- Mass/energy based allocation
- Economic value based allocation

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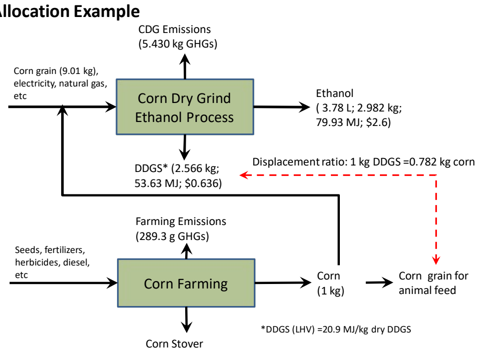
Steps in LCA: Life Cycle Inventory

Coproduct Allocation Example



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Steps in LCA: Life Cycle Inventory

Coproduct Allocation Example

Mass based allocation:

Fraction of DDGS produced = DDGS/(Ethanol+ DDGS) = 2.566/(2.982 + 2.566) = 0.4625

DDGS share of emissions = 0.4625 × 5.430 = 2.511 kg GHGs

Ethanol share of emissions = 5.430 - 2.511 = 2.920 kg GHGs

Similar calculations can be performed for energy and economic value based allocations using the data provided here.

System expansion:

1 kg DDGS≈ 0.782 kg corn; 1 kg of corn has 289.3 g GHGs

2.566 kg DDGS = 0.782 × 2.566 × (289.3/1,000) = 0.5860 kg GHGs.

⇨ Ethanol share of emissions = 5.430 - 0.5860 = 4.844 kg GHGs

Allocation method→	Mass	Energy	Price	Displacement
Ethanol	2.920	3.250	4.363	4.844
DDGS	2.511	2.180	1.067	0.586

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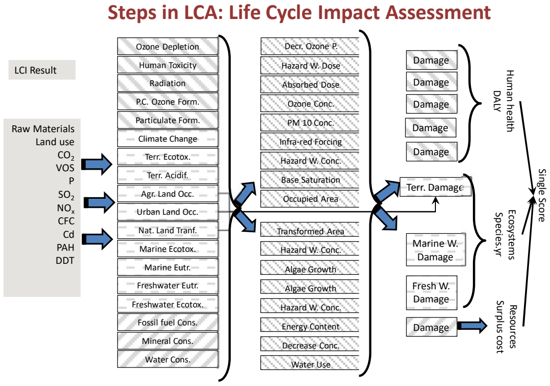
Steps in LCA: Life Cycle Impact Assessment



Ref: Modified Figure 1.2 from Goedkoop et al. 2009

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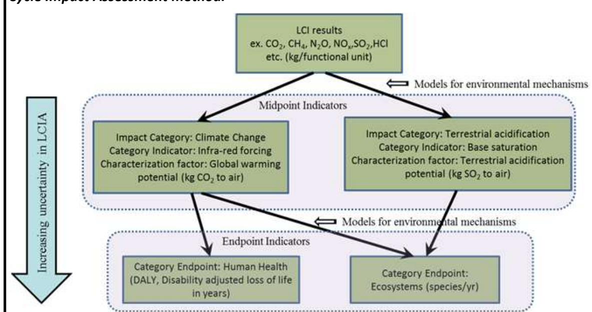
Steps in LCA: Life Cycle Impact Assessment

Example of LCI results mapped to midpoint and endpoint indicators in the ReCiPe- 2008 Life Cycle Impact Assessment method.



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Steps in LCA: Life Cycle Interpretation

- Evaluate to identify
  - Completeness
  - Sensitivity
  - Consistency
- Conclusions, limitations and recommendations are presented.

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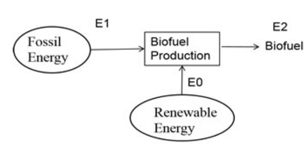
Important Terms in LCA Results

- **Functional Unit**: The measure (amount, weight or quality) of the function of the investigated system. It provides a reference to which inputs and outputs of the system are related. Example: 1000 MJ bioethanol or 1kg plastic
- **Net Energy Value (NEV)**: Energy in functional unit – fossil energy use to produce functional unit

  $NEV = E2 - E1$



- **Net Energy Ratio (NER)**

  $NER = \frac{Energy\ in\ functional\ unit}{Fossil\ Energy\ input} = \frac{E2}{E1}$

- **Equivalent**: Normalization of different values to a reference unit. For example 1 g CH_4 is considered equivalent to 25 g CO_2-equivalents for global warming potential

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Why are the results from various LCA analyses so different?

- *System boundaries*
- *Data quality, accuracy*
  - *Age of data, sources of data, geographical context*
- *Allocation of coproducts*
  - *Mass, energy and displacement methods*
- *Nitrous oxide emissions*
  - *Varying fertilizer use for different crops*
- *Indirect land use change (ILUC)*
  - *Variation in ILUC among first, second and third generation fuels.*
- *Reported units*
  - *GHG emissions/MJ of fuel or GHG emissions/Ha of land?*

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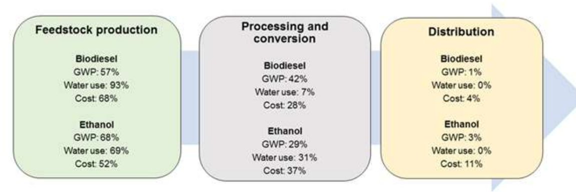
Importance of Feedstock Production Stage



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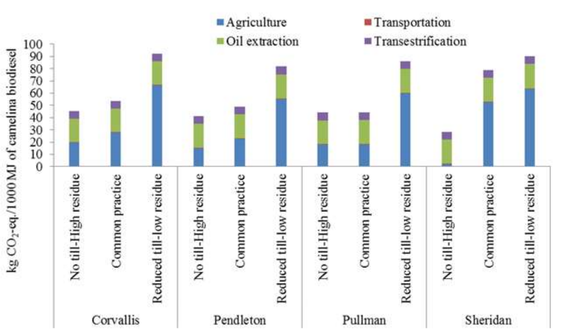
Importance of Feedstock Production Stage



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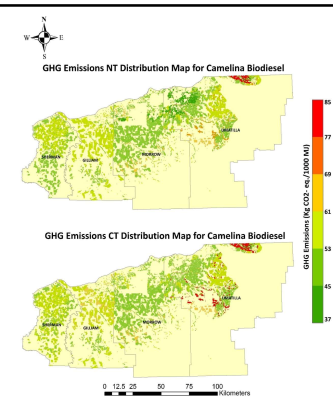

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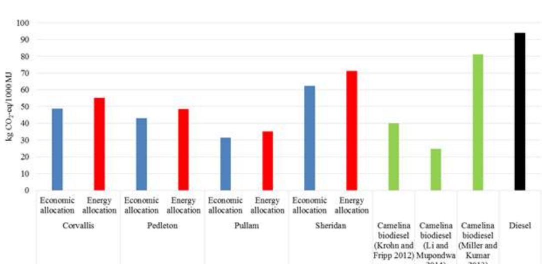
Impact of Allocation Methods



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Life Cycle Analysis: Summary of Process Steps

LCA is divided into four distinct stages:

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2. Life Cycle Inventory
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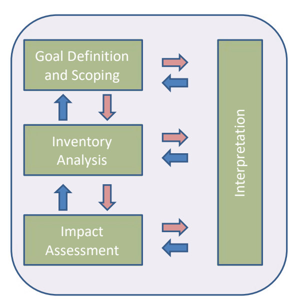
4. Life Cycle Interpretation



Ref: Life Cycle Analysis: Principles and Practice. EPA/600/R-06/060 (2006)

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Databases and Software for Performing Sustainability Analysis

Software

- GREET: http://greet.es.anl.gov/
- Open LCA: http://openlca.org/web/guest
- EIO-LCA: http://www.eiolca.net/index.html
- Eco-LCA: http://resilience.eng.ohio-state.edu/eco-lca/index.htm
- SPIonExcel: http://spionexcel.tugraz.at/

Databases

- USDA LCA Digital Commons: http://www.lcacommons.gov/
- US LCI Database: http://www.nrel.gov/lci/
- NAICS Sectors: http://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2002
- SPI Database: http://spionexcel.tugraz.at/

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Matrix method of LCA

- The matrix method of LCI also called the process based LCI was first introduced by Heijungs
- Technology Matrix, A: The matrix constructed with the rows representing the products and the columns representing the processes is called the process or technology matrix
- Demand vector, f : The demand for the products/services
- Scaling vector, x: Activity necessary to generate the functional unit

$$A_{n\times n}.x_{n\times 1} = f_{n\times 1} \text{ ....(1)}$$

$$x = A^{-1}f \text{ ....(2)}$$

- The above equation always has a solution since the technology matrix is invertible (why?).
- Note that the key assumption that make this possible: each process has only one main product associated with it and the processes are all independent.

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Matrix method of LCA

- Unit Emission matrix, B
- Emission inventory vector, g

$$g_{p\times 1} = B_{p\times n}x_{n\times 1} = B_{p\times n}A^{-1}_{n\times n}f_{n\times 1}\text{....................(3)}$$

- Characterization matrix, Q
- Environmental impacts vector, h

$$h_{m\times 1} = Q_{m\times p}g_{p\times 1} \text{ ....(4)}$$

$$h_{m\times 1} = Q_{m\times p}B_{p\times n}A^{-1}_{n\times n}f_{n\times 1}\text{....................(4a)}$$

- Endpoint indicators

$$ES_{e\times 1} = w_{e\times m}h_{m\times 1}\text{....................(5)}$$

$$ES_{e\times 1} = w_{e\times m}B_{p\times n}A^{-1}_{n\times n}f_{n\times 1} \text{ ....(5a)}$$

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Summary of the Matrix method of LCA

- Technology Matrix, A
- Demand vector, f
- Scaling vector, x

A x= f

➔x=A^{-1} f

- Unit Emission matrix, B
- Emission inventory vector, g

g=B.x

- Characterization matrix, Q
- Environmental impacts vector, h

h=Q.g =Q.(B.A^{-1})f

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Input-Output Method of LCA

- The matrix method of LCI leads to truncation errors.
- Input-output tables are available for entire economies.
- The IO matrix ($\tilde{A}_{n\times n}$) represents the intermediate consumption among various sectors in the economy
- Demand unit vector, y : The demand for the products/services
- Total demand vector, x: Activity necessary to generate the functional unit
- Equation for Total Economy is

$$x_{n\times 1} = \tilde{A}_{n\times n}.x_{n\times 1} + y_{n\times 1}\text{....................(1)}$$

$$x = (I - \tilde{A})^{-1}y \text{ ....(2)}$$

- Then the other steps of LCA follow the matrix method.

$$ES_{e\times 1} = w_{e\times m}B_{p\times n}\,(I - \tilde{A})^{-1}y \text{ ....(3)}$$

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Hybrid Method of LCA

- The hybrid method combines the matrix and IO methods of LCA.
- M represents the net emission matrix,
- X represents the upstream cut-off flows to the LCA system linked with the IO matrix. The elements in X have a unit of monetary value/operation time (scaling factor).
- Y represents the downstream cut-off flows to the LCA system linked with the IO matrix. The unit of each element of Y are physical unit/monetary value.

$$M = \begin{bmatrix} B & 0 \\ 0 & \tilde{B} \end{bmatrix} \begin{bmatrix} A & Y \\ X & I - \tilde{A} \end{bmatrix}^{-1} \begin{bmatrix} f_{n\times 1} \\ 0 \end{bmatrix}\text{....................(1)}$$

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Comparison of the Matric, IO and Hybrid Methods of LCA

	LCI based on process analysis		Input–output based LCI	Hybrid LCI		
	Process flow diagram	Matrix representation		Tiered hybrid analysis	IO-based hybrid analysis	Integrated hybrid analysis
Data requirements	Commodity and environmental flows per process	Commodity and environmental flows per process	Commodity and environmental flows per sector	Commodity and environmental flows per sector and process	Commodity and environmental. flows per sector and process-based LCIs	Commodity and environmental. Flows per sector and process
Uncertainty of source data	Low	Low	Medium to high	Depends[a]	Depends[a]	Low
Upstream system boundary	Medium to poor	Medium to poor	Complete	Complete	Complete	Complete
Technological system boundary	Complete	Complete	Medium to poor	Depends[a]	Depends[a]	Complete
Geographical system boundary	Not limited	Not limited	Domestic activities only	Depends[a]	Domestic activities only	Not limited
Applicable analytical tools	Rare	Abundant, e.g. in Heijungs and Suh [10]	Rare	Rare	Abundant (analytical tools for IOA disaggregated IO part)	Abundant (both analytical tools for IOA and LCA for entire system)
Time- and labour intensity	High	High	Low, if environm. data available	Depends[a]	Depends[a]	High
Simplicity of application	Simple	Simple	Simple	Simple	Complex	Complex
Required computational tools	Excel or similar (no matrix inversion)	Matrix inversion (e.g. MatLab, Mathematica.)	Excel or similar	Excel or similar	Matrix inversion (e.g. MatLab, Mathematica.)	Matrix inversion (e.g. MatLab, Mathematica.)
Available software tools	Most available LCA software tools	CMLCA	MIET, EIOLCA	MIET + LCA software tool	–	CMLCA

[a] Dependant upon the shares of process analysis and IO-based system.

Reference: Suh, S. and Huppes, G. 2005. Methods for Life cycle inventory of a product. Journal of Cleaner Production.13:687-697.

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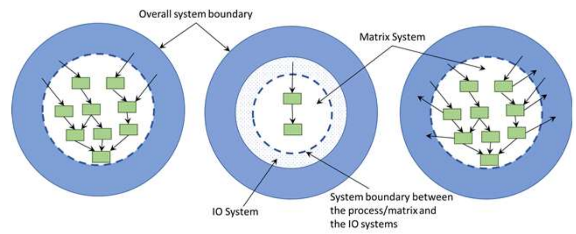
Comparison of the various Hybrid Methods of LCA



Reference: Suh, S. and Huppes, G. 2005. Methods for Life cycle inventory of a product. Journal of Cleaner Production.13:687-697.

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Class Discussion

- *A biofuels researcher wants to perform an environmental impact comparison of biofuels with fossil fuels. The researcher defines the functional unit as, "one liter of fuel available to the customer at the gas station." The researcher's colleague defines the functional unit as, "1000 MJ of energy available to the customer at the gas station." Which of these is an appropriate functional unit for comparison of biofuels with fossil fuels, and why?*
- *What happens if the system boundaries are not consistent among two systems being compared?*
- *What is the difference between attributional and consequential LCA?*
- *What is the importance of data quality in the LCA. How does the state of technology influence the data sources? What are different LCA databases?*

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Class Discussion

- *Consider the two data sets for corn yields and nitrogen use in Nebraska. Analyze possible reasons for these dramatic differences and discuss the implications of using one data set versus the other in LCA.*

	Corn yield (kg/ha)	Nitrogen use (kg/ha)	Year of data collection
Dataset A	4100	110	1965
Dataset B	9500	140	2005

Ref: http://cropwatch.unl.edu/web/cropwatch/archive?articleID=4585476

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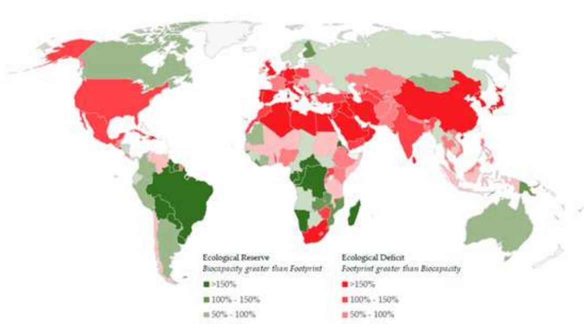
Other Environmental Impact Assessment Methods

Ecological Footprint



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How Much Water?

250 L/ 100 g

110 L/chapati

25L

255 L

125L

80 L

2600 L

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Image Source: WWW Data Source: Water Footprint.org

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How Much Water?

196 L/egg

4,330 L/kg

6,000 L/kg

15,400 L/kg

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Image Source: WWW Data Source: Water Footprint.org

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How Much Water?

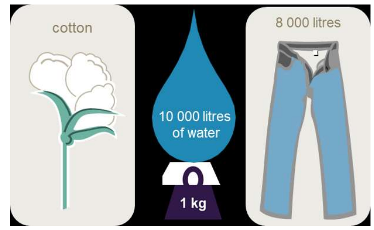

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Image Source: Water Footprint.org

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Water Demand is Mostly Invisible/Indirect

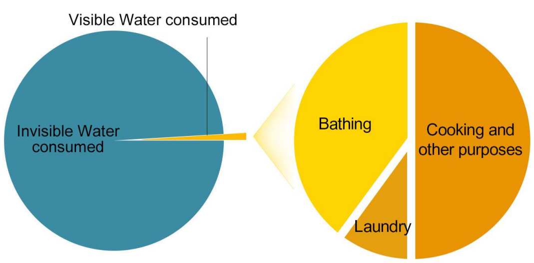

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Image Source: https://www.wsd.gov.hk/en/water-conservation/domestic/virtual-water/index.html

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Virtual Water Footprint

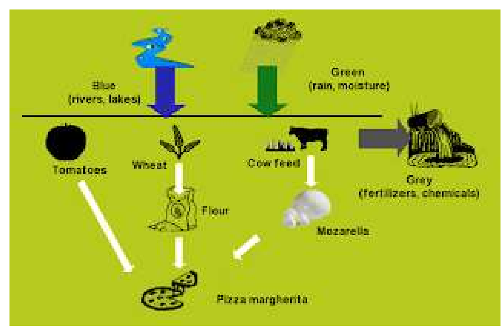

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Image Source: http://wateraflamed.blogspot.com/p/virtual-water-and-water-footprint.html

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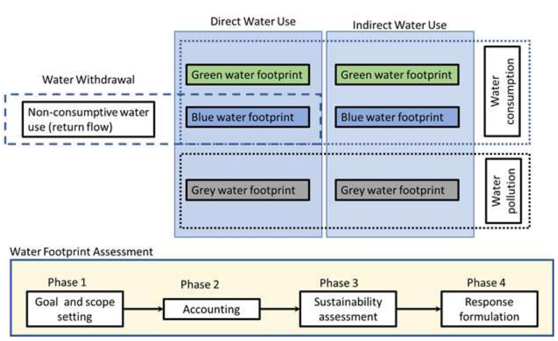
Other Environmental Impact Assessment Methods

Water Footprint



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Virtual Water Trade

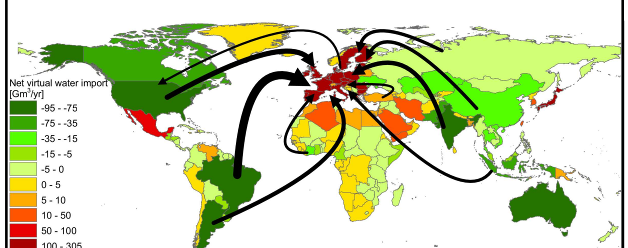

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Image Source: Water Footprint.org

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Introduce the Life Cycle Assessment(LCA)

Learning Objectives

By the end of this lecture, you must be able to:

1. Understand the importance of systems analysis.
2. Understand the LCA Process
3. Describe how environmental impacts are calculated using life cycle impact assessment method

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Module 4: Life Cycle Assessment

THANK YOU

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