Life Cycle Assessment - LCA

Maurizio Fermeglia

Maurizio.fermeglia@units.it

Department of Engineering & Architecture

University of Trieste

Agenda

- Life cycle thinking
- Quantitative methods and life cycle cost analysis
- The ISO LCA standard
- Life cycle inventory
  - Data needs and data quality
  - Data sources
  - Handling multifunction systems (disaggregation and allocation)
  - Uncertainty
  - Input-output LCA
- Impact assessment
- Conclusions

Uses of a Standard

- Want things done consistently
  - Common guidelines
- Want to set level playing field in a market
  - Following the standard is assessable, and determined compliant
- Analogous to ASTM and other "test standards"
  - e.g., consistent concrete is desired and can be specified in a construction bid request: "we want ASTM C94 concrete"
  - IEEE communication standards
  - NIST- UNI – ISO (ISO 9000 and ISO 14000 families) - …
- Standards generally voluntary, but may be required by contract
  - require ISO 9000 compliant firm

Type of Standard	Description	Example Application
Specifications	A prescriptive set of absolute requirements	Product Safety
Codes of practice	Recommendations of practices	Construction
Methods	A prescriptive way of measuring or testing	Materials testing
Terminology or Vocabulary	A set of terms and definitions	Conformity
Product or Process	A set of qualities or requirements to ensure effective function or level of service	Medical devices

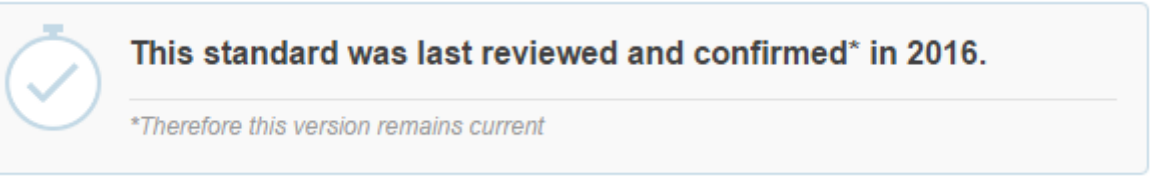
English

International Organization for Standardization

When the world agrees

- ISO is a global standards organization
- Principles:
  - Responds to market need
    - e.g., “need a way of measuring environmental impacts in an industry so we can make claims about them”
  - Based on global expert opinion
  - Developed in multi-stakeholder process
  - Based on consensus (75% agreement)
- Managed by a technical committee
  - Standard is drafted, commented on, edited, voted on until consensus (75% approval) is reached
- History of ISO LCA Standard
  - Part of ISO 14000 Environmental Management Standards
    - Similar to ISO 9000 Quality Standards
  - First draft of LCA standard – 1997
  - Revised in 2006 as ISO 14040 and ISO 14044
    - 14040 – Principles & framework (basic overview, something a manager might see)
    - 14044 – Requirements & guidelines (what a practitioner needs to know)

Source: https://www.iso.org/developing-standards.html



Additional recommendations in ISO LCA standard

Standard	Title
ISO 14047(2012)	Illustrative examples on how to apply ISO 14044 to **impact assessment** situations
ISO 14049(2012)	Illustrative examples on how to apply ISO 14044 to **goal and scope definition and inventory analysis**
ISO 14071(2014)	**Critical review processes** and reviewer competencies: Additional requirements and guidelines to ISO 14044
ISO 14072(2014)	Requirements and guidelines for **organizational life cycle assessment**

ISO 14040: Introduction -

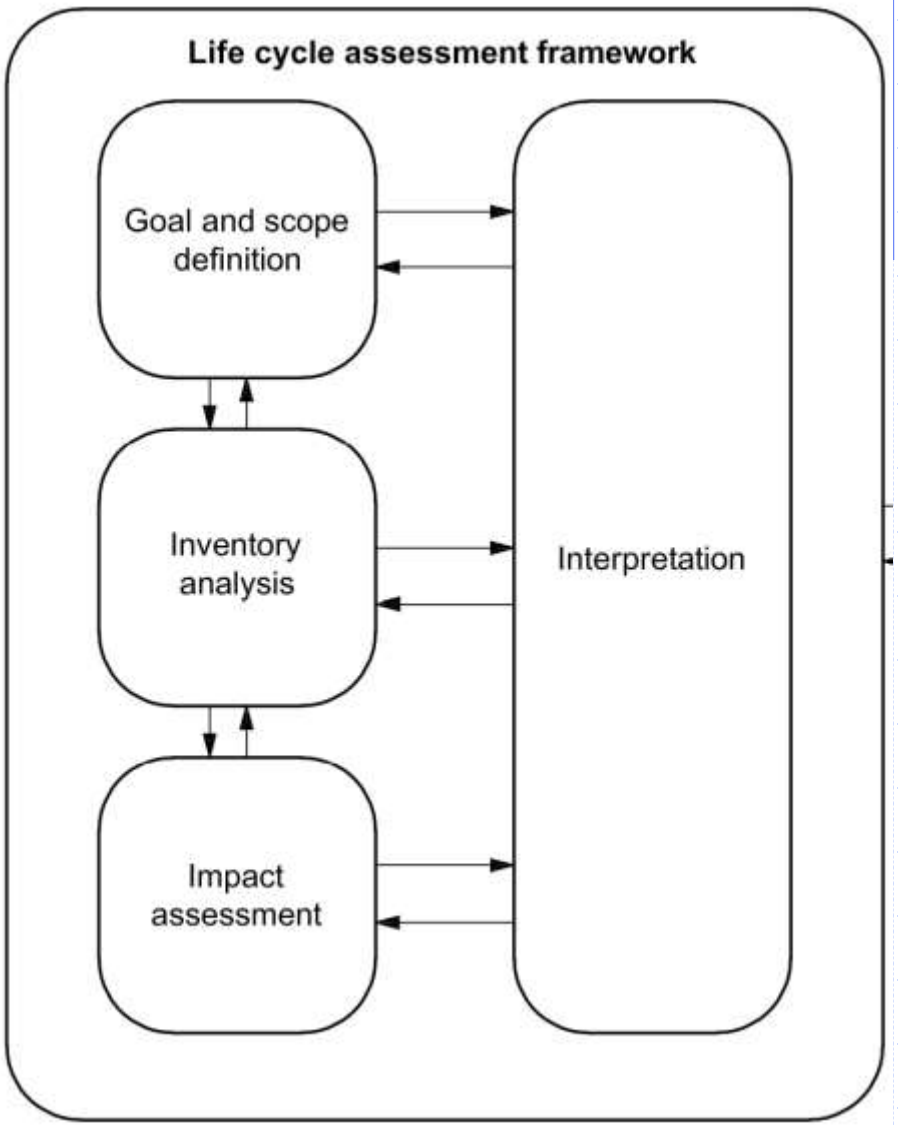
- **Uses and Needs** for LCA
  - Improve performance of products / services
  - Inform decisions by stakeholders
    - Strategic planning, priority setting, product or process design / redesign
  - Selection of relevant indicators (e.g., energy use)
  - Supporting marketing / performance claims
- **LCA is intended to be**
  - Focused on environmental aspects and impacts
  - Relative
  - Iterative
  - Transparent
  - Comprehensive
  - Based on science

ISO 14040: Phases of an LCA*

- Goal and scope definition
- Inventory
- Impact assessment
- Interpretation

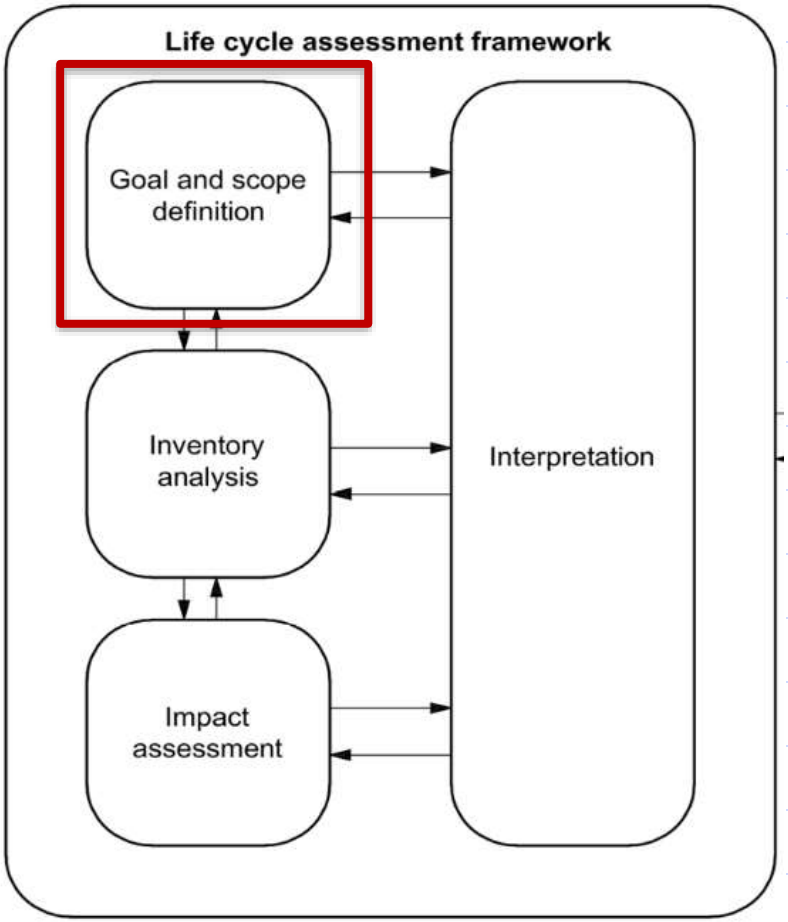
The A is underlined in LCA because many “LCA” studies exclude impact assessment. These are called “LCI studies” and otherwise conform to the ISO standard.

Assessment NOT analysis



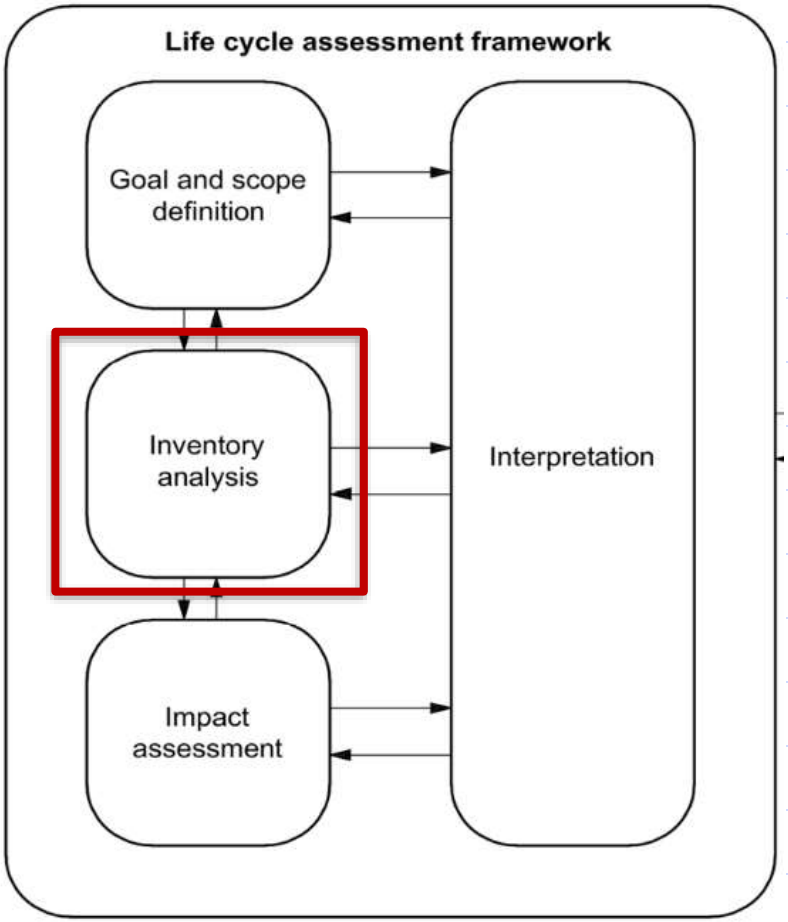
Phase 1: Goal and Scope Definition

- Goal and Scope
  - Parameters qualitatively and quantitatively described for an LCA study
  - Study Design Parameters (SDPs)
    - Product system
    - System boundaries
    - Functional unit
    - Inventory I/O
    - LCIA method used
- Collection of high level study aspects
  - Subset of required elements that give a quick idea of what study does
  - Critical items that need to be set; become key components of final report



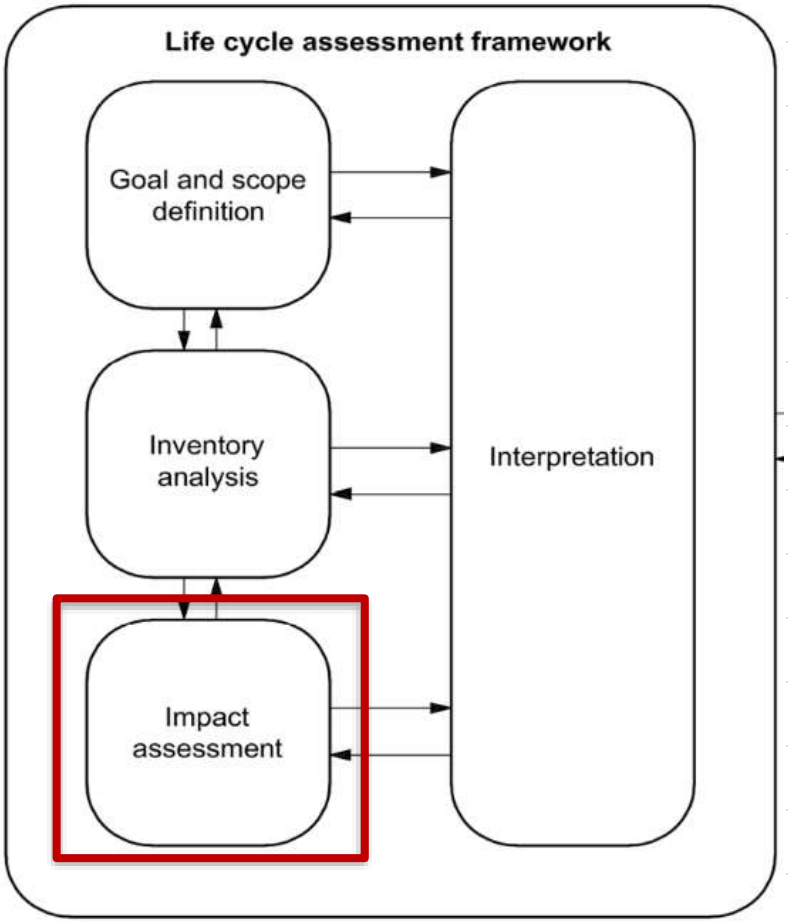
Phase 2: Inventory

- "Good research"
  - Time-intensive
- "Look up the data, add it up"
  - Need process data for all in boundary
  - Data availability varies
  - Adjust study scope if lacking data
- Consider inputs, outputs of interest
  - In: energy, resources, etc.
  - Out: emissions, waste, etc.
- Iterative



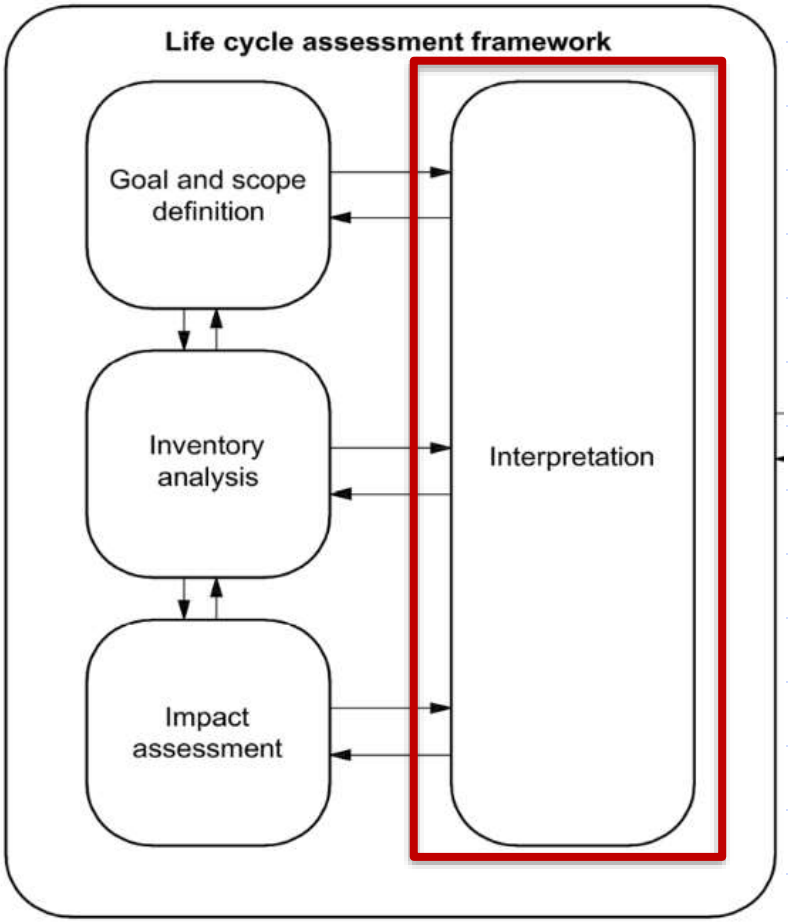
Phase 3: Impact Assessment

- Estimating significance of environmental impacts studied
  - Not just CO_2 and methane emissions, but global warming
  - Not just SO_x and NO_x, but acidification
  - Use frameworks to "convert" emissions into final impacts
- Least "mature" portion of LCA
  - Still subject of ongoing science and research
  - Can be subjective given choices and values
- High uncertainty



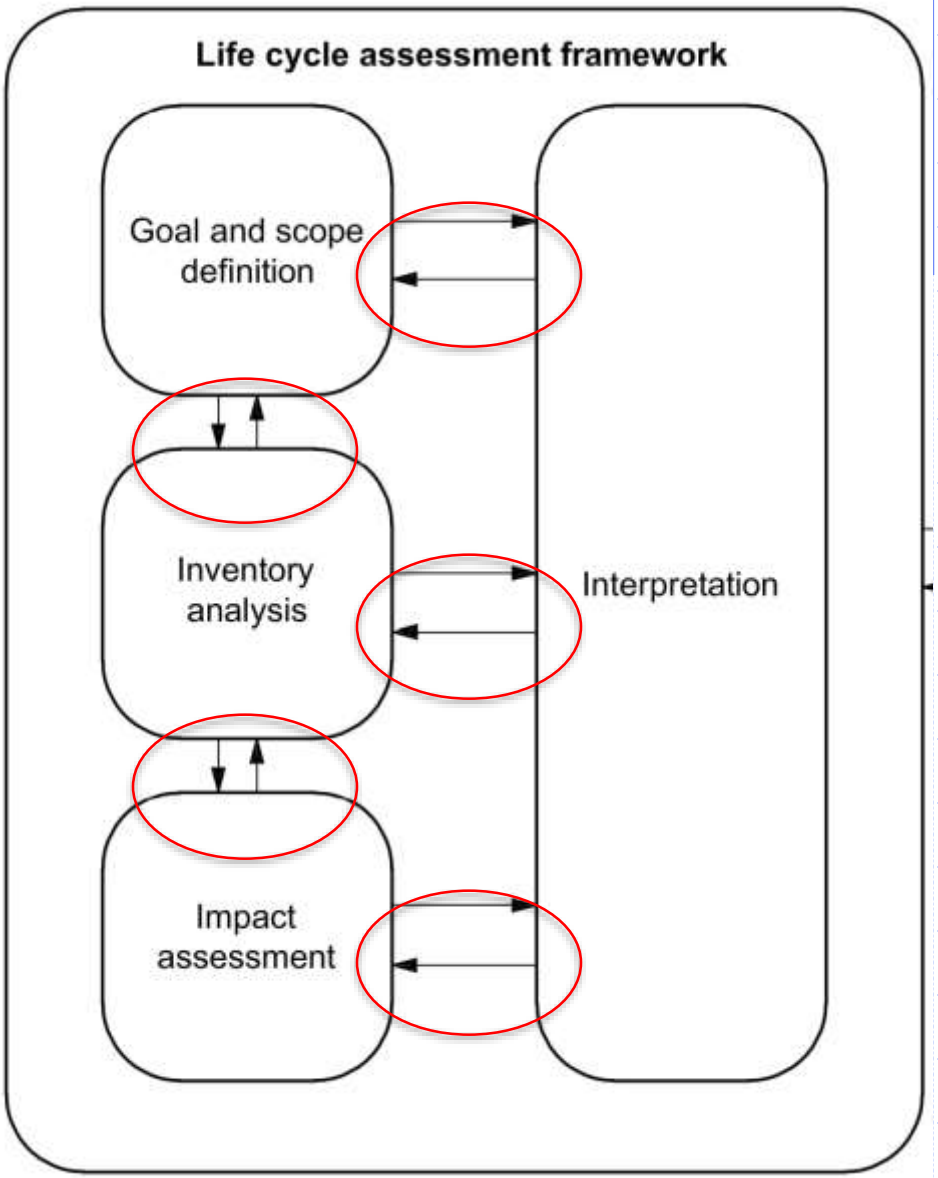
Phase 4: Interpretation

- How do results fit goal/scope?
  - Answer questions?
- Data quality
- Sensitivity analysis
- Conclusions and recommendations
- … and hopefully improvement
  - Hot spots for re-design?
  - Material with high energy requirements?
  - Life cycle stage that dominates?



Phases of an LCA - Iterative

- Not a once through process - all phases are iterative!
- Adjust as you go along
  - Can't find data for a process, redo the scope/boundary!
  - Can't make a solid conclusion, refine scope or collect more data
  - Unexpected result, may need to add impact or category
- Changes via iteration happen in ~100% of studies

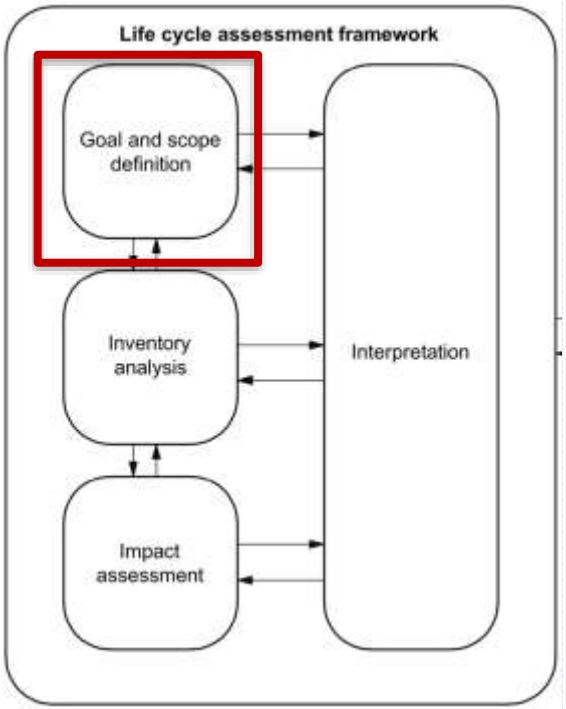


Summary definitions for LCA stages

- Life cycle assessment (LCA)
  - **Compilation and evaluation** of the inputs, outputs and the potential environmental impacts of a **product system** throughout its life cycle
- Life cycle inventory analysis (LCI)
  - **Phase of life cycle assessment** involving the compilation and quantification of inputs and outputs for a product throughout its life cycle
- Life cycle impact assessment (LCIA)
  - Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the **potential environmental impacts** for a product system throughout the life cycle of the product
- Life cycle interpretation
  - Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order **to reach conclusions and recommendations**

Phase 1: goal and scope definition

- **Study Design Parameters (SDP) of ISA LCA framework**



- Goal - "Goal should unambiguously state:"
  (1) the intended application,
  (2) the reasons for carrying out the study,
  (3) the audience, and
  (4) whether the results will be used in comparative assertions released publicly.

… or "who might care about this and why?" and "why we did it and what will we do with it?"

- Scope (goal could be few sentences, scope pages)
  - Product system studied
  - Functions and functional unit
  - System boundary
  - Inventory inputs and outputs
  - Impacts categories (for LCIA)

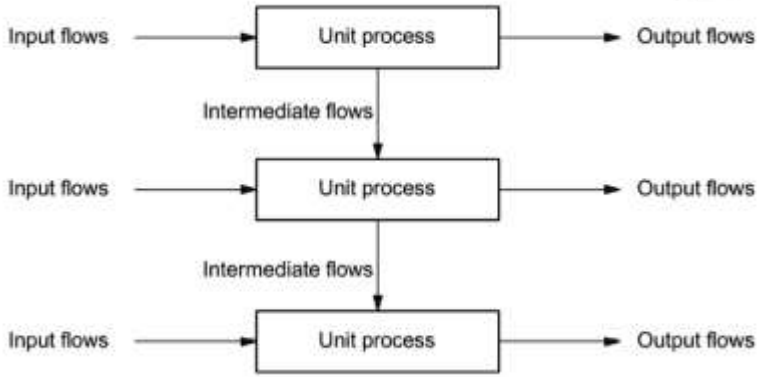
Study Design Parameters: Product System

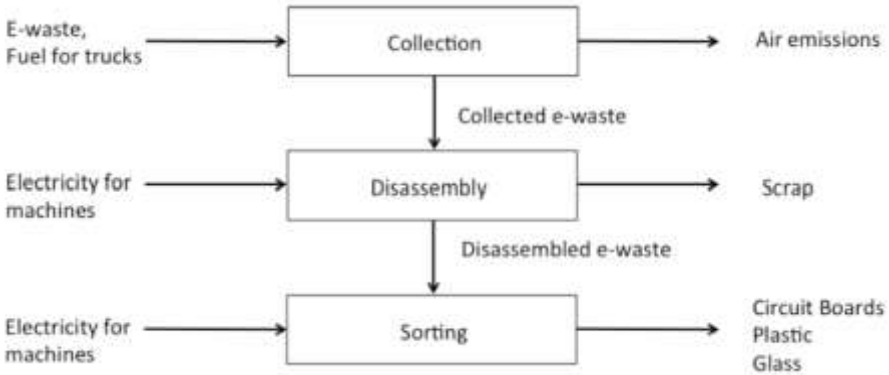
- **Product**: any kind of good or service
- **Product flow**: products entering from or leaving to another product system
- **Processes**: activities that transform inputs to outputs
- **Inputs / Outputs** – product, material or energy flow entering or leaving a unit process
  - In: fuel, energy, materials…
  - Out: products, emissions, waste…
- **Unit process**: smallest element for which input / output data are quantified
- **Elementary flows**:
  - material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation
- **Product system**:
  - collections of unit processes, elementary flows, and product flows that lead to one or more functions

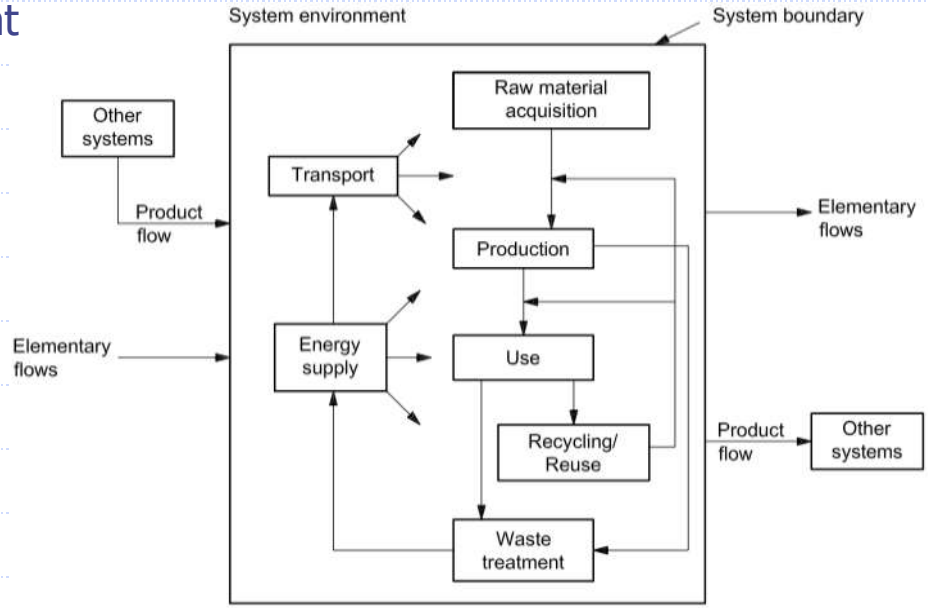
Detailed Product System (a.k.a. process flow diagram)

ISO 14040, Figure 2

- NOT ISO required, but really helpful!
  - Identify system boundaries
  - All unit processes described with text
- Elementary flows
  - Product systems have elementary flows: directly from and to environment
  - They ARE part of the system
  - Unit process (smallest element)
  - Unit process example: Waste treatment





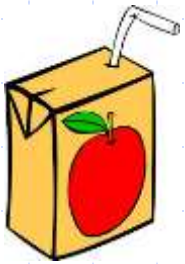


ISO 14040: 5.2.2
ISO 14044: 4.2.3.2

SDP: Function and Functional Unit

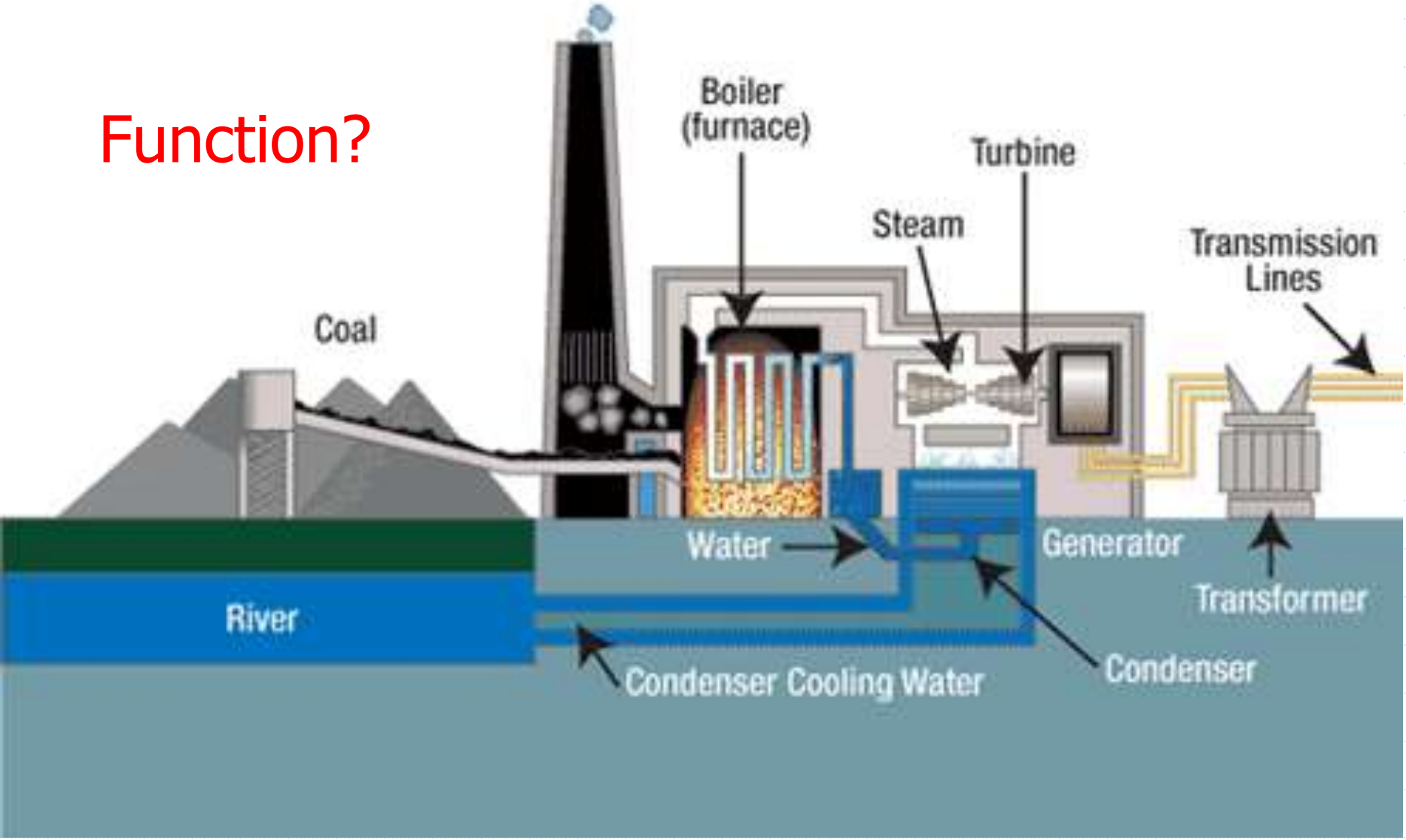
- What is the **function** of the system studied?
  - What does it do? Performance characteristics?
    - Christmas tree → provides Christmas Joy
    - Public utility → provides energy
    - Beverage container → conveys beverage
- Functional unit "quantifies the function"
  - Reference to which inputs and outputs are related
  - Quantitative
    - It's the denominator in your inventory
    - Input/functional unit, Output/functional unit
  - Explicit unit for comparisons within study, and future studies
    - Ex: displaying one unlit, undecorated Christmas tree with tree stand in the home during one holiday season
    - Ex: providing 1000 lumens of light for an hour via a fixture
    - Ex: drying 1 pair of hands



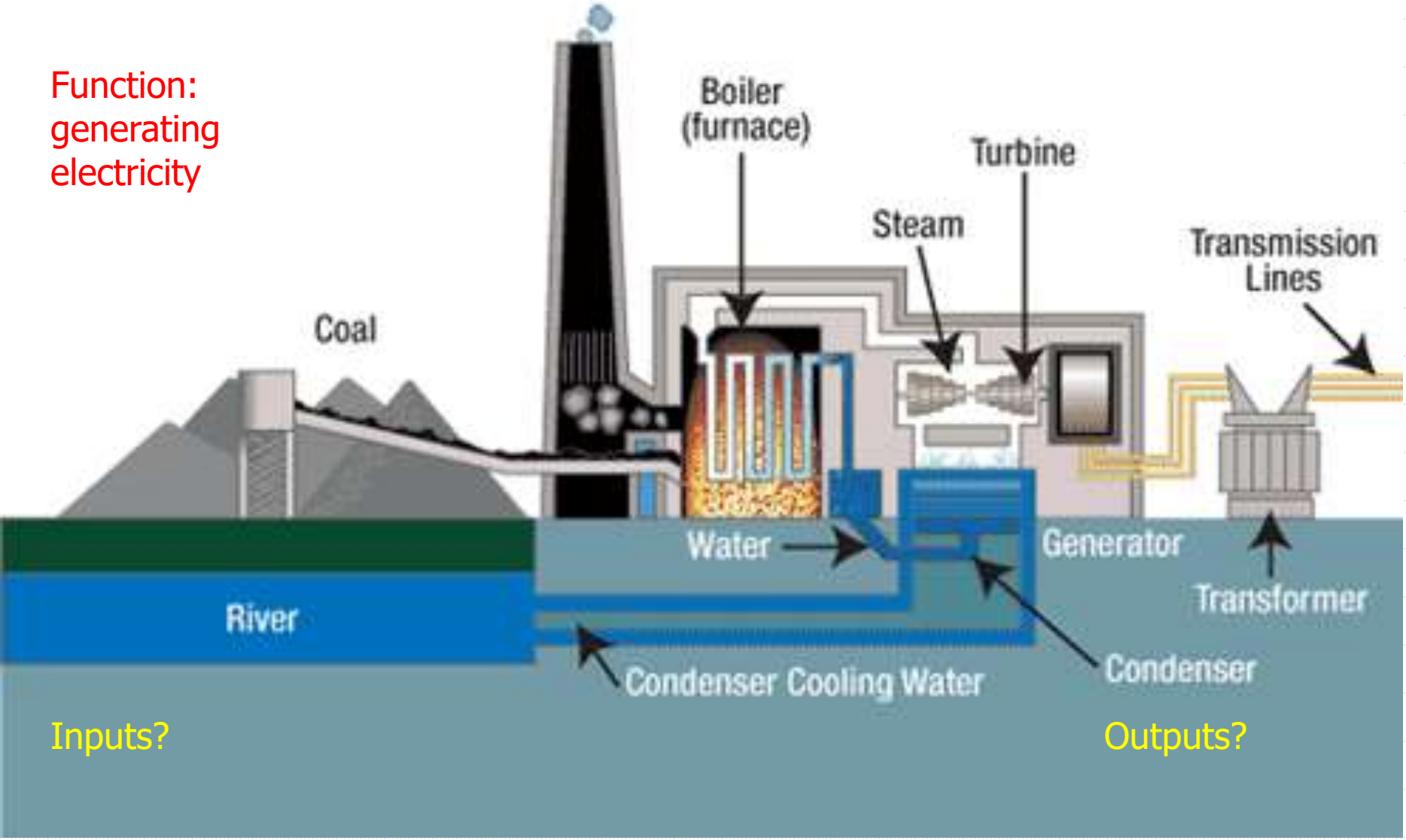

Thermo-Electric Power Plant

Function?



Thermo-Electric Power Plant

Function:
generating
electricity

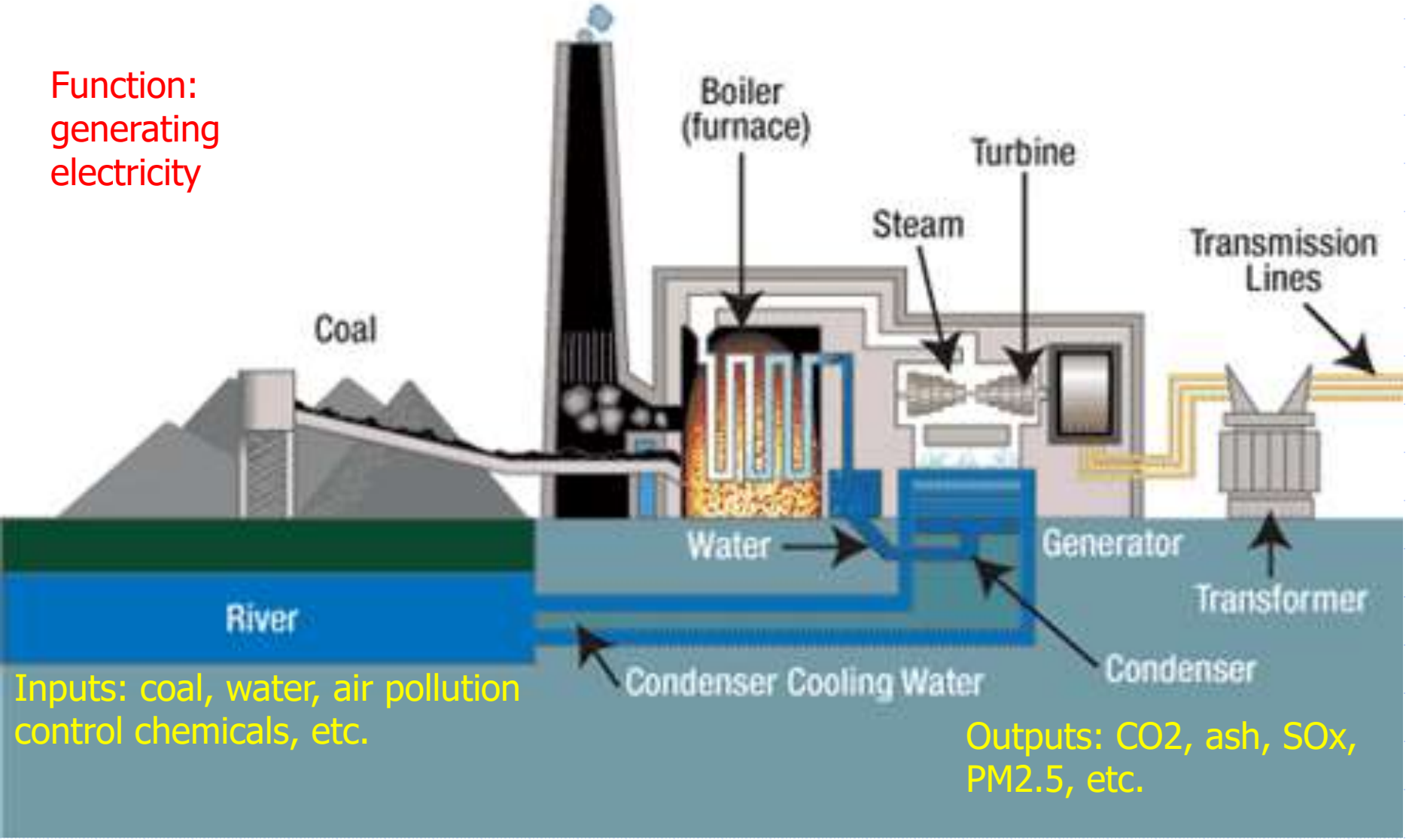


Inputs?

Outputs?

Thermo-Electric Power Plant

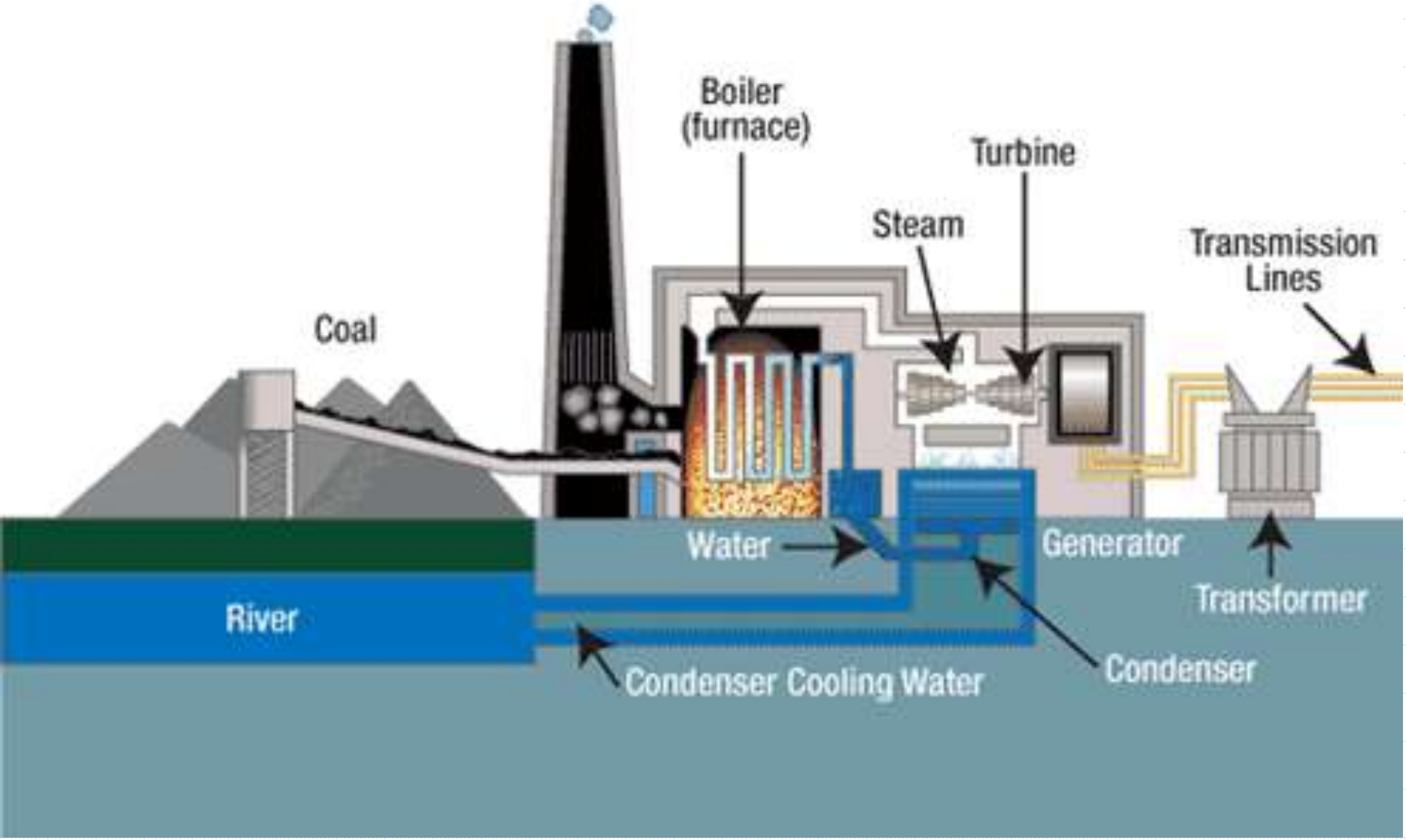
Function: generating electricity



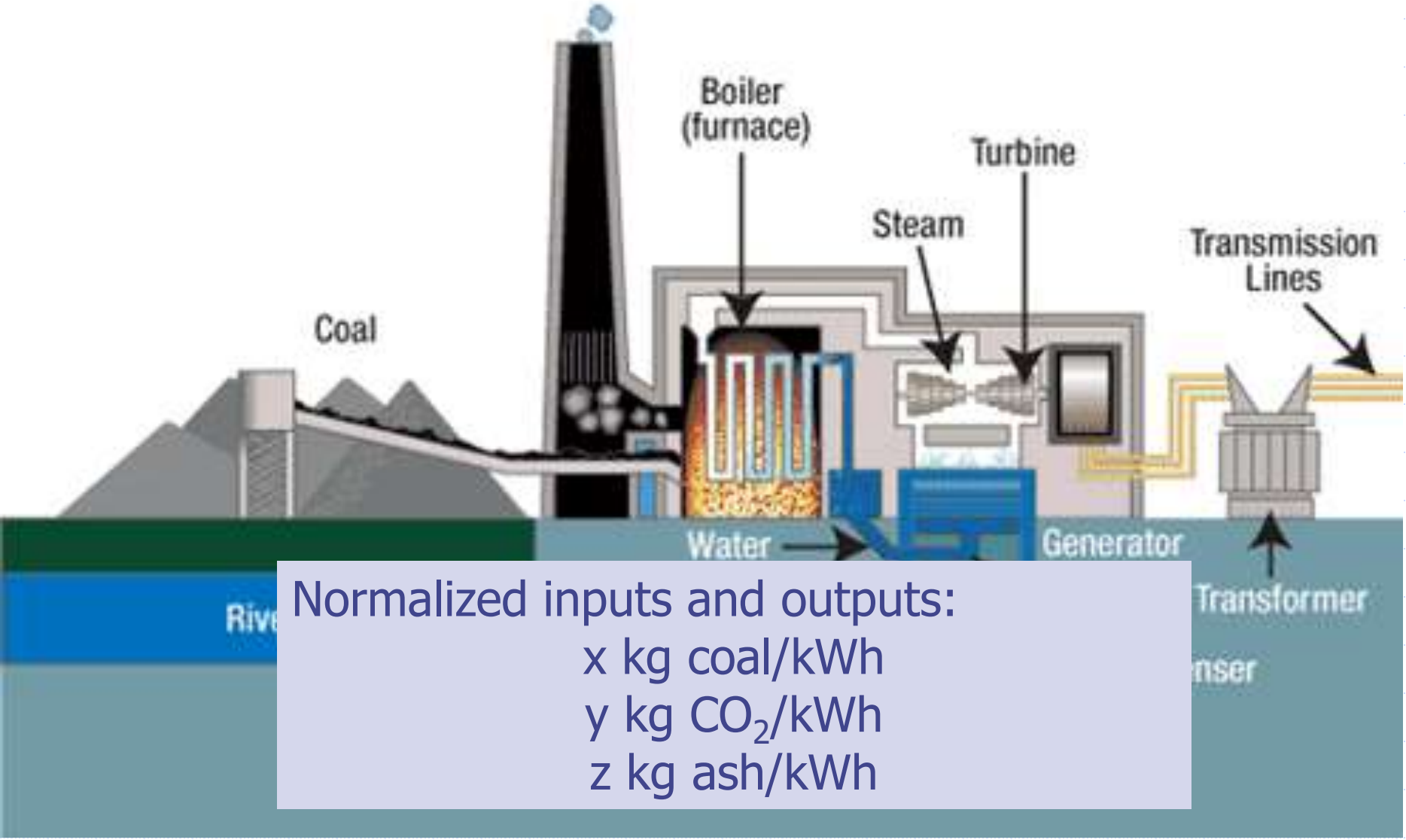
Inputs: coal, water, air pollution control chemicals, etc.

Outputs: CO2, ash, SOx, PM2.5, etc.

Functional unit: what would be a good way to normalize inputs and outputs?



Functional unit: kilowatt hour (kWh) (other scales might work)



Normalized inputs and outputs:

x kg coal/kWh

y kg CO_2/kWh

z kg ash/kWh

Functional Unit bridges Function → Inventory results

Product System	Function	Functional Unit	Example LCI Results
Power Plant	Generating electricity	1 kWh of electricity generated	kg CO_2 per kWh
Christmas Tree	Providing holiday joy	1 undecorated tree over 1 holiday season	MJ energy per undecorated tree per holiday season
Hand Dryer	Drying hands	1 pair of hands dried	MJ energy per pair of hands dried
Light Bulb	Providing light	100 lumens light for 1 hour (100 lumen-hrs)	g Mercury per 100 lumen-hrs

Functional Units

- When **Functional Units Go Wrong**
  - Getting the functional unit wrong causes lots of wasted effort
    - Not including units (too much like a function)
    - Error: "functional unit is generating electricity"
    - Not including quantity
    - Error: "kWhs of electricity"
    - Confusing with inventory result
    - Error: CO_2 per kWh
  - Your functional unit bridges function and inventory
    - it doesn't replace them.

- Functional Units **for Comparisons**
  - If functional unit isn't related to a generic function, might be impossible to compare
  - Ex: Different fuels. Can't have functional unit be "driving a car 1 mile on gasoline" and then compare gasoline to ethanol
  - Fixed: Generalized functional units:
    - "driving a car 1 mile"
    - "using 1 gallon-equivalent (MJ basis) in a car"
    - "using 1 MJ of energy in a car"

Group Exercise

- Teams of 2 or 3, mix it up again
- Work through the list of product systems, completing each of the following:
- Describe function
- Draft a functional unit

Hold off on the last 2 columns for now

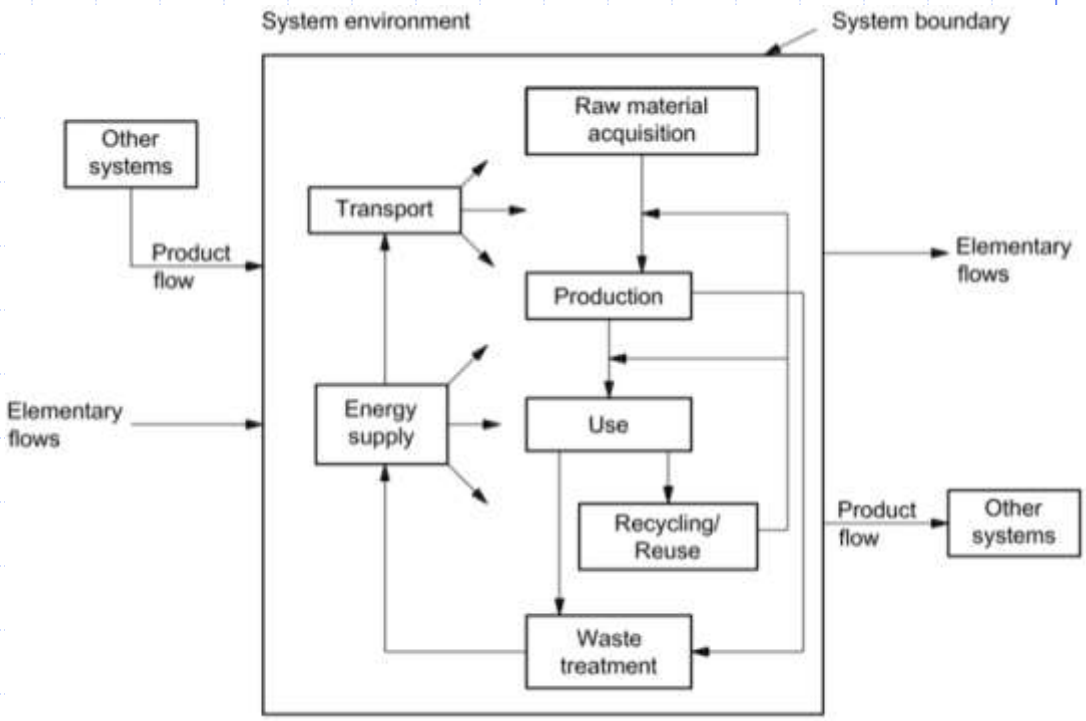
- 10 minutes work, then we'll discuss

Product or process	Function	Functional unit	Normalized input	Normalized output
Grocery bag (plastic vs cloth)				
Diapers (cloth vs disposable)				
Roofing material (asphalt shingles vs metal shingles)				
Snow removal (shovel vs snow blower)				
Going to NYC for the weekend (transport only)				
Cup of coffee (home vs at a café)				

ISO 14040: 5.2.3
ISO 14044: 4.2.3.3

SDP: System Boundaries

- What **processes and flows** of the product system are part of the study?
  - Initially arbitrary
  - Ideally, drawn large enough that all inputs and outputs are elementary flows
- What's excluded?
  - "The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study."
  - But how would you know it wouldn't change conclusions!?
  - You can omit things if you explain why



Example: process flow for a mobile phone

System Boundary Example: artificial vs. natural tree

- For the artificial tree the system boundary includes:
  - Cradle-to-gate material environmental impacts;
  - The production of the artificial tree with tree stand in China;
  - Transportation of the tree and stand to a EU retailer, and subsequently a customer's home; and
  - Disposal of the tree and all packaging.
- For the natural tree the system boundary includes:
  - Cradle-to-gate material environmental impacts;
  - Cultivation including initial growth of the tree in a nursery, transplant of the seedling to the field, harvesting the full size tree, and post harvest treatment of the tree;
  - Transportation from the farm to retailer, and subsequently to a customer's home;
  - Use phase watering;
  - Disposal of the tree and all packaging; and
  - Cradle-to-grave impacts of a natural tree stand.

Example: Summary of system boundary

Table 1: Tree System Boundary – Inclusions and Exclusions

Inclusions	Exclusions
Production/Cultivation of raw materials	Construction of capital equipment
Energy production	Maintenance and operation of support equipment
Processing of materials	Human Labor
Operation of primary production equipment	Manufacture and transport of packaging materials not associated with final product
Transport of raw materials and finished products	Internal transportation of materials within production facilities
Packaging of products	Overhead – heating and lighting of manufacturing facilities, warehouses, and retail stores.
End-of-Life treatm	

Summarize System Boundary Assumptions:

- Table
- Process flow diagram
- Report body

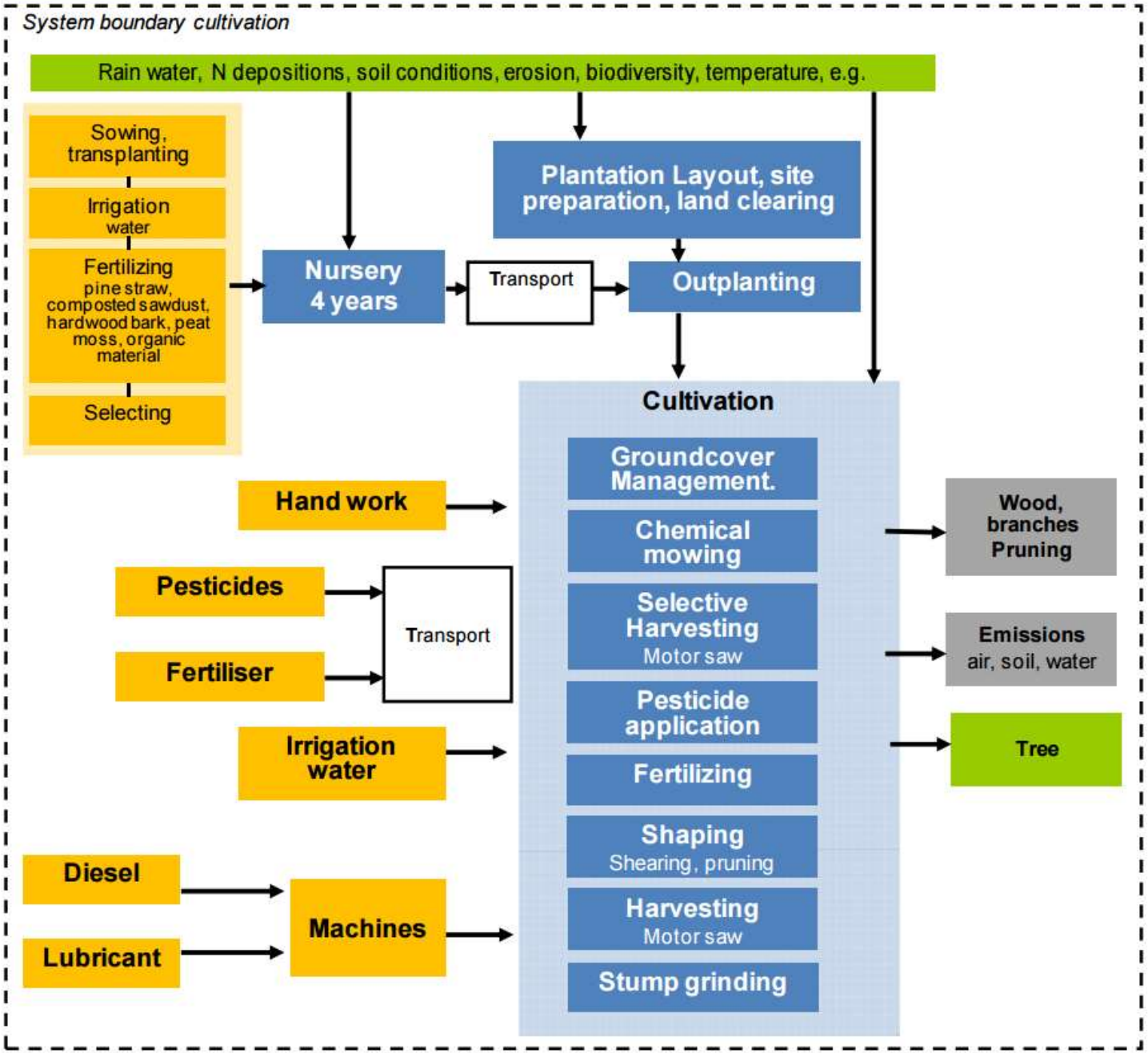


Figure 10: System Boundaries of Natural Tree Cultivation

ISO 14040: 5.2.3
ISO 14044: 4.2.3.3.1

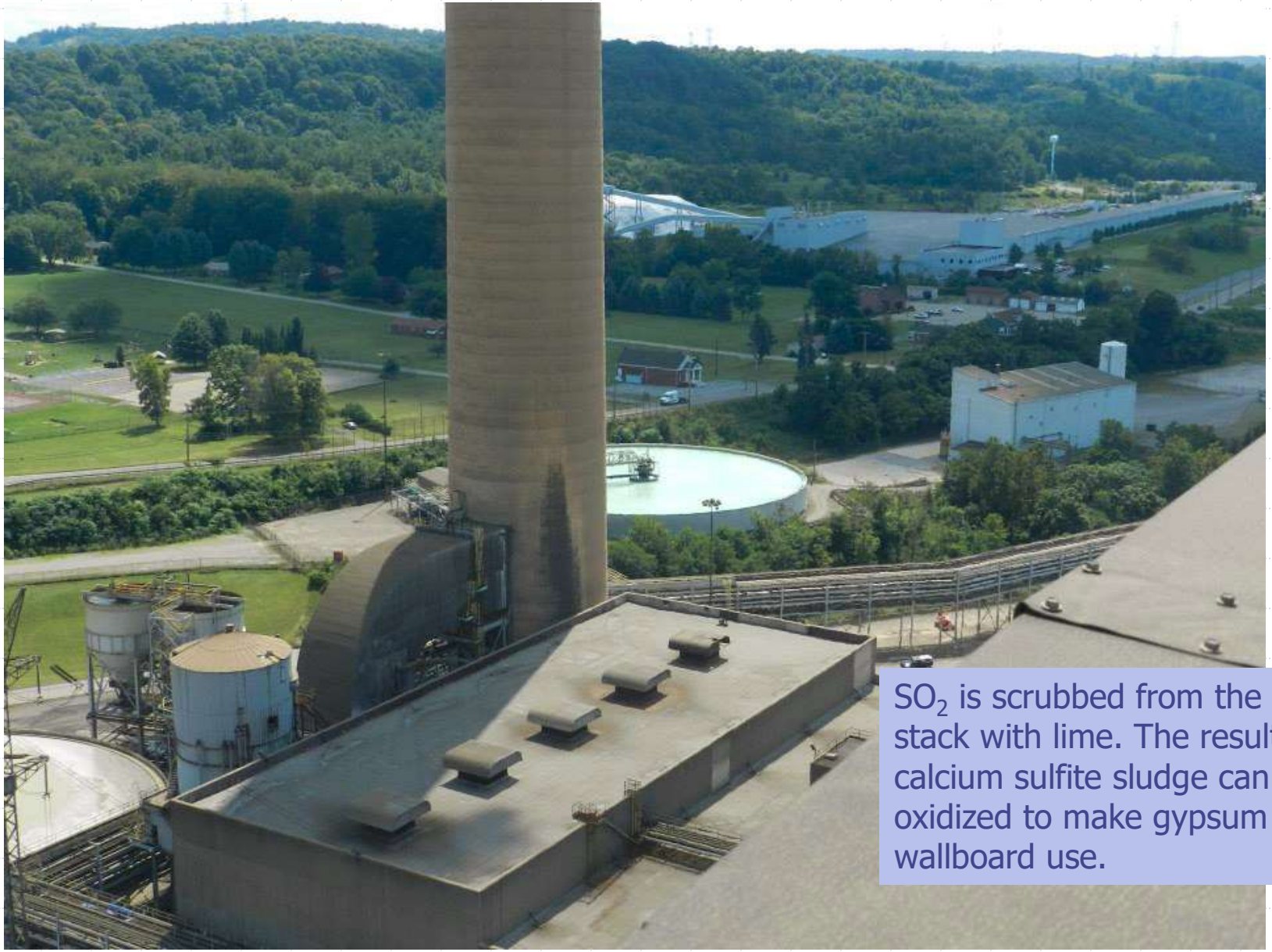
Study design parameters (SDP): inventory I/O

- Aim **to include** …
  - Acquisition of raw materials
  - Inputs and outputs of main manufacturing/processing sequence
  - Distribution/transportation
  - Production and use of fuels, electricity and heat
  - Use and maintenance of products
  - Disposal of process wastes and products
  - Recovery of used products
  - Manufacture of ancillary materials
  - Manufacture, maintenance and decommissioning of capital equipment
  - Additional operations, such as lighting and heating
- Inventory = **catalog of flows** entering and leaving system
- Scope specifies list of flows to be tracked
  - All or one, specify in your scope
  - Energy
  - GHG emissions
  - Water
  - Waste
  - Others?

Modeling what comes "in" is easy... Harder for "what comes out"

- Inputs
  - Materials, resources, etc., fairly straightforward
- Lots of "outputs" – emissions, products, waste
  - Product – the single useful output of the process
  - Co-product – when there are more than one
  - Waste – an output that has to be disposed of
  - By-products – partly product, partly waste (could be uncertain, confusing)
- SDP: Inventory Inputs and Outputs
  - Avoid generic categories "air emissions" or "water emissions", or "everything".
  - Specify which emissions of gases or substances
    - e.g., CO_2, SO_2, benzene, water, uranium...

Powerplant gypsum by-product?



SO_2 is scrubbed from the powerplant stack with lime. The resultant calcium sulfite sludge can be oxidized to make gypsum for wallboard use.

Group Exercise

- Teams of 2 or 3, mix it up again
- Work through the list of product systems, completing each of the following:
- Describe function
- Draft a functional unit
- List one inventory input, normalized
- List one inventory output, normalized

Now complete the last 2 columns

- 10 minutes work, then we'll discuss

System boundary: "Cut-off" criteria

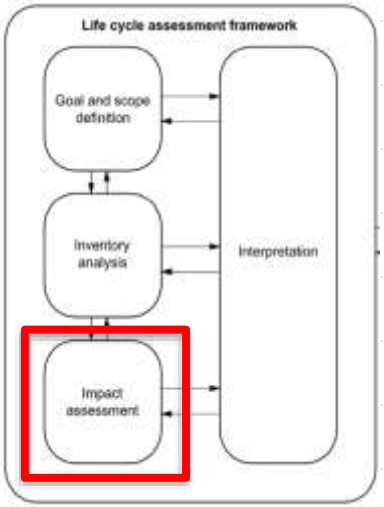
- **Threshold** by which you can exclude inputs and outputs
  - Describe assumptions and effect of cut-off on results
- Intention: "answer wouldn't change with more data"
  - Problem is – how do you know?
  - Often a qualitative statement discussing potential effects
- Mass – "exclude anything with mass < 1g" or "less than 1% of product mass"
- Energy – similar
- Environmental significance
- Easy to start excluding important items

Try to avoid using cut-offs!

SDP: Life Cycle Impact Assessment Categories and Methods

ISO 14040: 5.4
ISO 14047

- Impact evaluation is not new:
  - scientist are doing it since decades
- Key element of LCA is the connection of the flows to a **functional unit**
- Impacts are focused on that specific normalized quantity

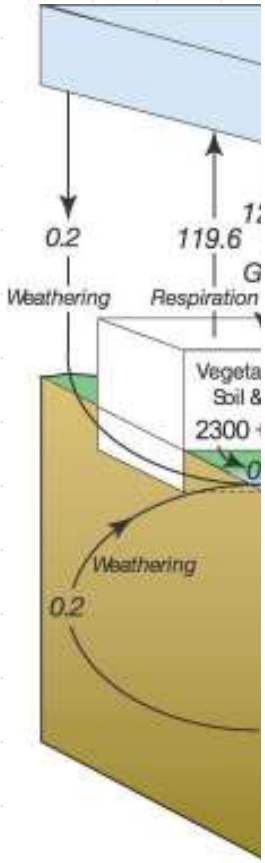


Impact Category	Scale	Examples of LCI Data (i.e. classification)
Global Warming	Global	Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), Methane (CH_4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Methyl Bromide (CH_3Br)
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Halons, Methyl Bromide (CH_3Br)
Acidification	Regional, Local	Sulfur Oxides (SO_x), Nitrogen Oxides (NOx), Hydrochloric Acid (HCl), Hydrofluoric Acid (HF), Ammonia (NH_4)
Eutrophication	Local	Phosphate (PO_4), Nitrogen Oxide (NO), Nitrogen Dioxide (NO_2), Nitrates,Ammonia (NH_4)
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish
Human Health	Global, Regional, Local	Total releases to air, water, and soil.
Resource Depletion	Global, Regional, Local	Quantity of minerals used, Quantity of fossil fuels used
Land Use	Global, Regional, Local	Quantity disposed of in a landfill or other land modifications
Water Use	Regional, Local	Water used or consumed

Figure 10-2: Summary of Impact Categories (US EPA 2006)

Environmental impact categories: global warming

CO_2 eq.



Shorter-term climate change

Rate of climate change:

- Movement of species (Ecosystem adaptation
- Heat stress, malnutrition (Human adaptation)
- Extreme weather events
- ...

Emission

Atmospheric Concentration

Radiative Forcing

Atmospheric Temperature

Climate Change Impacts

AoP Human Health

AoP Ecosystem Quality

AoP Natural Resources and Ecosystem Services

Long-term climate change

Long-term climate change:

- Sea level rise
- Polar caps melting
- Coral bleaching
- Changing biomes
- ...

Figure 3.1: Simplified impact pathway for climate change (AoP: Area of protection)

https://www.ipcc.ch/

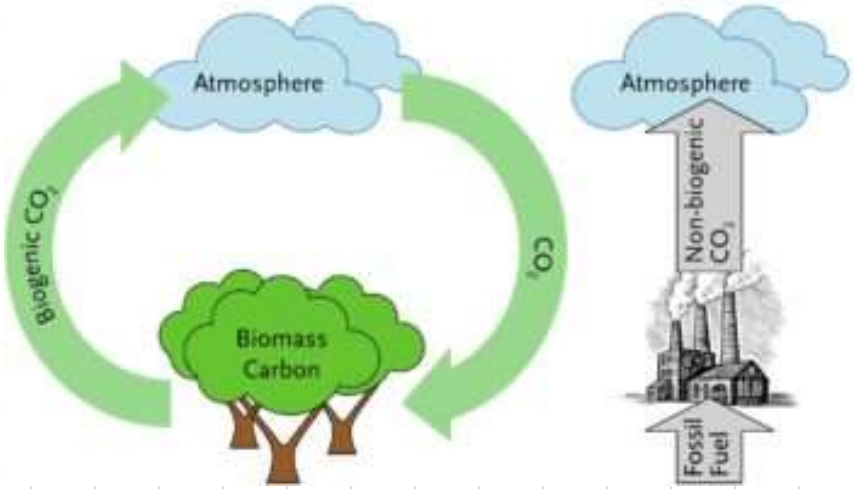
Environmental impact categories: global warming

ARx = IPCC Assessment Report x (ARx)

Table 3.1: IPCC 5th AR climate change impact indicators

Indicator & TH	Impact measured	Interpretation
GWP 20	Radiative forcing; cumulative	Assesses warming over the next two decades only; high importance to NTCFs and very short-lived GHGs
GWP 100	Radiative forcing; cumulative	The most common in LCA; represents integrated forcing over 100 years; numerical values are similar to those of GTP40 (i.e. proxy for temperature impacts in about 40 years
GTP 20	Temperature; instantaneous	Measure of potential temperature rise 20 years from today
GTP 50	Temperature; instantaneous	Measure of potential temperature rise 50 years from today
GTP 100	Temperature; instantaneous	Measure of potential temperature rise 100 years from today; numerically similar to GWP with TH of several centuries

Radiative forcing is the difference between solar irradiance (sunlight) absorbed by the Earth and energy radiated back to space



Environmental impact categories: global warming

Substance	AR1 (1990)	AR2 (1995)	AR3 (2001)	AR4 (2007)	AR5 (2013)
Carbon dioxide, fossil (CO_2)	1	1	1	1	1
Methane, fossil (CH_4)	21	21	23	25	28
Methane, biogenic (CH_4)	18.25	18.25	20.25	22.25	25.25
Dinitrogen monoxide (N_2O)	290	310	296	298	265
HCFC-141b	440	-	700	725	782
HFC-134a	1200	1300	1300	1430	1300
HCFC-22	1500	-	1700	1810	1760
HCFC-142b	1600	-	2400	2310	1980
CFC-11	3500	-	4600	4750	4660
CFC-12	7300	-	10600	10900	10200
Sulfur hexafluoride	-	23900	22200	22800	23500

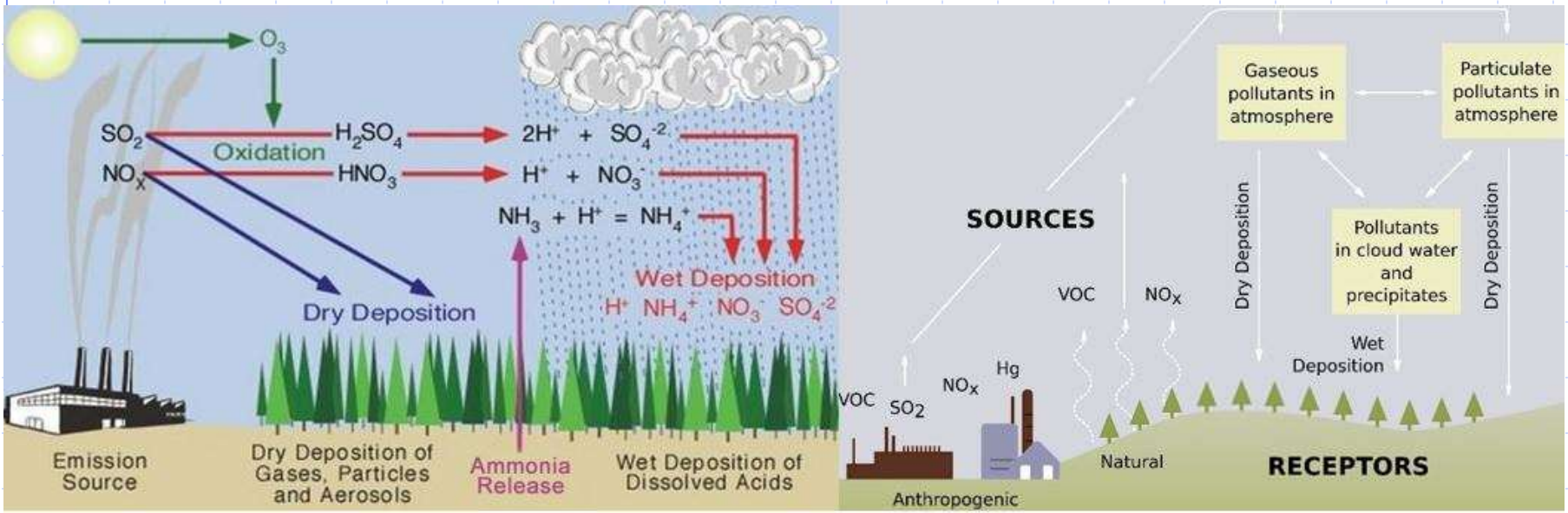
ARx = IPCC Assessment Report x (ARx)

Product	Region	Source	Unit	AR4 (2007)	AR5 (2013)
Milk	Global	FAO	kg	2.8	2.9
Beef	Global	FAO	kg	46	47
Eggs	Global	FAO	kg	3.7	3.6
Chicken meat	Global	FAO	kg	5.4	5.2
Wheat	Global	ecoinvent	kg	0.88	0.85
Rice	Global	ecoinvent	kg	2.0	2.1
Electricity med. volt.	Netherlands	ecoinvent	kWh	0.179	0.179
Car transport	Europe	ecoinvent	1000 km	0.326	0.327

Environmental impact categories: acidification

- Acidification is evaluated normalizing H^+ ions of the specific substance with respect to the H^+ ions of SO_2

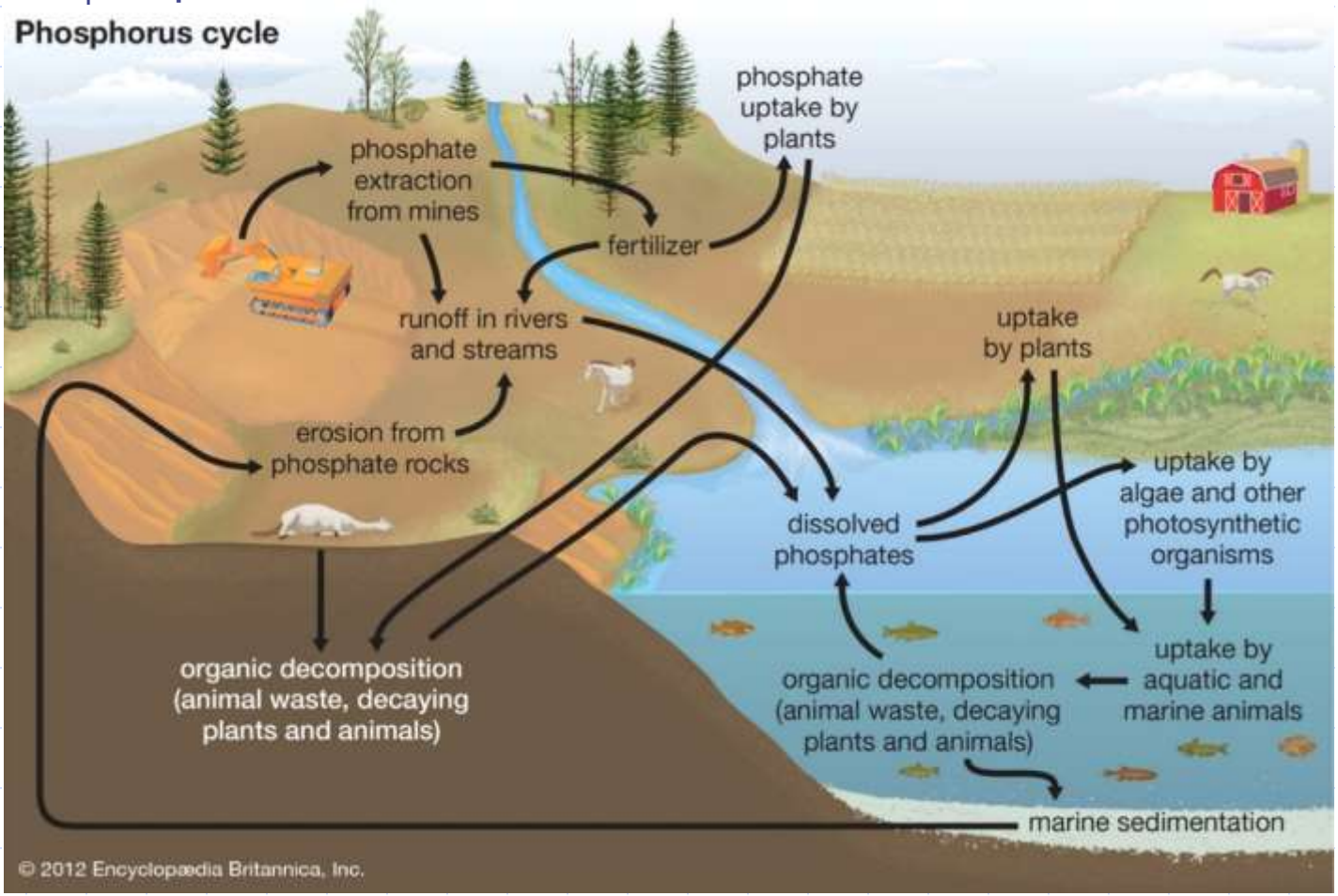
➡ Unit = 1 kg SO_2 eq.



Environmental impact categories: Eutrophication

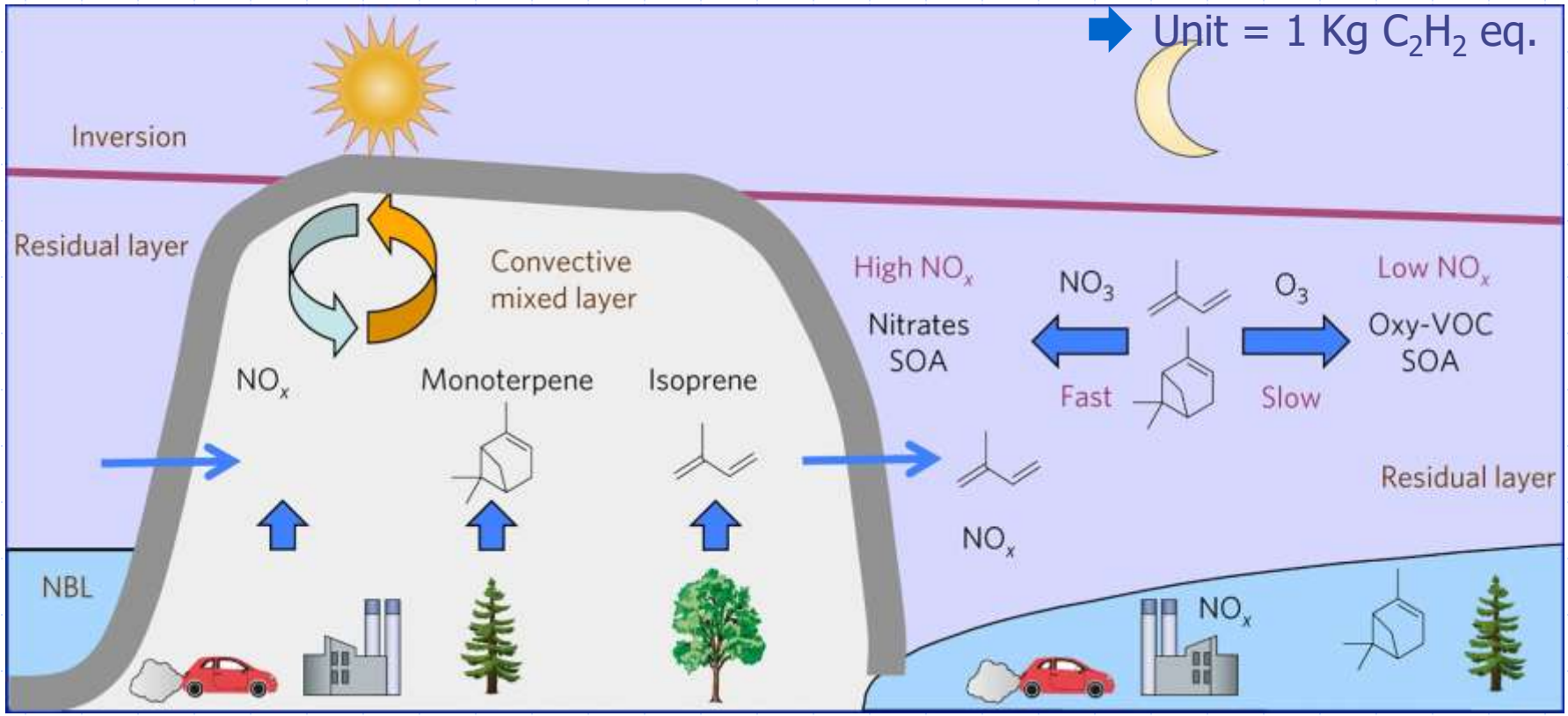
- In LCA eutrophication includes the increase of nutrients in the ecosystem and the impact of the organic matter degradation.

➡ Unit = 1 Kg PO_4^{---} eq.



Environmental impact categories: Photochemical oxidation formation

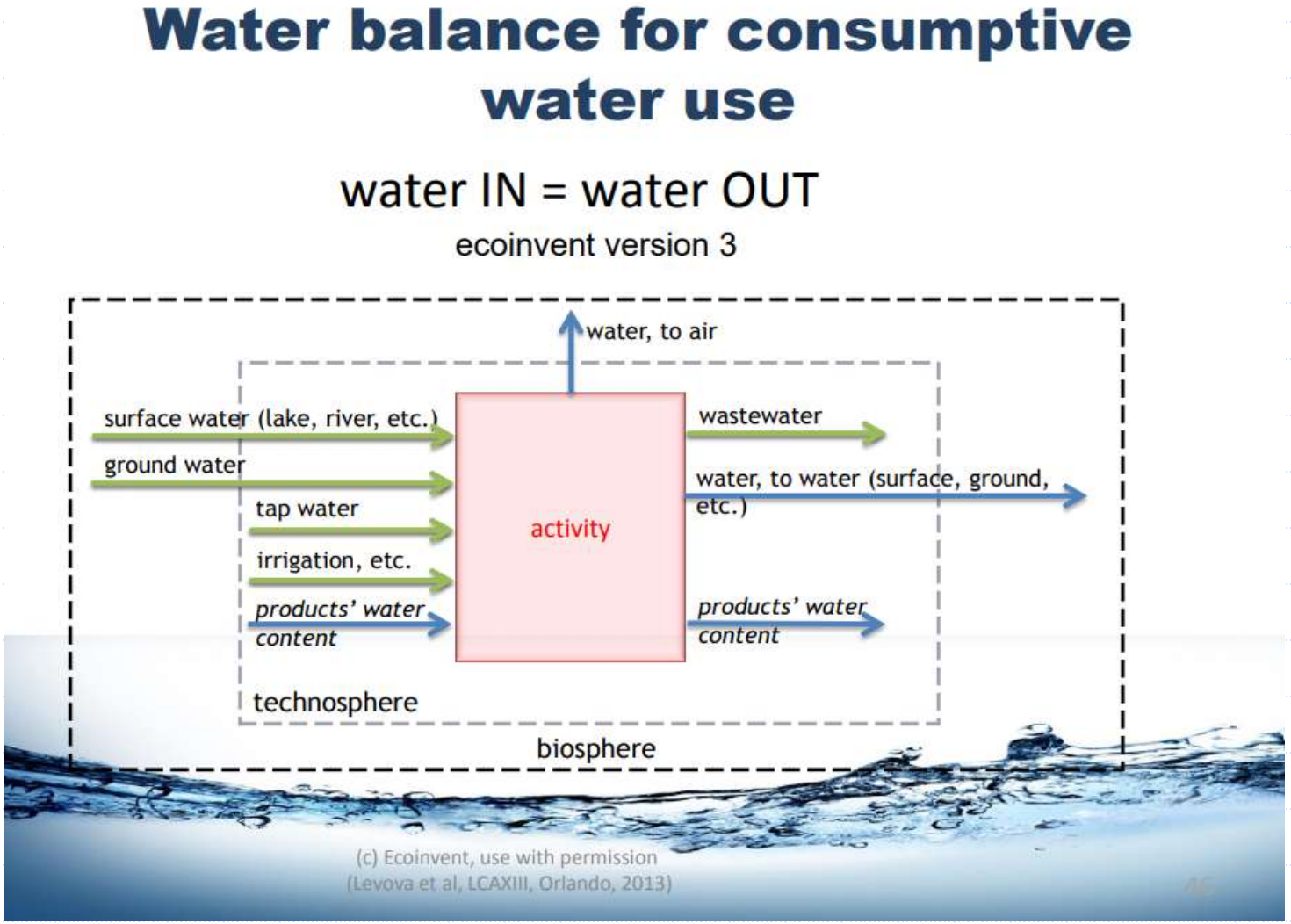
- The POCP (Photo-oxidant creation potential) is evaluated for each substance belonging to this category, based on the model CML 2002
  - POPC for 5 days transportation in EU
  - and for the reactivity increase of the substance for a reduced interval of time in urban area in America



Environmental impact categories: Water scarcity – AWARE (Available Water Remaining)

http://www.wulca-waterlca.org/training-materials.html

Environmental impact categories: Water scarcity – AWARE (Available Water Remaining)



http://www.wulca-waterlca.org/training-materials.html

SDP: Life Cycle Impact Assessment Categories and Methods

- List specific impact assessment methods to be used
  - Ex: climate change assessed using IPCC method
  - Ex: eutrophication assessed using stoichiometric approach (establishing equivalency of macronutrients on basis of their occurrence in biomass)

Environmental Indicators for Christmas Tree LCA:

- Primary Energy Demand
- Global Warming Potential
- Eutrophication
- Acidification
- Smog

ISO 14040: Section 6
ISO 14044: Section 5

Reporting

- Report
  - Critical aspect of LCA!
  - Record of the study
  - Indicator of study quality
  - May or may not be made public (most are not)
  - Use specified ISO terminology: goal, scope, functional unit, etc.
- Define type and format in Goal & Scope phase

- Results/conclusions completely and accurately reported without bias to intended audience
- Results, data, methods, assumptions and limitations
- Transparent
- Detailed enough to describe complexities / trade-offs
- Allow results/interpretation to be used in a manner consistent with study goals

ISO 14040: Section 7
ISO 14044: Section 6

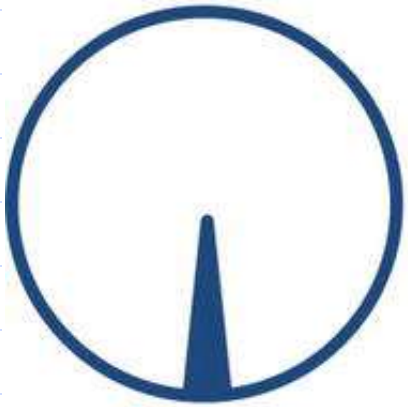
Critical Review

- Critical Review required if making comparative assertions for public release
  - Checking for "ISO compliance"
  - Methods used are scientifically/technically valid
  - Data used are appropriate/reasonable
  - Interpretations reflect the limitations identified and goal of the study
  - Study report is transparent and consistent
- Chance for inconsistencies, errors, etc. to be found

Quick Word on LCA Types

- Two "types" of environmental LCAs
  - Attributional: studies an existing product
  - Consequential: studies the effects of potential changes to a product, process, etc.
  - Nearly all to date attributional

Attributional LCA



What part of the global environmental burdens should be assigned to the product?

XX kg CO2-equ.
etc.

Two types of LCA
To respond to
different questions

Consequential LCA

What is the impact of the product on the global environmental burdens?

ZZ kg CO2-equ.
etc.

Criticisms / Limitations / Alternatives of LCA

- **Criticism / limitations** of LCA
  - No single, accepted method (just 1 framework)
  - Data reliability and quality is questionable
  - Models based on assumptions
  - Problem boundaries are arbitrary
  - Scale issues – global → local
  - Uncertainty is everywhere
  - Spatial and temporal issues
  - Comparisons between studies difficult
- **Alternatives** to LCA Modeling Approaches
  - Risk analysis
  - Environmental impact assessment
  - Environmental audit
  - Benefit-cost analysis
- **LCA is not perfect**, but it is a helpful tool.
  - Life cycle assessment is not required to address economic or social aspects (key part of sustainability!) and so may differ from above.
  - Models may be combinable