Vaclav Smil! Read him.

Jevon's Paradox

Between 1900 and 1999, the United States consumed 4500 million tonnes of cement. That's in one century. Between 2011 and 2013, China consumed 6500 million tonnes of cement. That is, in three years, the Chinese consumed 50% more cement than the United States had consumed in the entire preceding century.

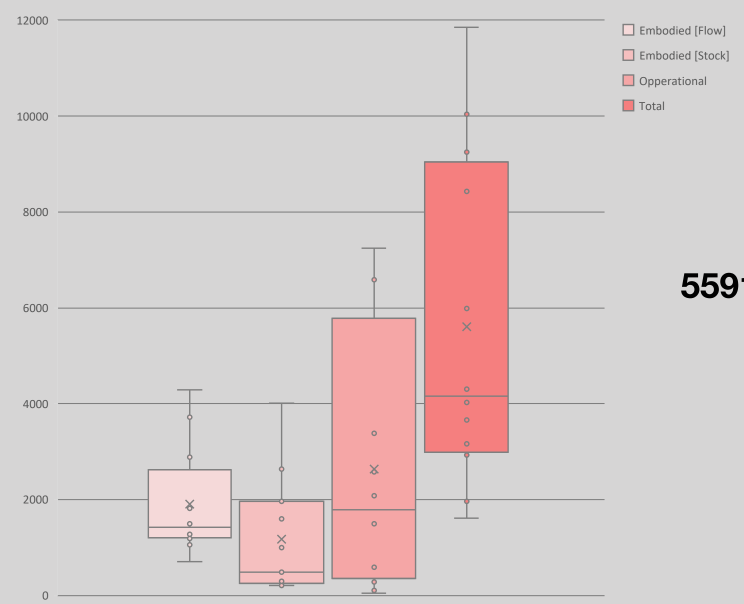
During the financial crisis of 2009, China decided to overproduce raw and bulk materials in order to stabilize their economy. In other words, to keep the population working in paid jobs. They did this despite the fact that the rate of construction worldwide had fallen dramatically because of the financial crisis. Then between 2011 and 2013, China began a series of ambitious infrastructure projects to consume all this surplus steel and cement and to further keep people working in paid jobs.

synchronous

asynchronous

Week	Date	Lecture Topic (45 min)	Workshop (45 min)	Guest (45 min) (*Exact date TBD)	Assign. Due	Reading
1	9/2	Course introduction				
2	9/9	Materials Ecology	R1: Operative vs Embodied		A0: Student Introductions	R1
3	9/16	Material Characterization	W1: Granta CES			R2
4	9/23	Material Characterization	R3: Discussion W2: S-LCA		A1.1: Weigh-your-day data	R3 (long)
5	9/30	The Anthropocene and env. justice	R3: Discussion W2: S-LCA	9/30HouseZero Tour	A1.2: Weigh-your-day review	R4
6	10/7	Life cycle assessment	W2: Athena			R5
7	10/14	Embodied carbon in buildings	W3: Tally for Revit	G2 Billie Faircloth	A2.1: House Zero Athena	R6
8	10/21	Low-carbon materials	W4: EC3	G3 Kate Simonen	A2.2: House Zero Tally	R7
9	10/28	The circular economy		G4* Henning Fjeldheim	A2.3: House Zero EC3	
10	11/4	Beyond carbon mitigation		G5 David Keith	A3.1 Proposals	R8
11	11/11	Low-carbon technology disruptors		G6 Daniel Nocera	A3.2 Project Update	R9
12	11/18	Open topic		G7 Kathryn Yussof	A3.3 Project Update	
13	11/25			**Recess**		
14	12/2	Scheduled desk crits			A3.4 Project Update	
15	TBA			**Final Exam (Project Review)**		

A2.1 Up w/ Athena workshop



5591 kg CO_2e/yr/per
±3441

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All materials sit within an ecology. All ecologies include economics.

This is a question of material reserves and resources.

Reserves is an economic term representing how much can be extracted at that time, it grows with demand.

Resource is the actual amount we think is there…we measure these things about 30 years out.

Simon-Ehrlich wager: In 1980 Biologist Paul Ehrlich famously bet the economist Julian Simon that five metals (aluminum, copper, chromium, gold, nickel, tin, tungsten or zinc) would become scarcer and hence more expensive by the end of the decade; he lost all five bets.

Ehrlich bet $200 dollars on each material on September 29, 1980 (totalling $1K). If in ten years the price went up, Simon would pay the combined difference, if it went down, Enrlich would pay Simon.

From 1980 and 1990, the world's population grew by more than 800 million, the largest increase in one decade in all of history. But by September 1990, the price of each of Ehrlich's selected metals had fallen. For example, Chromium, which had sold for $3.90 a pound in 1980, was down to $3.70 in 1990. Tin, which was $8.72 a pound in 1980, was down to $3.88 a decade later. As a result, in October 1990, Paul Ehrlich mailed Julian Simon a check for $576.07 to settle the wager in Simon's favor—> **Nearly half the price.**

The reality is that as the most easily extracted supplies of materials become scarcer, their prices rise, encouraging people to conserve it, but we also work to get at the less accessible reserves or find a cheaper substitute.

It is often said that the Stone Age did not end because the world ran out of stones, and the has been true of energy as well. “Plenty of wood and hay remained to be exploited when the world shifted coal” Ausubel notes “coal abounded when oil rose. Oil abounds now as methane (natural gas) rises”

Clift, Roland, and Angela Druckman. Taking Stock of Industrial Ecology. 2015.

The late 60’s were a time of “sustainable awakening”: oil crisis, concerns about population growth, the Limits of Growth led to environmental movements in many countries.

Environmental life cycle assessment (LCA) has developed fast over the last three decades. The first studies that are now recognized as (partial) LCAs date from the late 1960s and early 1970s, a period in which environmental issues like resource and energy efficiency, pollution control and solid waste became issues of broad public concern.

One of the first studies quantifying the resource requirements, emission loadings and waste flows of different beverage containers was conducted by Midwest Research Institute (MRI) for the Coca Cola Company in 1969.

Coca-Cola anecdote, the company assess life cycle for each container holding their product. Instead of just banning the bad ones, they challenged those industries to improve. Coca Cola quantified the raw materials and fuels used, as well as the environmental impact of the manufacturing processes. In the case of aluminum, the manufactures worked with governments to develop recycling infrastructure, reducing primary energy demand (and associated cost) by 90 percent. This methodology was known as Resource and Environmental Profile Analysis (REPA).

The period 1970–1990 comprised the decades of conception of LCA with widely diverging approaches, terminologies and results. There was a clear lack of international scientific discussion and exchange platforms for LCA. LCAs were performed using different methods and without a common theoretical framework. The obtained results differed greatly, even when the objects of the study were the same.

The 1990s saw a remarkable growth of scientific and coordination activities worldwide, which among other things is reflected in the number of LCA guides and handbooks produced.

This was over in 1997, when the International Standards Organization ISO published the standard ISO 14000, including ISO 14040, which defined the correct process of a Life Cycle Assessment. ISO 14040 has gone through many updates, and is still the standard for Life Cycle Assessment used today.

The period 1990–2000 showed convergence and harmonization of methods through SETAC's coordination and ISO's standardization activities, providing a standardized framework and terminology, and platforms for debate and harmonization of LCA methods. During this period, LCA also became increasingly part of policy documents and legislation, particularly focusing on packaging. It is also the period that the scientific field of industrial ecology (IE) emerged, with life cycle thinking and LCA as one of its key tools.

The first decade of the twenty-first century has shown an ever-increasing attention to LCA … LCA was increasingly used as a tool for supporting policies and (bio-energy) performance-based regulation. Life cycle-based carbon footprint standards were established worldwide in this period.

New methods also emerged…Economic Input-Output LCA (EIO-LCA), Process-based LCA, Hybrid LCA, Life cycle costing (LCC) and social life cycle assessment (SLCA)

This broadening of environmental LCA to LCC and SLCA draws on the three-pillar (or triple bottom line, TBL) model of sustainability, distinguishing environmental, economic and social impacts of product systems along their life cycle.

'three-pillar' interpretation of sustainability, referred to as 'people, planet and prosperity' at the World Summit on Sustainable Development in Johannesburg in 2002. The triple bottom line approach basically says that for achieving more sustainable futures, environmental, economic as well as social impacts of activities have to be taken into account.

On Green Washing

“People Start Pollution. People Can Stop It.” — Keep America Beautiful Public

Service TV Commercial With “Iron Eyes” Cody — famous Italian American actor who portrayed indigenous people

From The People of the Advertising Council (1971)

Is it your issue, my issue, big businesses issue?
Not to mention the cultural appropriation!

Directly from WIKI:

Keep America Beautiful was founded in December 1953 by a group of American businesses (including companies such as American Can Company, Continental Can Company, Owens-Illinois Glass Co.), nonprofit organizations (Izaak Walton League of America, National Council of State Garden Clubs, U.S. Brewers Foundation), government agencies (Connecticut State Highway Dept., N.Y. State Department of Public Works), and concerned individuals in reaction to the growing problem of highway litter that followed the construction of the Interstate Highway System, and an increasingly mobile and convenience-oriented American consumer. The original goal of the organization was to reduce litter through public education, including public service announcement (PSA) campaigns, and engage trisector partnerships through the support of industry, government and nonprofits.

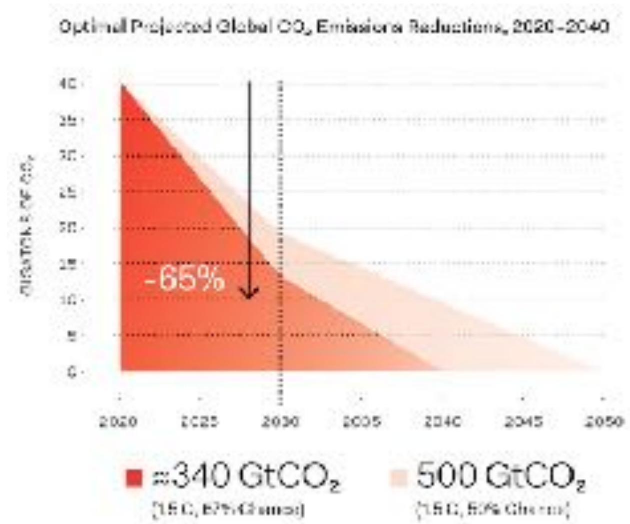
Heather Rogers, creator of the 2005 documentary film Gone Tomorrow: The Hidden Life of Garbage and book of the same name, classifies Keep America Beautiful as one of the first greenwashing corporate fronts, alleging that the group was created in response to Vermont's 1953 attempt to legislate a mandatory deposit to be paid at point of purchase on disposable beverage containers and banning the sale of beer in non-refillable bottles.

The Keep America Beautiful narrow focus on litter, and indeed construction of the modern concept of litter, is seen as an attempt to divert responsibility from industries that manufacture and sell disposable products to the consumer that improperly disposes of the related non-returnable wrappers, filters, and beverage containers.

Elizabeth Royte author of Garbage Land, describes Keep America Beautiful as a "masterful example of corporate greenwash", writing that in contrast to its anti-litter campaigns, it ignores the potential of recycling legislation and resists changes to packaging.

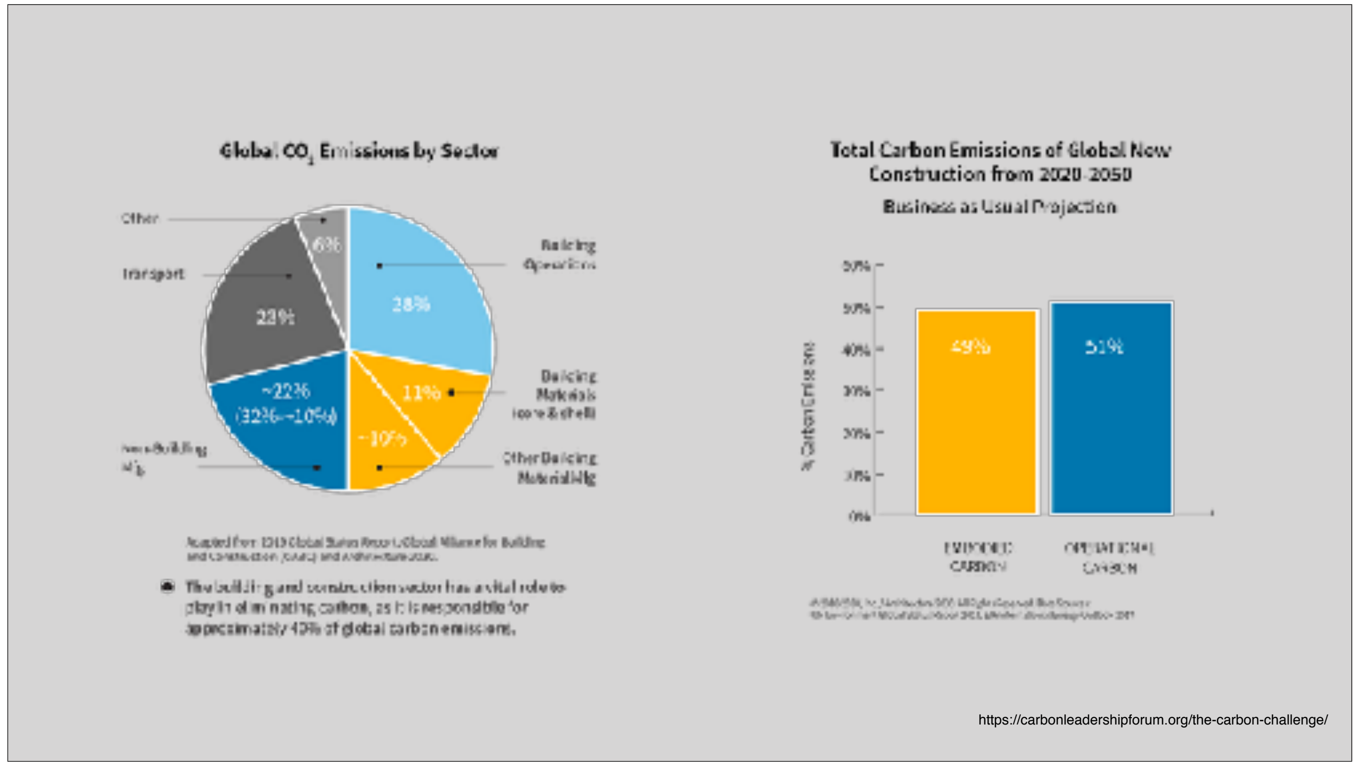
The tobacco industry developed programs with Keep America Beautiful that focused on cigarette litter solutions acceptable to the tobacco industry such as volunteer clean-ups and ashtrays, instead of smoke-free policies at parks and beaches. The tobacco industry has funded Keep America Beautiful and similar organizations internationally.

The slow moving ship that is architecture may have had a moment this month…



To maintain even a 67% chance of limiting warming to 1.5 C above preindustrial levels, humanity has to limit its total emissions to a “carbon budget” of about 340 gigatons of CO2 starting in 2020. The numbers may be abstract, but the implications are firm: a 65% reduction in greenhouse gas emissions by 2030, and full decarbonization by 2040

1000Gton budget!



Globally, the building and construction sectors account for nearly 40% of global energy-related carbon dioxide emissions in constructing and operating buildings (including the impacts of upstream power generation). Current building codes address operating energy but do not typically address the impacts ‘embodied’ in building materials and products. However, more than half of all GHG emissions are related to materials management (including material extraction and manufacturing) when aggregated across industrial sectors. As building operations become more efficient, these embodied impacts related to producing building materials become increasingly significant. - Carbon Leadership Forum

UNEP and IEA, “Global Status Report 2017: Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector,” 2017.
OECD, “Global Material Resources Outlook to 2060: Economic Drivers

Life Cycle Assessment

An understanding of embodied [carbon] suggest that architecture is improperly defined. Architecture involves a longer duration and wider geography—more time and space—than we typically consider.

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Architecture is constant state of transformation

Embodied energy connects the smallest part of a building to territories of extraction, **transformations**, and transportation (add labor), rendering once and for all mute the possibility of architecture as an autonomous object (CITE, likely from David Benjamin's new book)

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Buildings are not static objects, but rather one component within a complex environmental, social, and economic system (Moe)

Harold J. Morowitz’s (who we just met) book Energy Flow in Biology laid out his central thesis that "the energy that flows through a system acts to organize that system,”

“In every instance considered, natural selection will so operate as to increase the total mass of the organic system, to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system, so long as there is presented an unutilized residue of matter and available energy” -Lokta

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Life Cycle Assessment (LCA) is a standardized method of tracking and reporting the environmental impact of a product or process throughout its full life cycle (ISO 2006a: 8)

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LCA is oddly flexible, lack of useful data for MEP, demolition energy, or tenant improvements might reframe an LCA study from:

"determining a comprehensive understanding of full life cycle impacts of the building"

to

"identifying components with relatively significant contributions to the total environmental impact of the building"

LCA is oddly flexible, **lack of useful data for MEP, demolition energy, or tenant improvements might reframe an LCA study from:**

"**determining a comprehensive understanding of full life cycle impacts of the building**" i.e how much does your boiling weigh, carbon-wise.
to

"**identifying components with relatively significant contributions to the total environmental impact of the building"** i.e how much does insulation reduce harmful impact.

“There is no single method for conducting LCA”

—ISO14040

“Ripe for agency and leadership”

—Me and others

“ISO 14040: Environmental management — Life cycle assessment— Principles and framework.”
International Organization for Standardization, Geneva, Switzerland, 2006.

“ISO 14044 Environmental management — Life cycle assessment — Requirements and guidelines.”
International Organization for Standardization, Geneva, Switzerland, 2006.

“EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method” European Committee for Standardization, 2011.

ISO 14040/44 and EN 15978 are the key standards.

ISO standards are in the readings, EN coming.

En 15603: 2008 Energy performance of Buildings. Overall energy use and definition of energy rating”

“EN 15804:2012+A2:2019 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products”
European Committee for Standardization, 2011.

ISO, “ISO 21930: Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.”
International Organization for Standardization, Geneva, Switzerland, 2017.

“ASTM E2921-16a Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems.”
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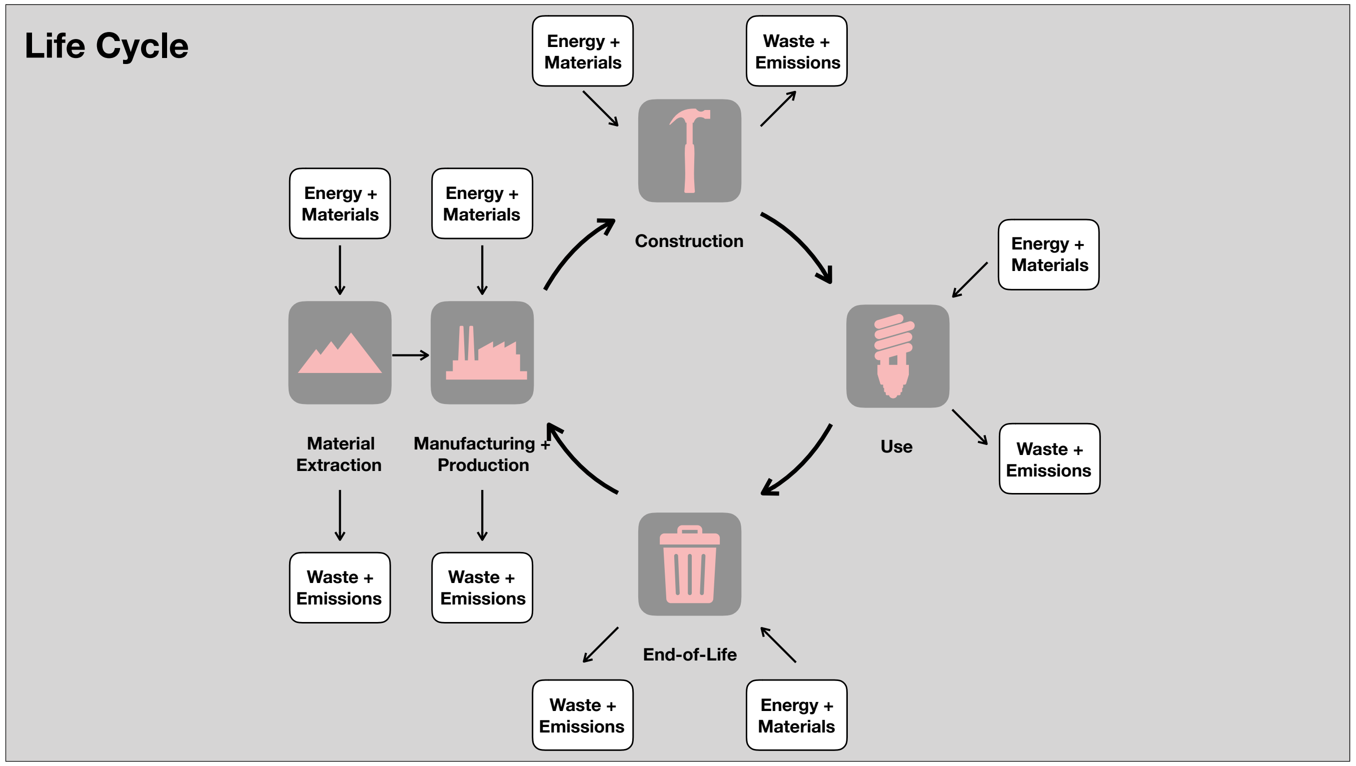


LCA tracks the extraction from and emission to nature across many stages of a building or products life..

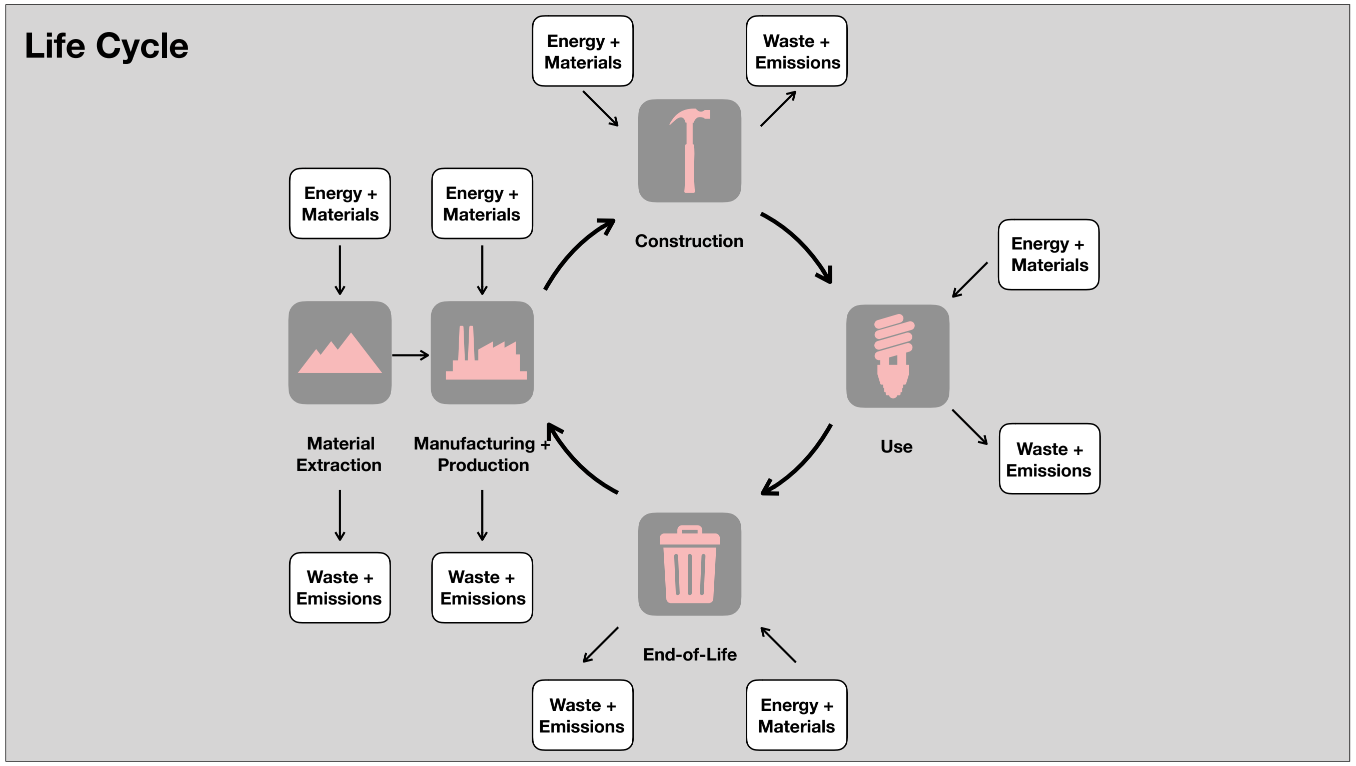
Raw material extraction:
Manufacturing (product)
Construction
Operation and use
End-of-life (demo, disposal, reuse and recycling)

It is helpful to describe the system using a process flow diagram showing the unit processes and their inter-relationships. Each of the unit processes should be initially described to define

— where the unit process begins, in terms of the receipt of raw materials or intermediate products,

— the nature of the transformations and operations that occur as part of the unit process, and

— where the unit process ends, in terms of the destination of the intermediate or final products.



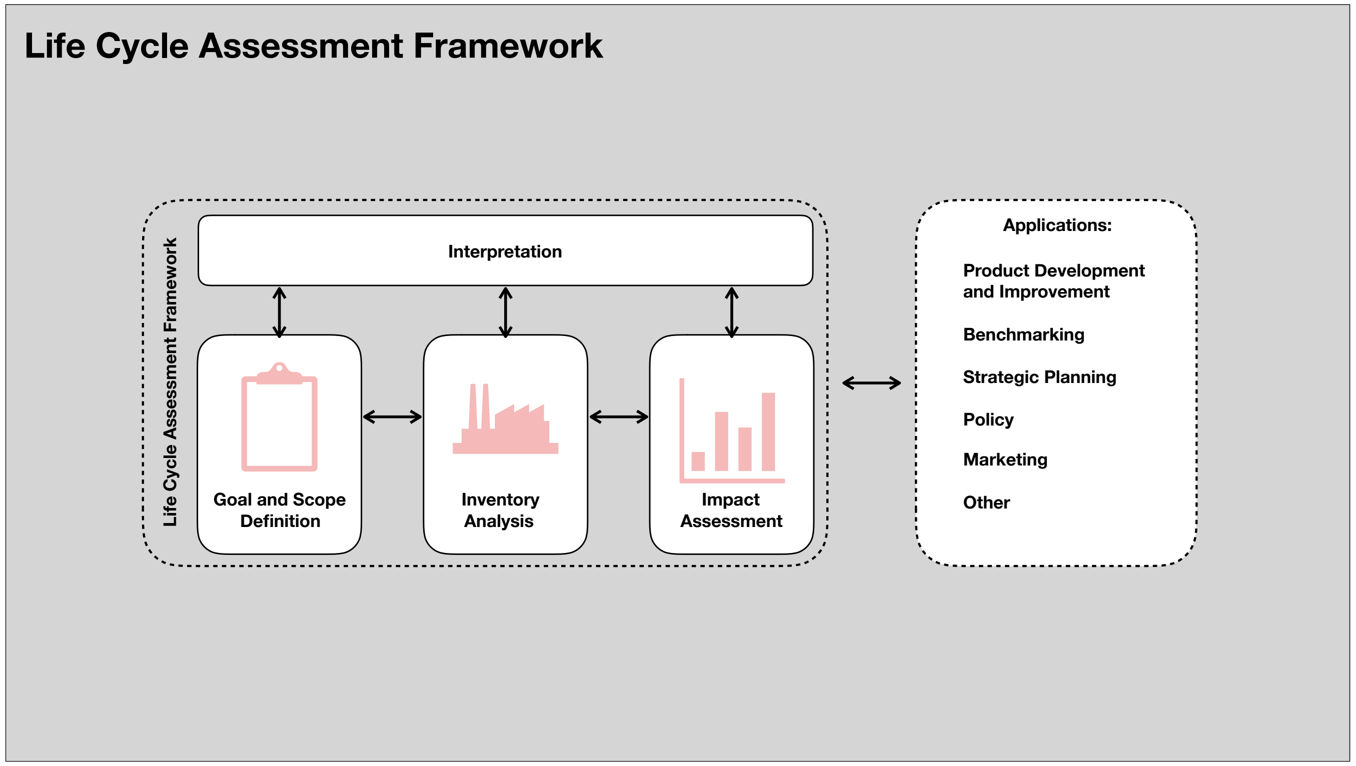
Inputs may include, but are not limited to, use of mineral resources (e.g. metals from ores or recycling, services like transportation or energy supply, and use of ancillary materials like lubricants or fertilizers).

As part of emissions to air, emissions of carbon monoxide, carbon dioxide, sulfur oxides, nitrogen oxides, etc.may be separately identified.

Emissions to air, and discharges to water and soil, often represent releases from point or diffuse sources, after passing through pollution control devices. These data should also include fugitive emissions, when significant. Indicator parameters may include, but are not limited to,

— biochemical oxygen demand (BOD),
— chemical oxygen demand (COD),
— absorbable organic halogen compounds (AOX),
— total halogen content (TOX), and
— volatile organic chemicals (VOC).

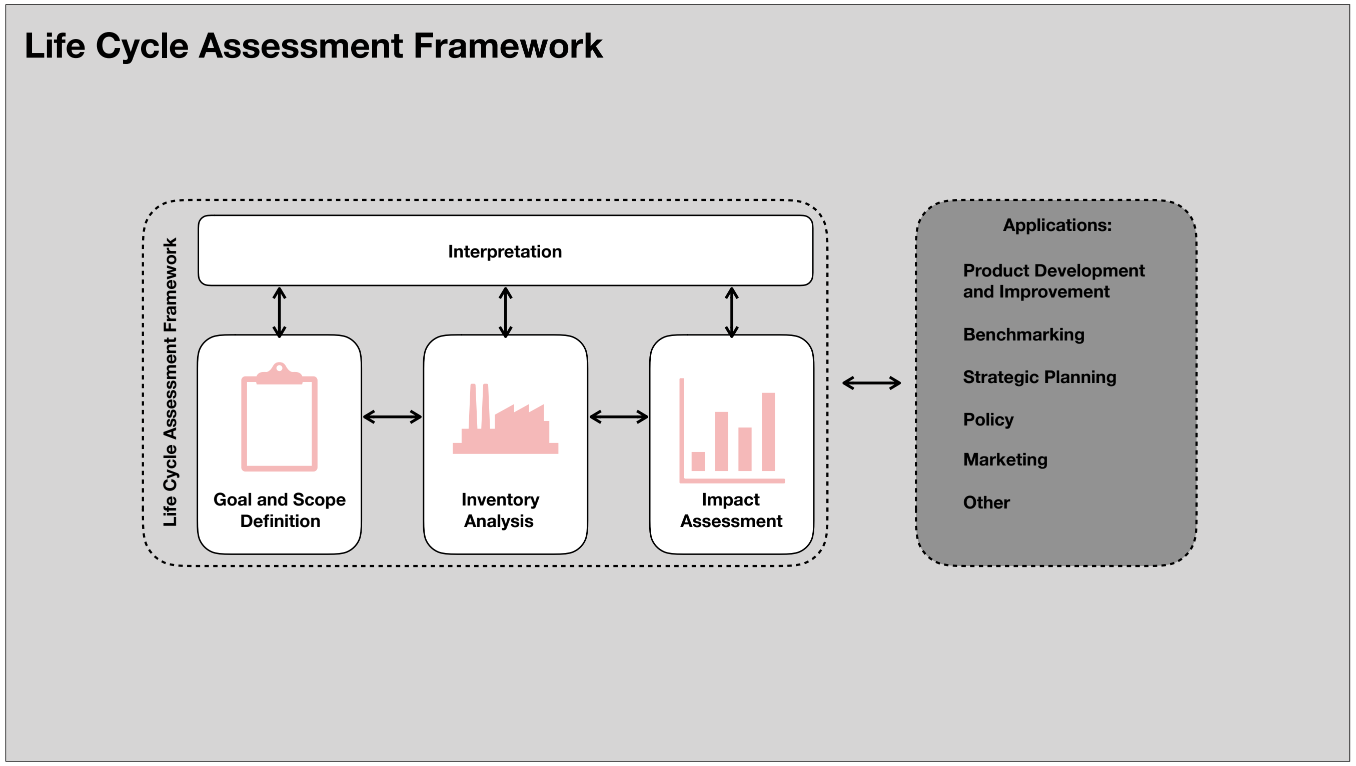
In addition, data representing noise and vibration, land use, radiation, odour and waste heat may be collected.



most notes are direct form ISO14044

There are four phases in an LCA study:

a) the goal and scope definition phase,
b) the inventory analysis phase,
c) the impact assessment phase, and
d) the interpretation phase.



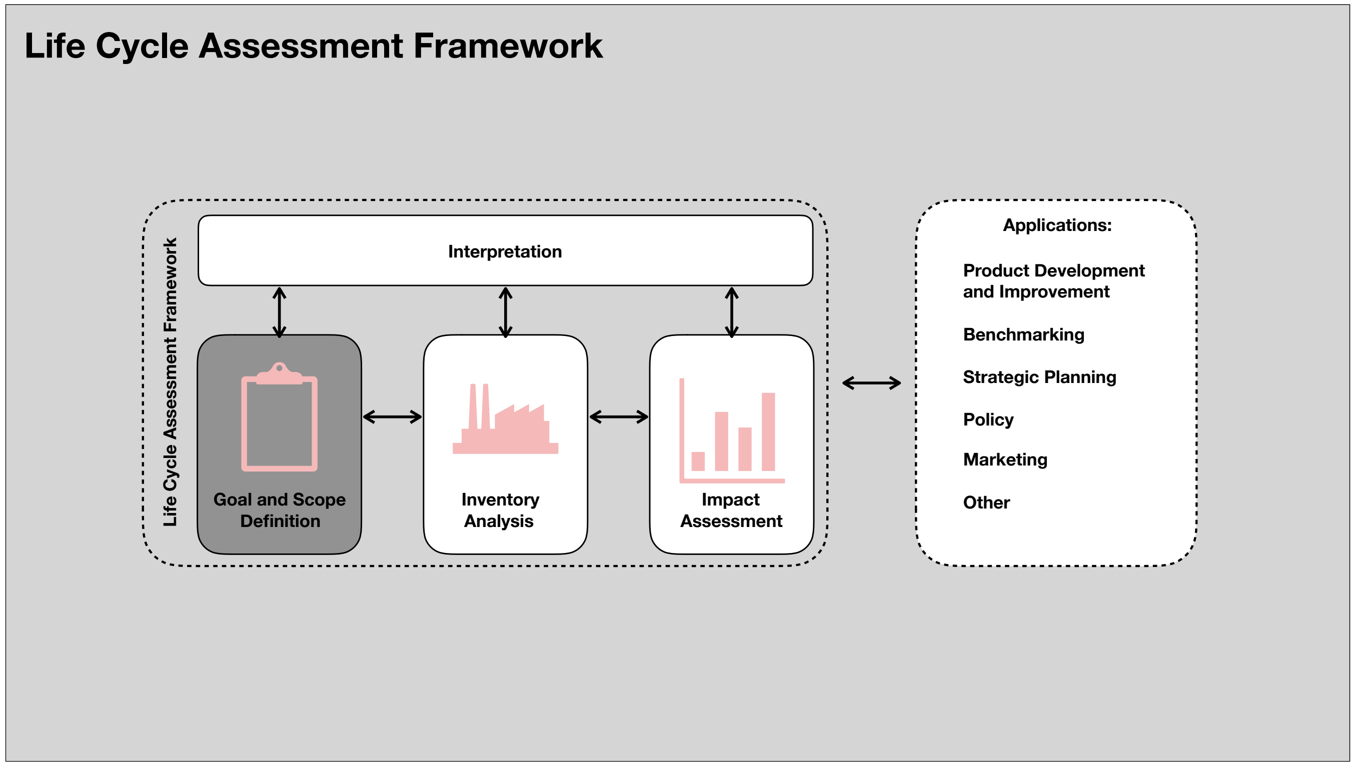
LCA can assist in

— identifying opportunities to improve the environmental performance of products at various points in their life cycle,

— informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),

— the selection of relevant indicators of environmental performance, including measurement techniques, benchmarks to evaluate a building's performance, and

— marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).



LCA flexibility means we have to be very specific about what we are studying

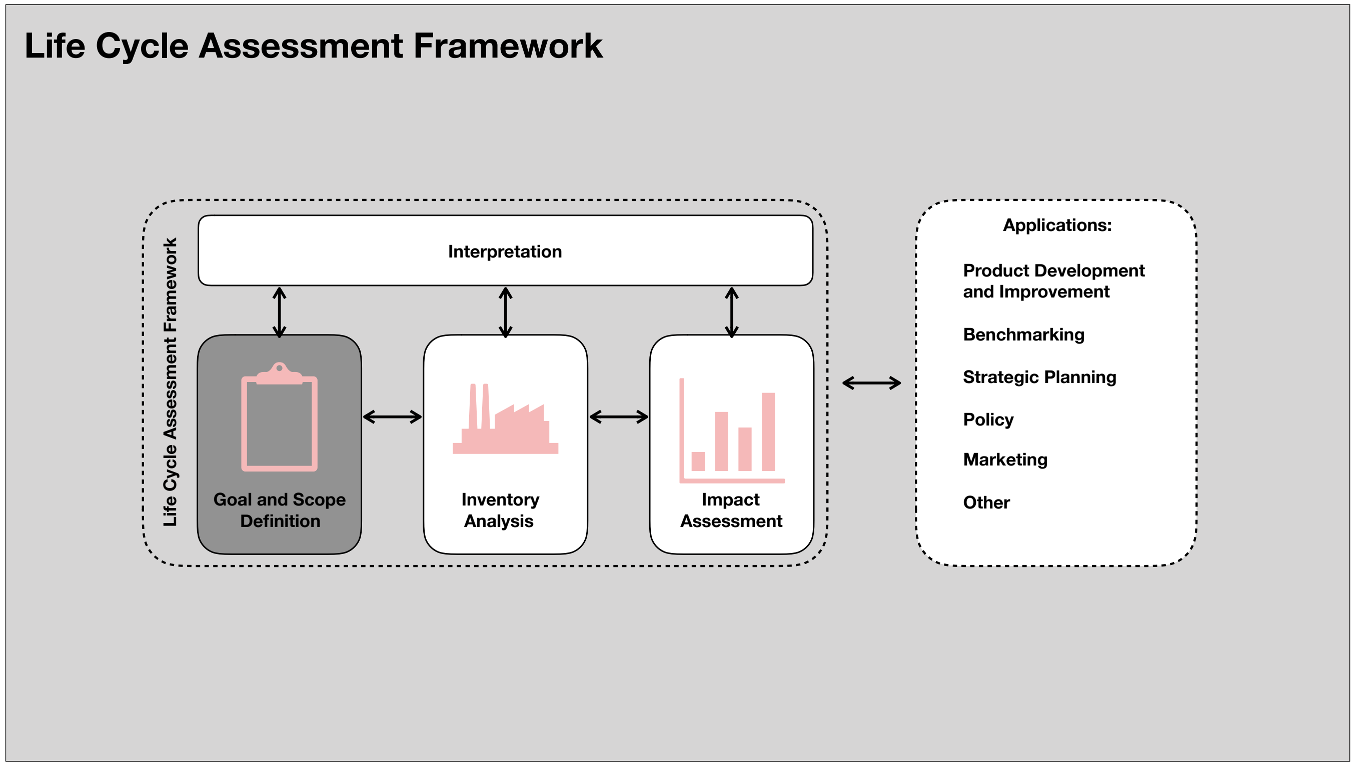
Definition of goal and scope:

The scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.

In defining the goal of an LCA, the following items shall be unambiguously stated:

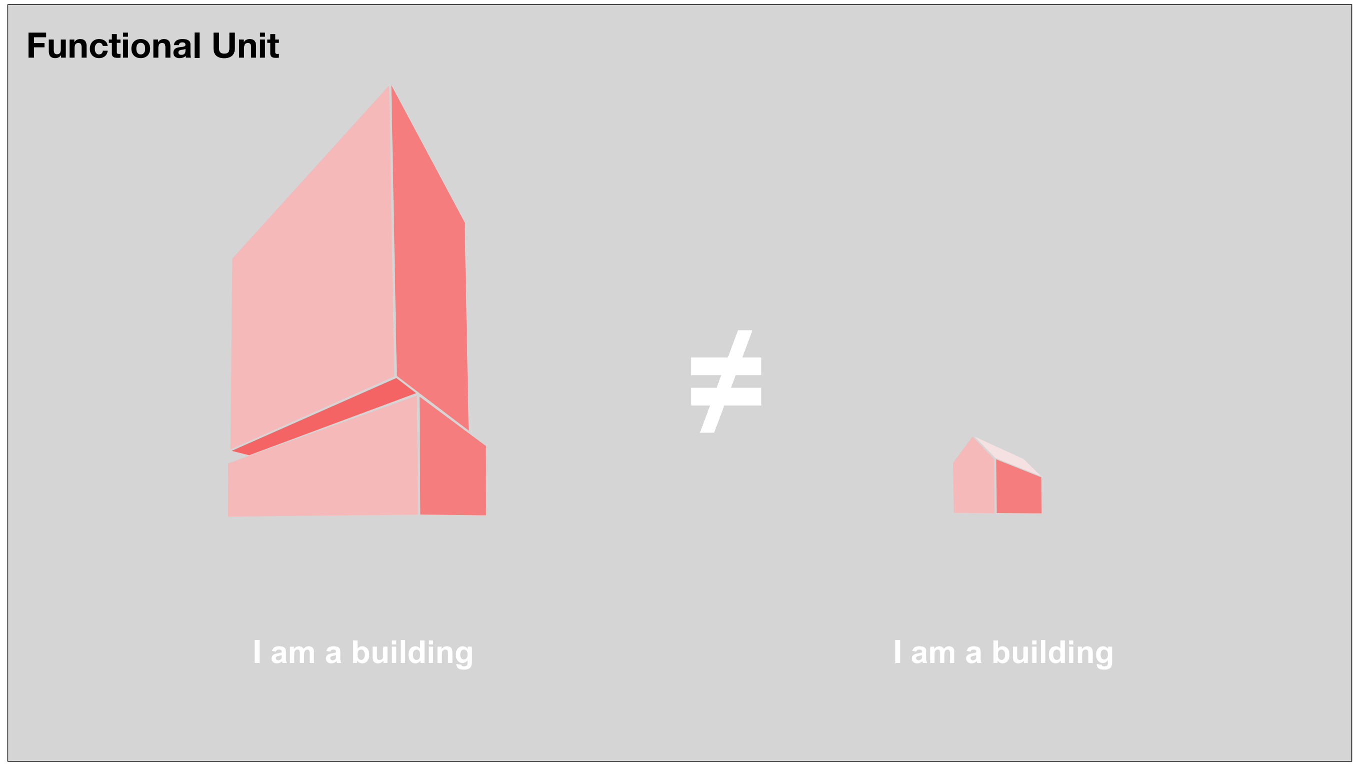
— the intended application;
— the reasons for carrying out the study:
— the intended audience, i.e. to whom the results of the study are intended to be communicated:
— whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

In defining the scope of an LCA, the following items shall be considered and clearly described



In defining the scope of an LCA, the following items shall be considered and clearly described

— the product system to be studied;
— the functions of the product system or, in the case of comparative studies, the systems;
— <u>the functional unit;</u>
— the system boundary;
— allocation procedures;
— LCIA methodology and types of impacts;
— interpretation to be used;
— data requirements;
— assumptions;
— value choices and optional elements;
— limitations;
— data quality requirements;
— type of critical review, if any;
— type and format of the report required for the study.



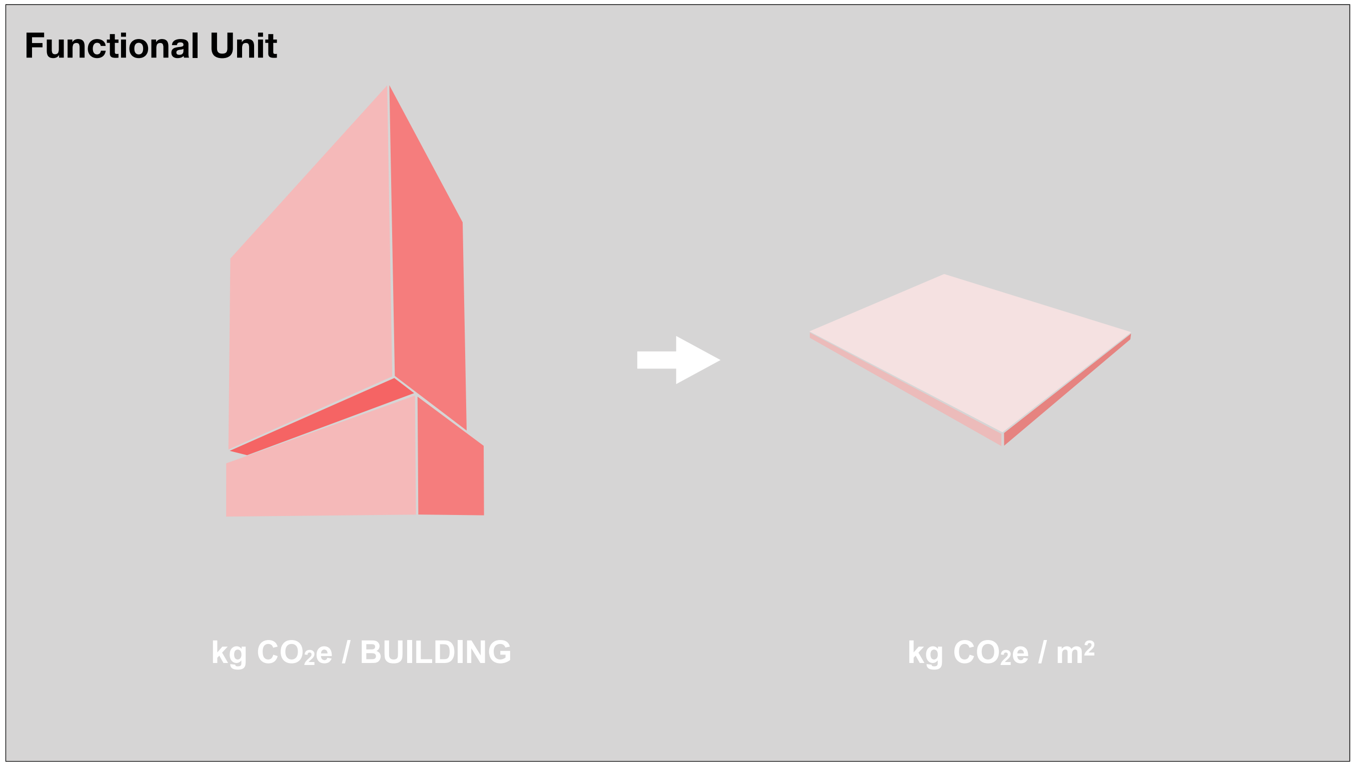
Function and functional unit:
The scope of an LCA study shall clearly specify the functions of the system being studied. A functional unit is a measure of the performance of the functional outputs of the product system. Comparisons between systems shall be made on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows.

Functional Equivalent: relates to the technical characteristic and functionality of the building for purpose of comparative assessment (building type, function, pattern of use, service life)

Typically LCA is used to compare two design options. Is carpet better than vinyl? Is a standard local window or high performance window from overseas better? Which structural system is better, steel concrete or wood?

For example, wood siding might be a 1m2 by 0.01m thick board with primary function of weather protection, performance of wind, fire, and water protection with maintenance requirements, over a time duration of 60 year.

In a comparative study, the equivalence of the systems being compared shall be evaluated before interpreting the results. Consequently, the scope of the study shall be defined in such a way that the systems can be compared. Systems shall be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment. Any differences between systems regarding these parameters shall be identified and reported. If the study is intended to be used for a comparative assertion intended to be disclosed to the public, interested parties shall conduct this evaluation as a critical review.



Buildings are best assessed on a per-square meter basis which makes it easier to compare to other buildings.

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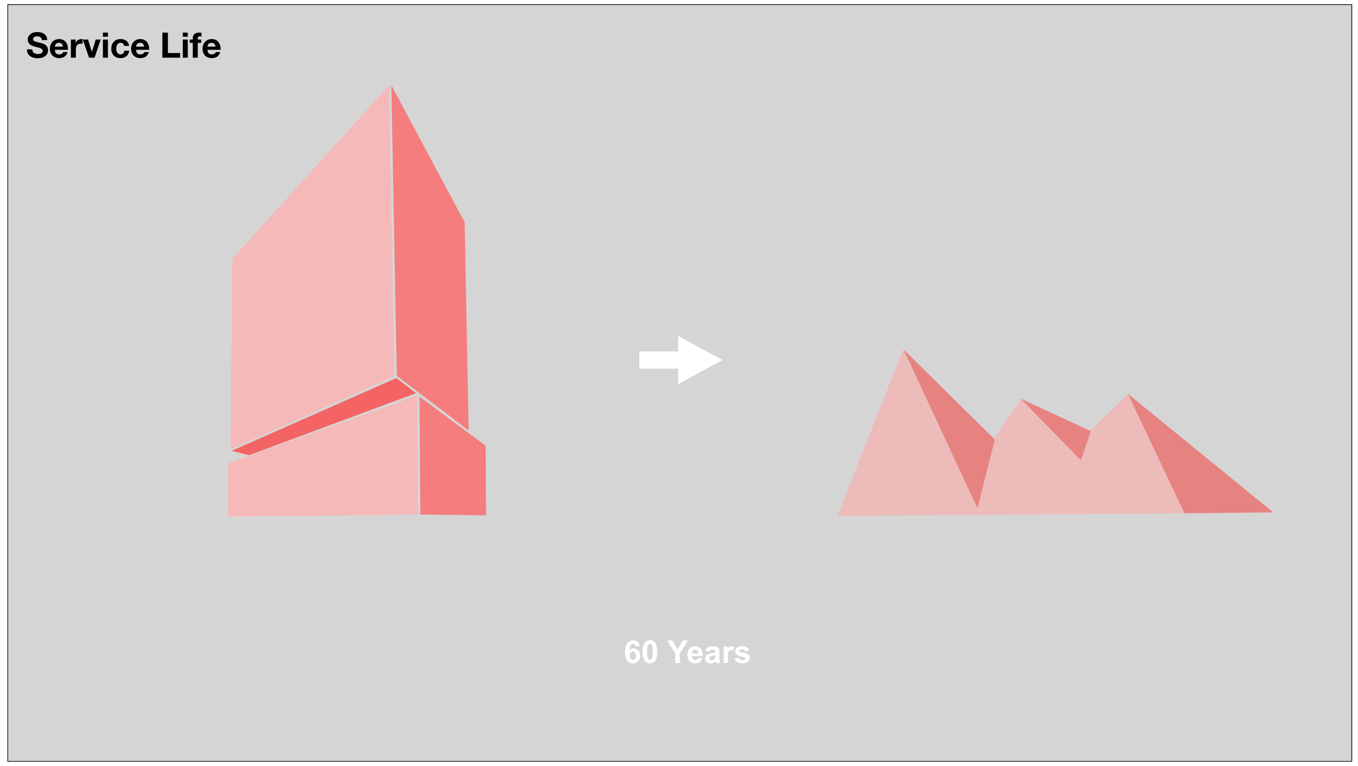


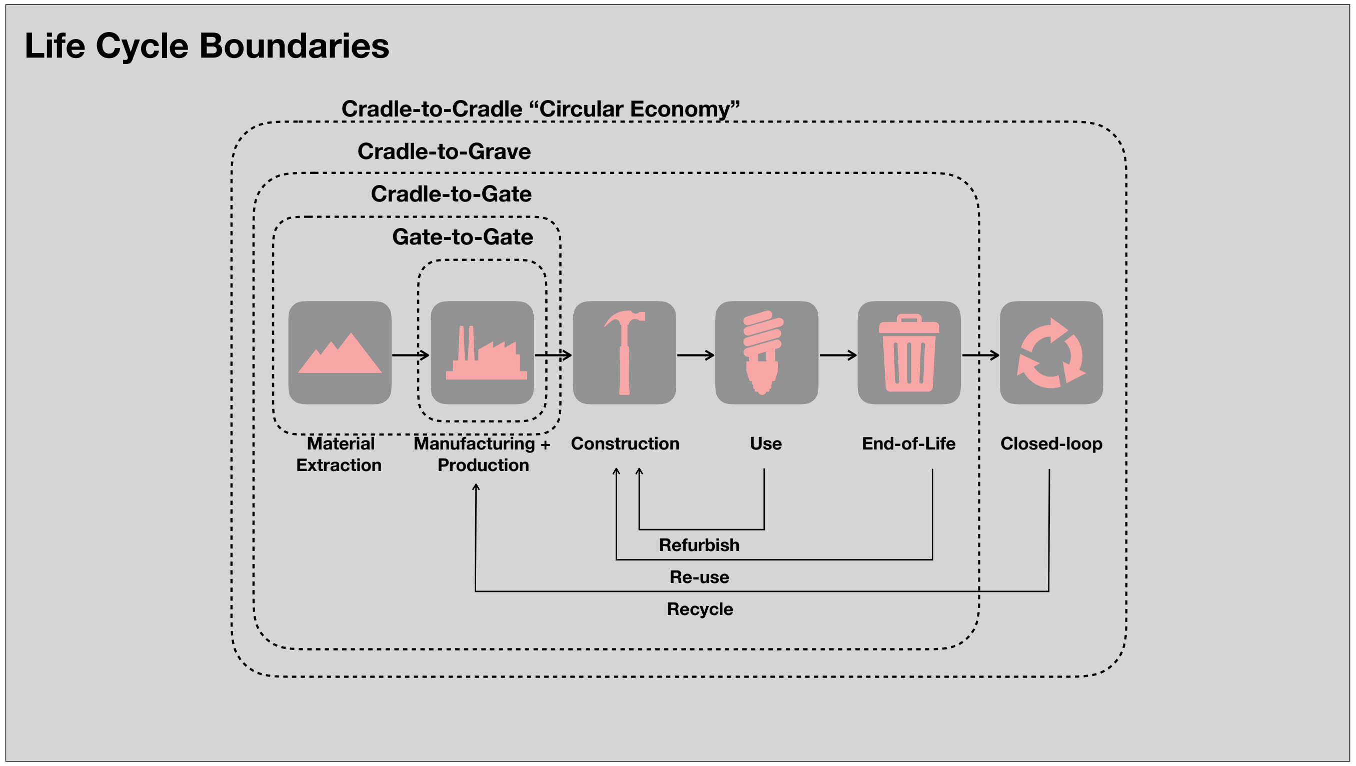
<u>Reference study period</u> (RSP) and <u>required service life (ReqSL).</u>

<u>The default RSP is the building's ReqSL, which is 60 yrs by default.</u> Other service life can be used, but they have to be defined.

<u>For existing buildings, the system boundary shall include only the remaining life cycle stages beginning at the stage where the assessment is conducted, i.e. the remains serve life.</u>

<u>Duration is an issue!</u> We usually use a life cycle of 60 years:

- For example in the UK 46% of structures are demolished with 11 to 32 years,
- The typical life span of Japanese building is 30 year for steel and almost 40 for concrete.
- Studies show that degradation was the cause of demolition in only 25% of buildings.



System boundaries:
The system boundary determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study. The system should be modeled in such a manner that inputs and outputs at its boundaries are elementary flows.

Thermodynamically we know system boundaries have states, phases, temporal conditions

Gate-to-gate which only includes impacts related to manufacturing of product inside of a factory

Cradle-to-gate which only includes impacts related to manufacturing of product up to the 'gate' of the factory.

Cradle-to-grave which includes extraction to end of life

Cradle-to-cradle would track how products at end of life become material resources for other products.

Cradle-to-cradle is the same idea of a **Circular Economy**, or **Odums feedback**, or even possibly maximum power systems

Goal
ISO 14040 and 14044 require that the goal of LCA study are unambiguous stated and include: the intended application (what); the reason for carrying out the study (why); the intended audience (to whom); whether results are for comparative assessment or to disclose to the public.

Scope
ISO 14040 and 14044 has specific requirements as to what must be included in the scope of a LCA study and include: the product to be studied (functional unit): the system boundary (what is included and excluded); methodological choice (assumption and interpretation methods); Analysis details (source of data, its quality and critical review).

Functional Unit
Here functional unit defines a unit of analysis that includes quantity, quality and duration of the product or service provided. For example, wood siding might be a $1m^2$ by 0.01m thick board with primary function of weather protection, performance of wind, fire, and water protection with maintenance requirements, over a time duration of 60 year. Buildings are best assessed on a per-square meter basis which makes it easier to compare to other buildings.

System Boundary
The system boundary of a LCA study is what is to be studied and which components of the system are included. Often LCA will exclude: Manufacturing of fixed equipment (the factory), manufacturing of mobile equipment (trucks); hygiene-related water use (toilets, sinks for workers), employee labor (commuting). Others can include construction energy all together (as in the case of Athena package, but not others) and mechanical and electrical systems.

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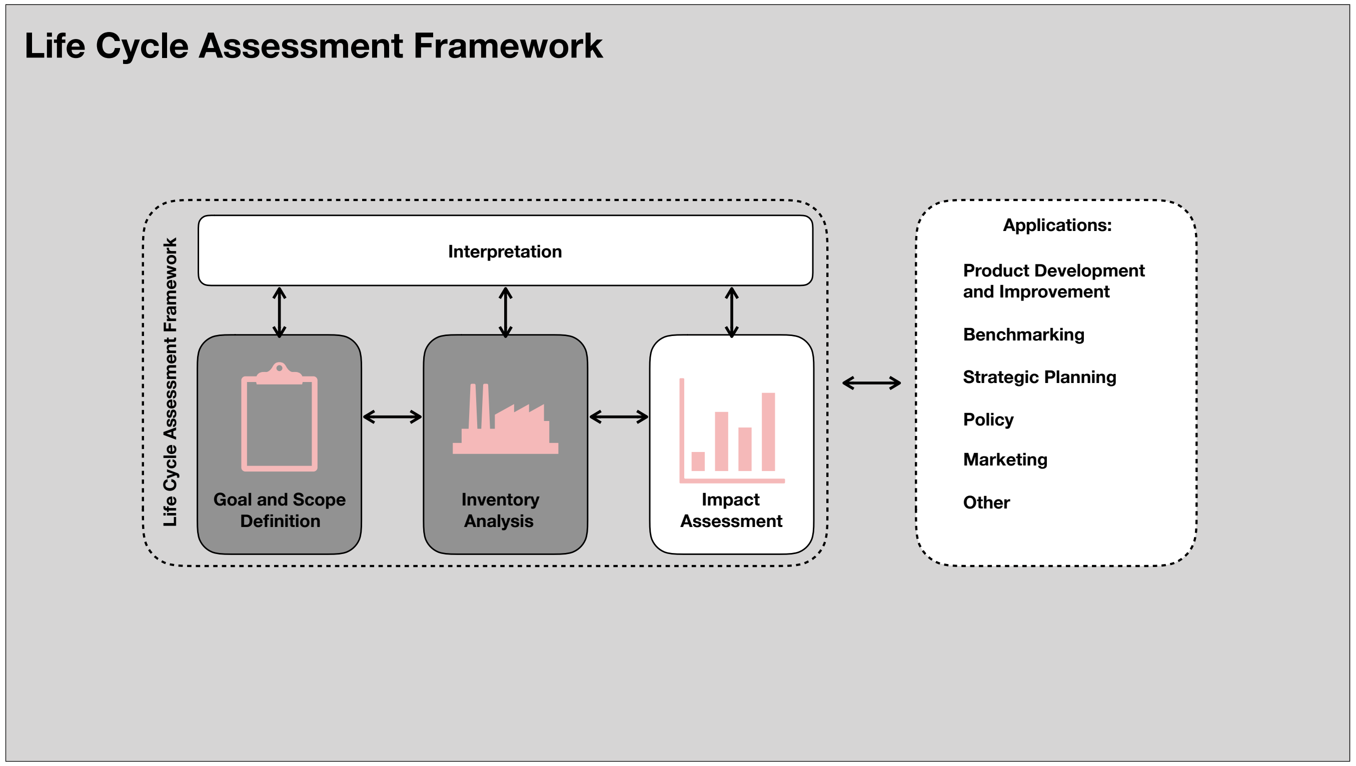
System Boundary

The system boundary of a LCA study is what is to be studied and which components of the system are included. Often LCA will exclude: Manufacturing of fixed equipment (the factory), manufacturing of mobile equipment (trucks); hygiene-related water use (toilets, sinks for workers), employee labor (commuting). Others can include construction energy all together and mechanical and electrical systems (as in the case of Athena package, but not others).



We'll spend more time here in a bit

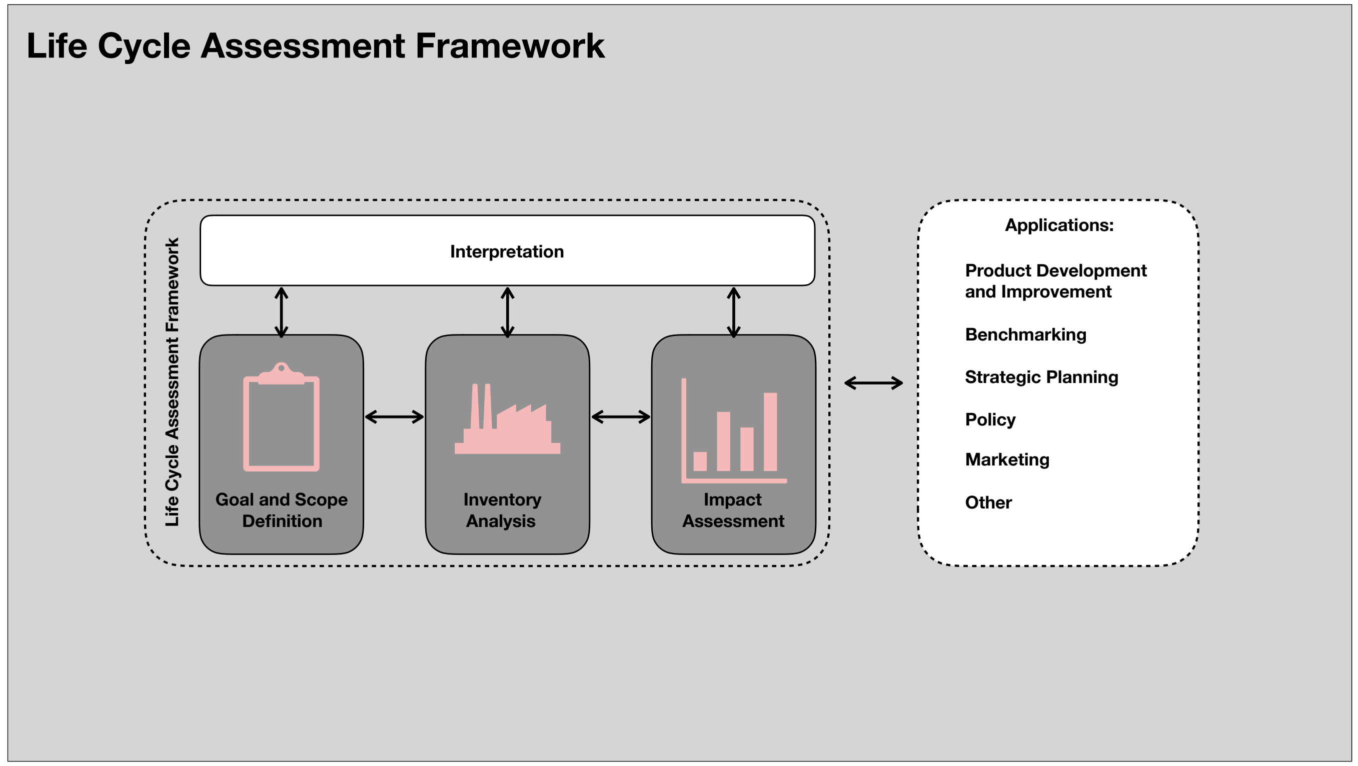
Life cycle inventory analysis

The life cycle inventory analysis phase (LCI phase) is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied.

It involves the collection of the data necessary to meet the goals of the defined study <— this is where most of the work happens

Data collection and calculation procedures
The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundaries.

The major headings under which data may be classified include
— energy inputs, raw material inputs, ancillary inputs, other physical inputs,
— products, co-products and waste,
— releases to air, water and soil, and
— other environmental aspects

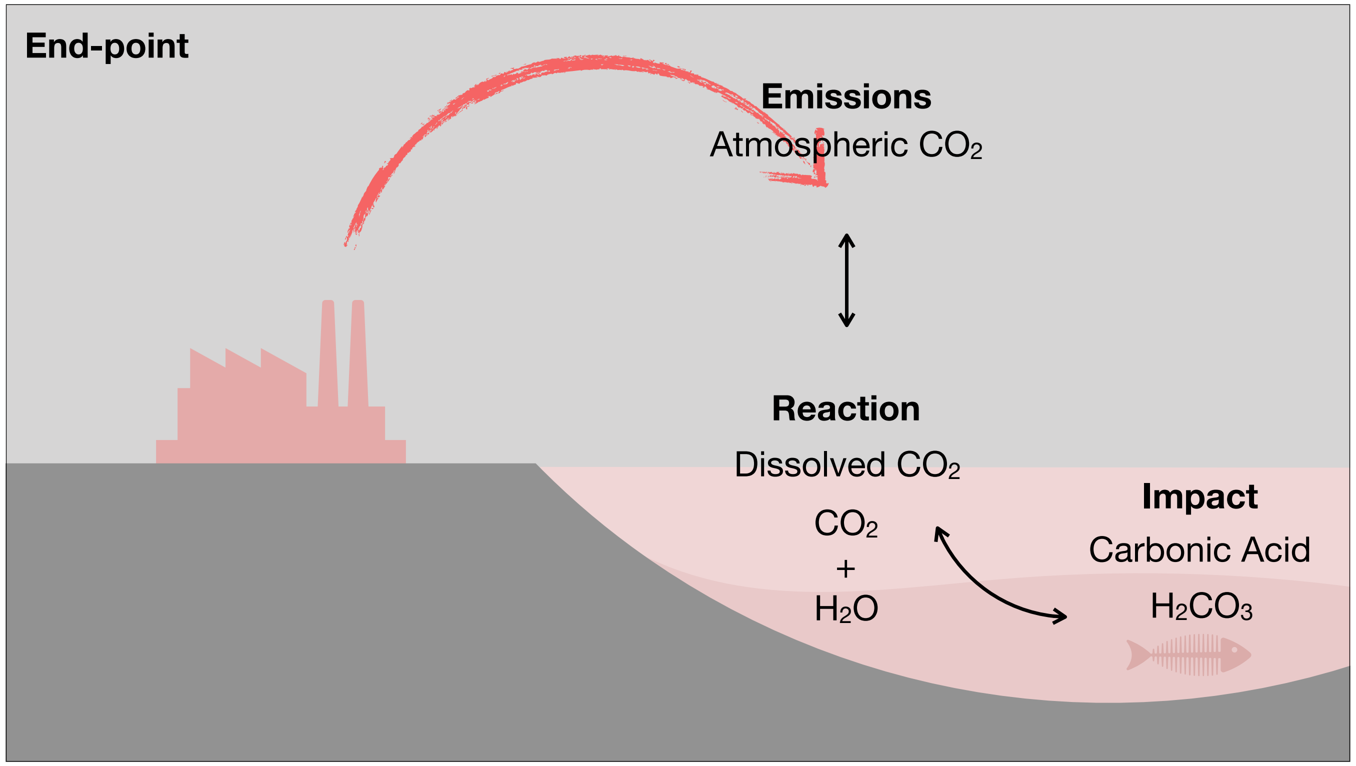


Life cycle impact assessment

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance.

The impact assessment phase of LCA is aimed at evaluating the <u>significance of potential environmental impacts using the results of the life cycle inventory analysis.</u>

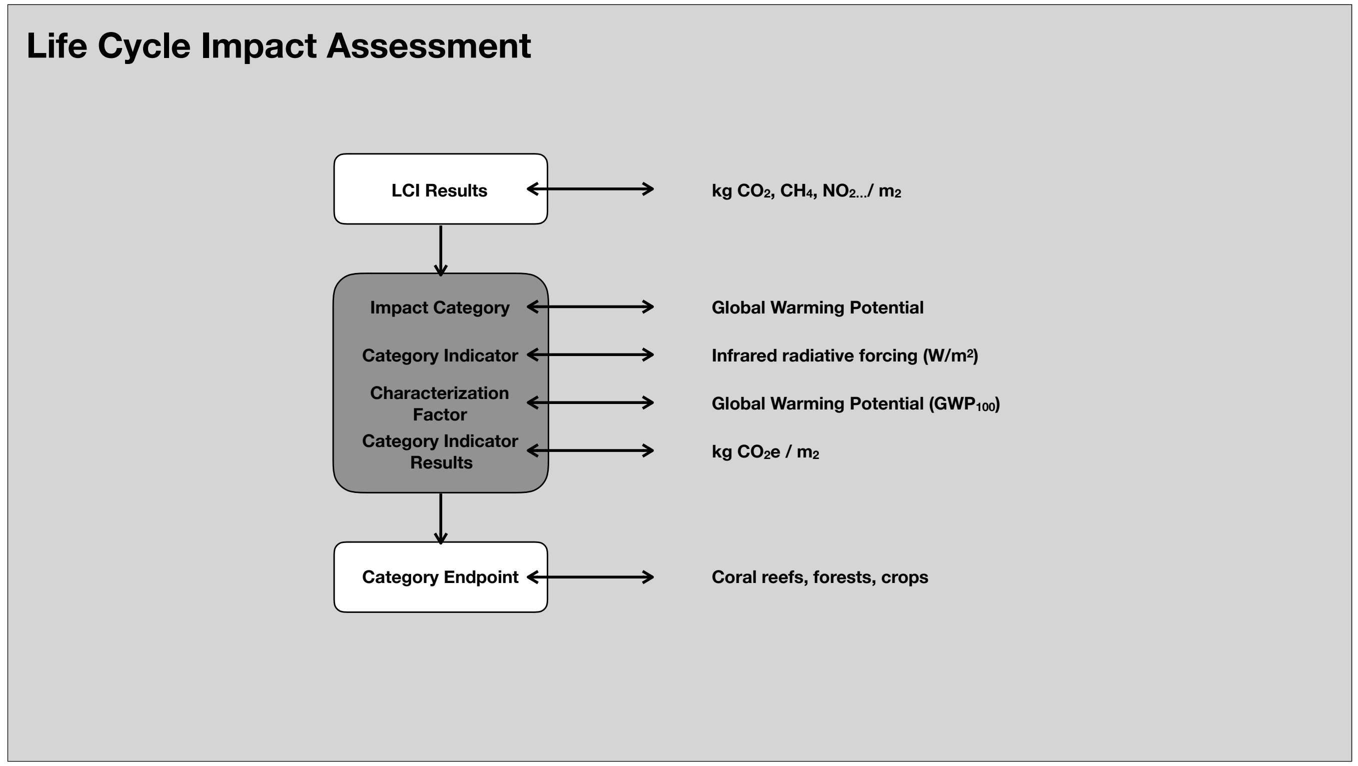
This is the "what does it mean" phase.



Chemical emissions (including sulfur dioxide and nitrogen oxides) from sources such as coal power plant are released into the air. These chemicals are transported in the air depending on wind and climate conditions (transport) and often carried to ground or water bodies via rain (fate). **The final, or "end-point" environmental impact** of acid rain includes a broad range of impacts ranging from corrosion of buildings to lack of productivity of soils.

Global —>GHG,
Regional—>Acidification
Local—>Smog.

Emissions and impacts are interconnected. <u>Combustion of fossil fuels impacts acidification, climate change, eutrophication and ozone production.</u> Carbon Dioxide causes both climate change and acidification. Eutrophication results in increased decomposition of organic matter that reduces oxygen and increased decomposition. **At the highest level, we are looking to protect human and ecosystem health .**



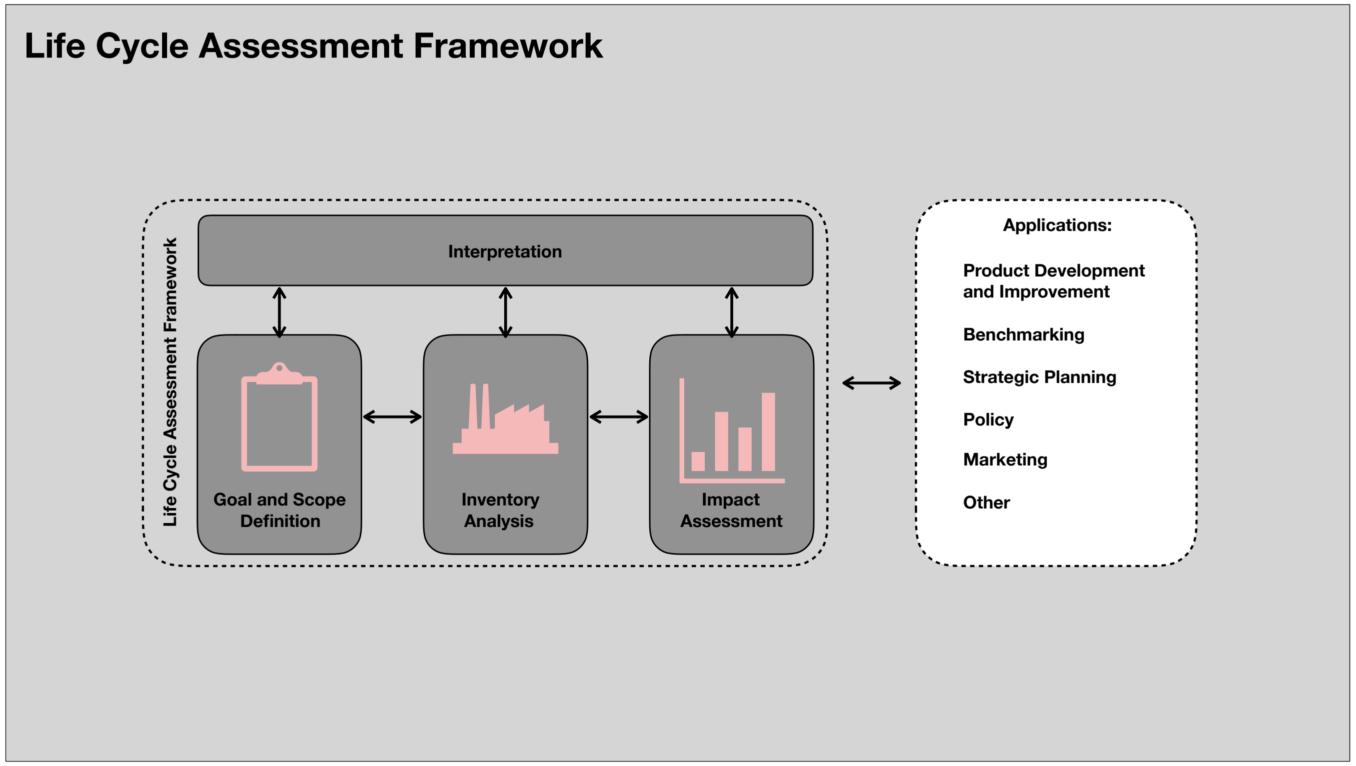
The impact assessment phase includes elements such as:

—selection of impact categories, category indicators and characterization models

—assigning of inventory data to impact categories (classification) <— some impact categories relate to more than one impact category, for example CO2 increases radiative forcing and ocean acidification.

—modeling of the inventory data within impact categories (characterization) <— most of these exist, key is they have environmental relevance.

—possibly aggregating the results in very specific cases and only when meaningful (weighting) <—There is no scientific basis for reducing LCA results to a single overall score or number,



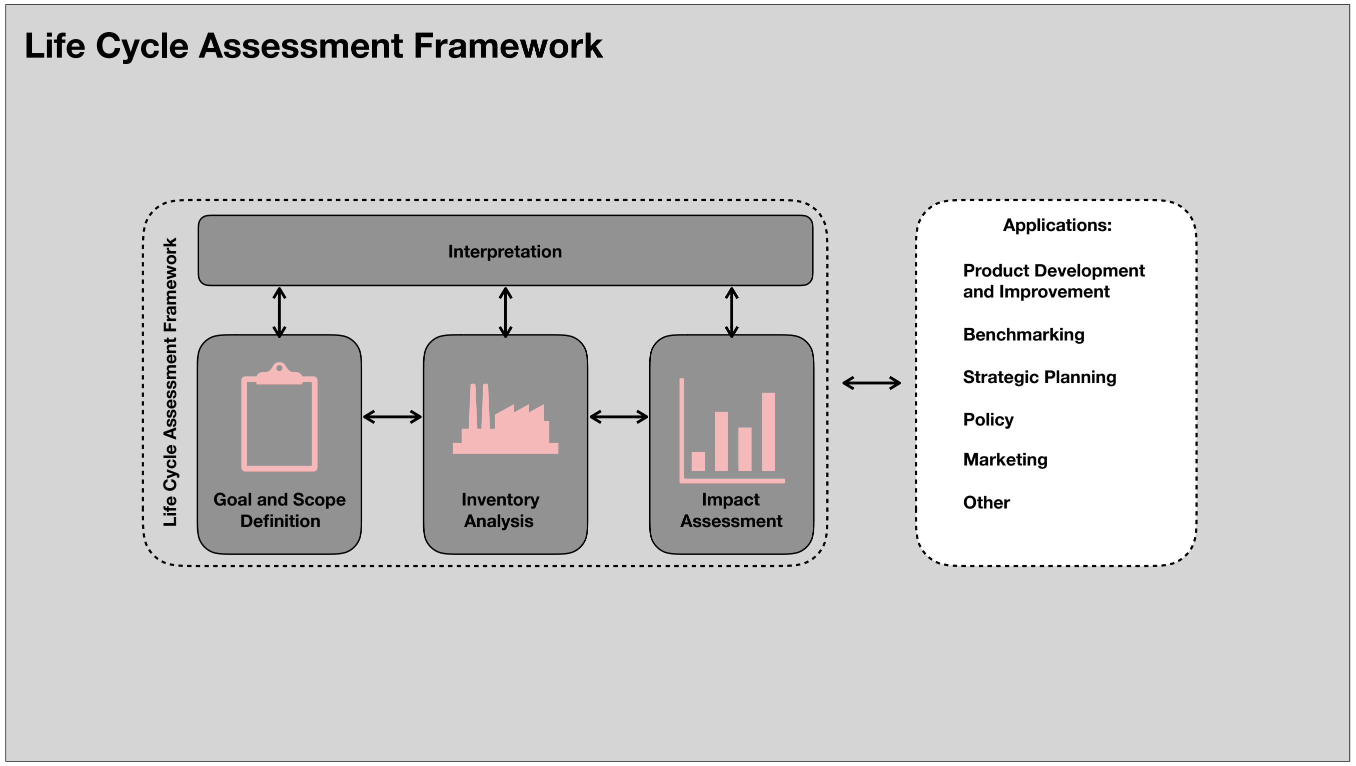
Life cycle interpretation

Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

<u>The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected consistent with the defined goal.</u>

The findings of the interpretation phase should reflect the results of any sensitivity analysis that is performed.

Though subsequent decisions and actions may incorporate environmental implications identified in the findings of the interpretation, they lie beyond the scope of the LCA study, since other factors such as technical performance, economic and social aspects are also considered.



Life cycle interpretation

— identification of the significant issues based on the results of the LCI and LCIA phases of LCA;

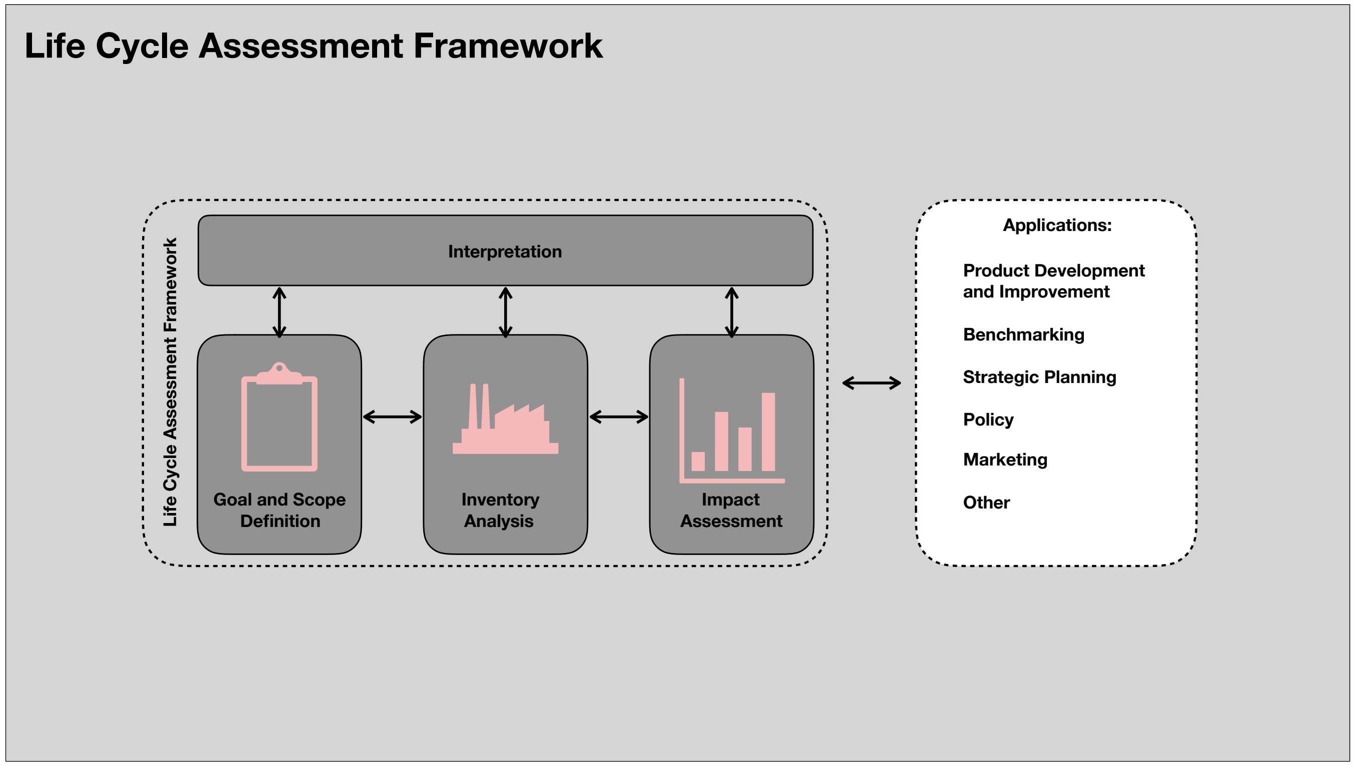
— inventory data, such as energy, emissions, discharges, waste,

— impact categories, such as resource use, climate change, and

— significant contributions from life cycle stages to LCI or LCIA results, such as individual unit processes or groups of processes like transportation and energy production.

— <u>an evaluation that considers completeness, sensitivity and consistency checks;</u>

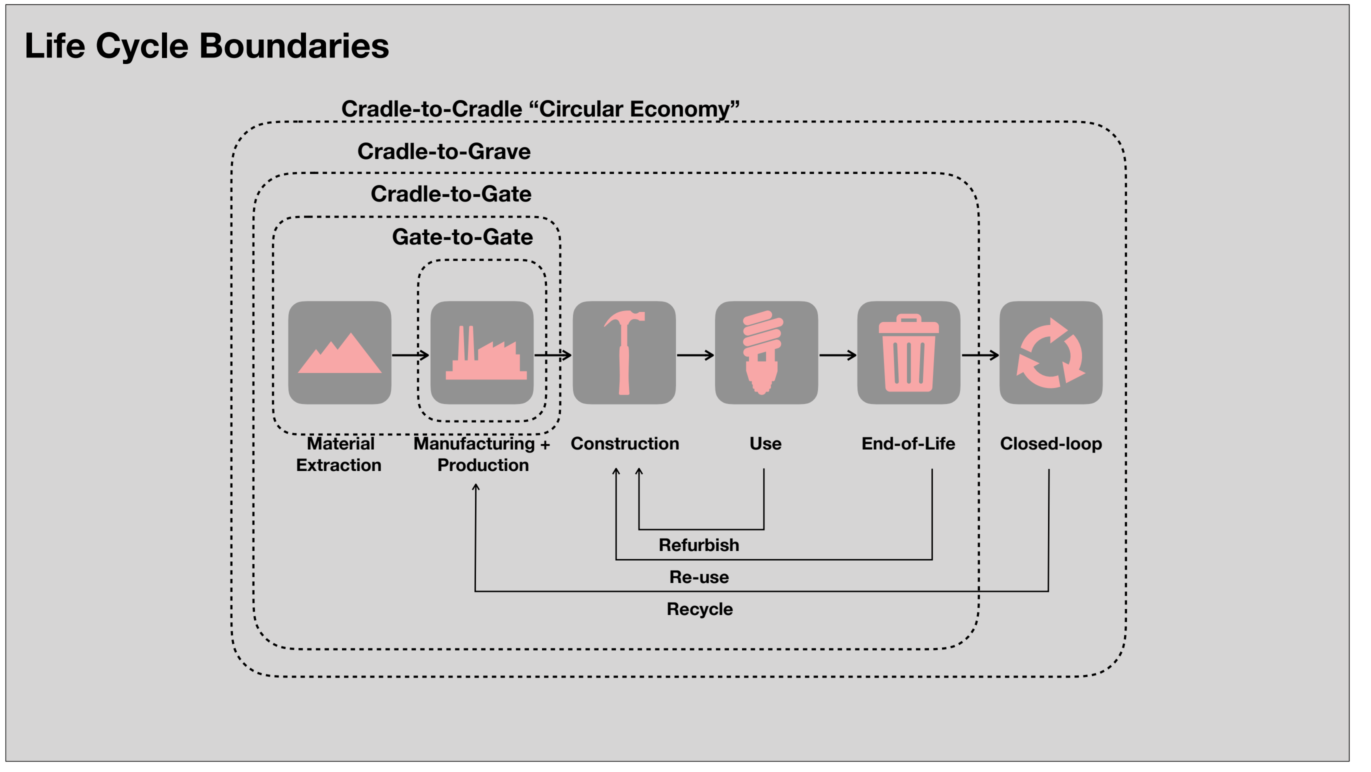
— conclusions, limitations, and recommendations.



**For student's notes, covered latter

Additional techniques and information may be needed to understand better the significance, uncertainty and sensitivity of the LCIA results in order

a) Gravity analysis (e.g. Pareto analysis) is a statistical procedure that identifies those data having the greatest contribution to the indicator result. These items may then be investigated with increased priority to ensure that sound decisions are made.
b) Uncertainty analysis is a procedure to determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the LCIA.
c) Sensitivity analysis is a procedure to determine how changes in data and methodological choices affect the results of the LCIA.



System boundaries:
The system boundary determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study. The system should be modeled in such a manner that inputs and outputs at its boundaries are elementary flows.

Gate-to-gate which only includes impacts related to manufacturing of product inside of a factory

Cradle-to-gate which only includes impacts related to manufacturing of product up to the ‘gate’ of the factory.

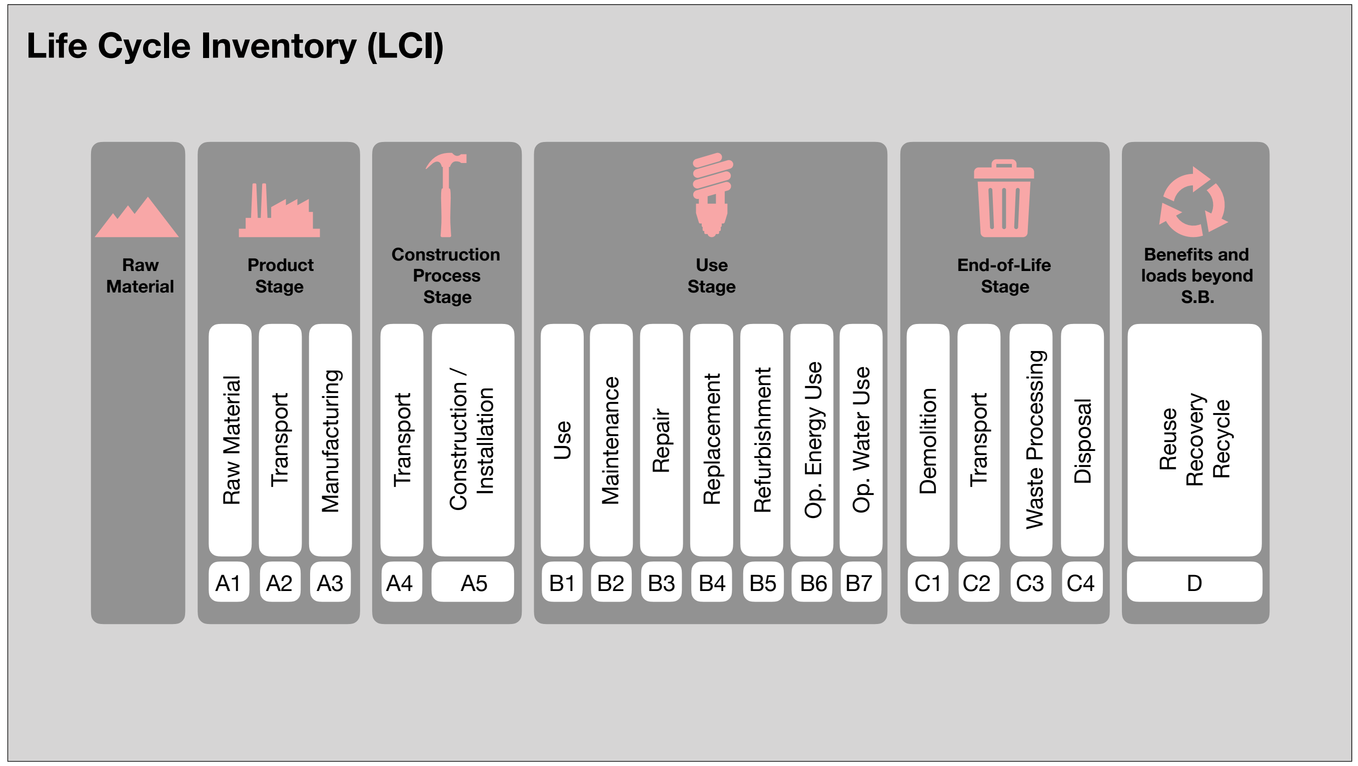
Cradle-to-grave which includes extraction to end of life

Cradle-to-cradle would track how products at end of life become material resources for other products.

Cradle-to-cradle is the same idea of a **Circular Economy**, or **Odums feedback**, or even possibly maximum power systems

Aggregate efficiency (economic term) for the steps of conversion in a value chain and the energy loss in that conversion, the ratio of the potential work and the actual useful work embedded in that good or service.

Allocation of burden for products in open loop production systems presents considerable challenges for LCA. Various methods, such as the avoided burden approach have been proposed to deal with the issues involved.



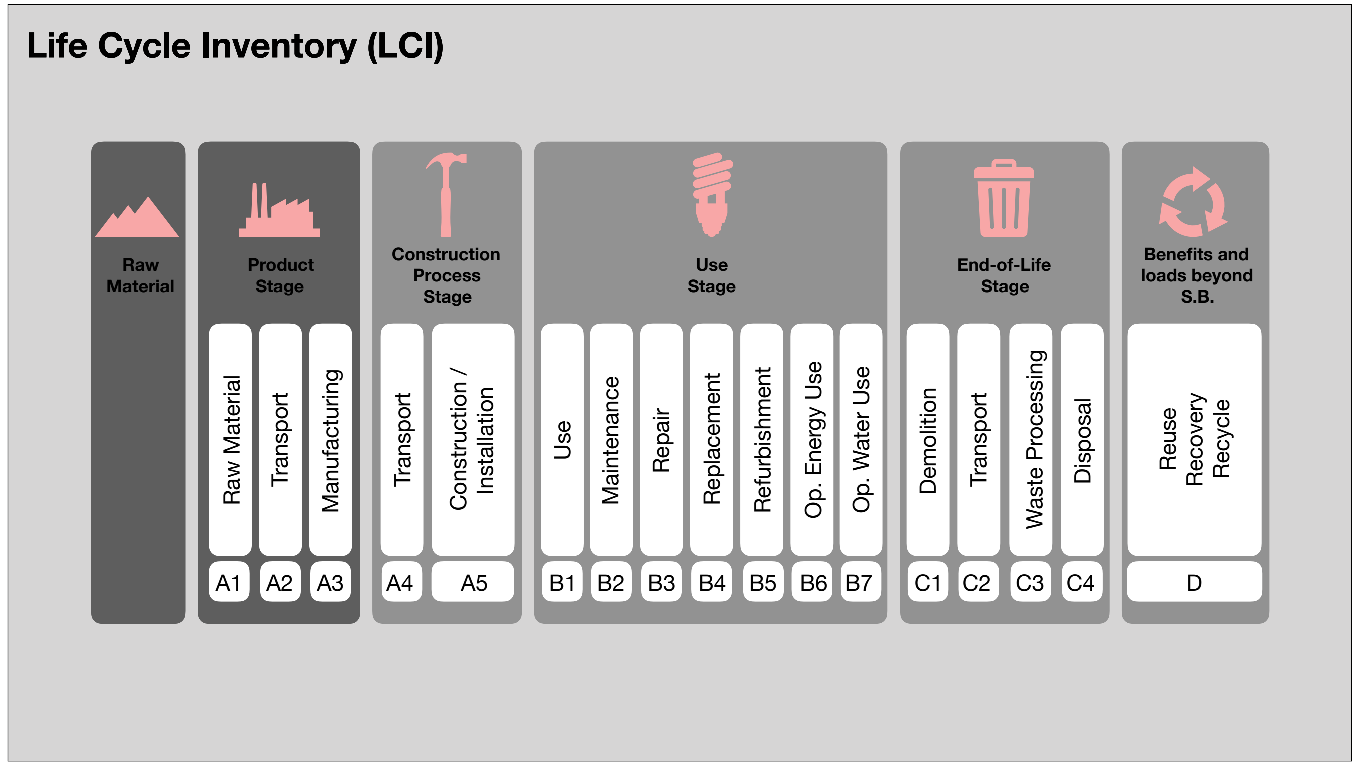
<u>A life cycle inventory (LCI) is a detailed accounting of the quantities of raw materials used, the products produced, the waste outputs and the emissions to air, land, and water.</u>

LCA can assess many environmental impacts, but GWP is often the focus of LCA studies. Embodied carbon commonly refers to the GWP attributed to materials and energy used in the construction and maintenance of buildings. Operating carbon refers to the GWP attributed to operation and use of the building.

<u>In reality LCI is most of the work, LCA is the full scoping, accounting and reporting of impact (through your interpretation).</u>

Energy Mix: How we get our energy matters, each stage is effected by the Energy Mix use of the region it is done in. For example the US is hight fossil fuel consumption, France is mostly nuclear, and Norway is mostly hydroelectric (and they pump out TON of fuel).

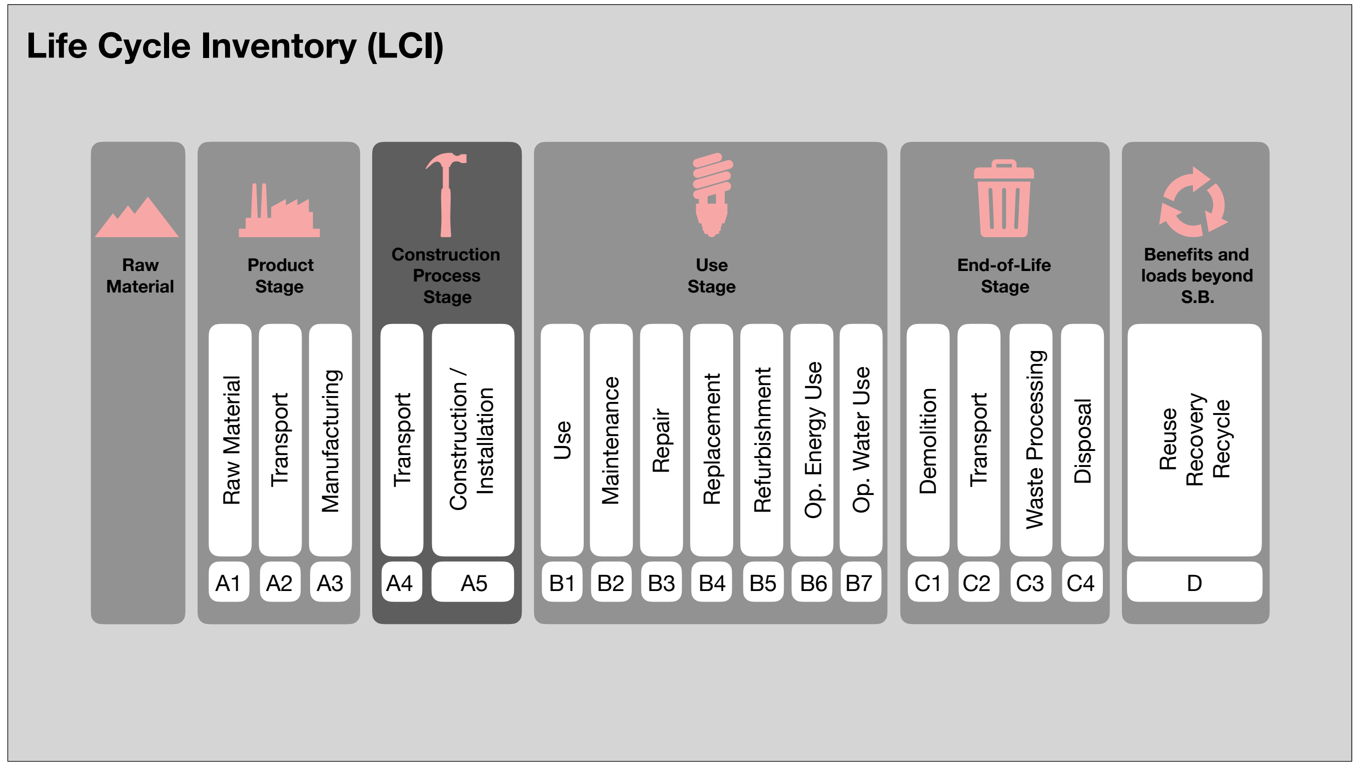
86 Percent of the Global energy mix ratio is from hydrocarbons.



Product [EN 15978 A1-A3]:

- Product encompasses the material's complete manufacturing from raw material extraction and processing to intermediate transportation and final manufacturing and assembly. (the extraction of raw materials is wrapped into A1).
- The product stage scope is listed for each entry and details any specific inclusions or exclusions that fall outside of the cradle-to-gate scope.
- <u>Infrastructure such as the buildings and machinery required for the manufacturing and assembly of building materials are not included and are considered outside the scope of assessment.</u>

*Why the extra column for raw material? Those taking on emergy analysis would account for the ejoules of bio-geologic material formation.



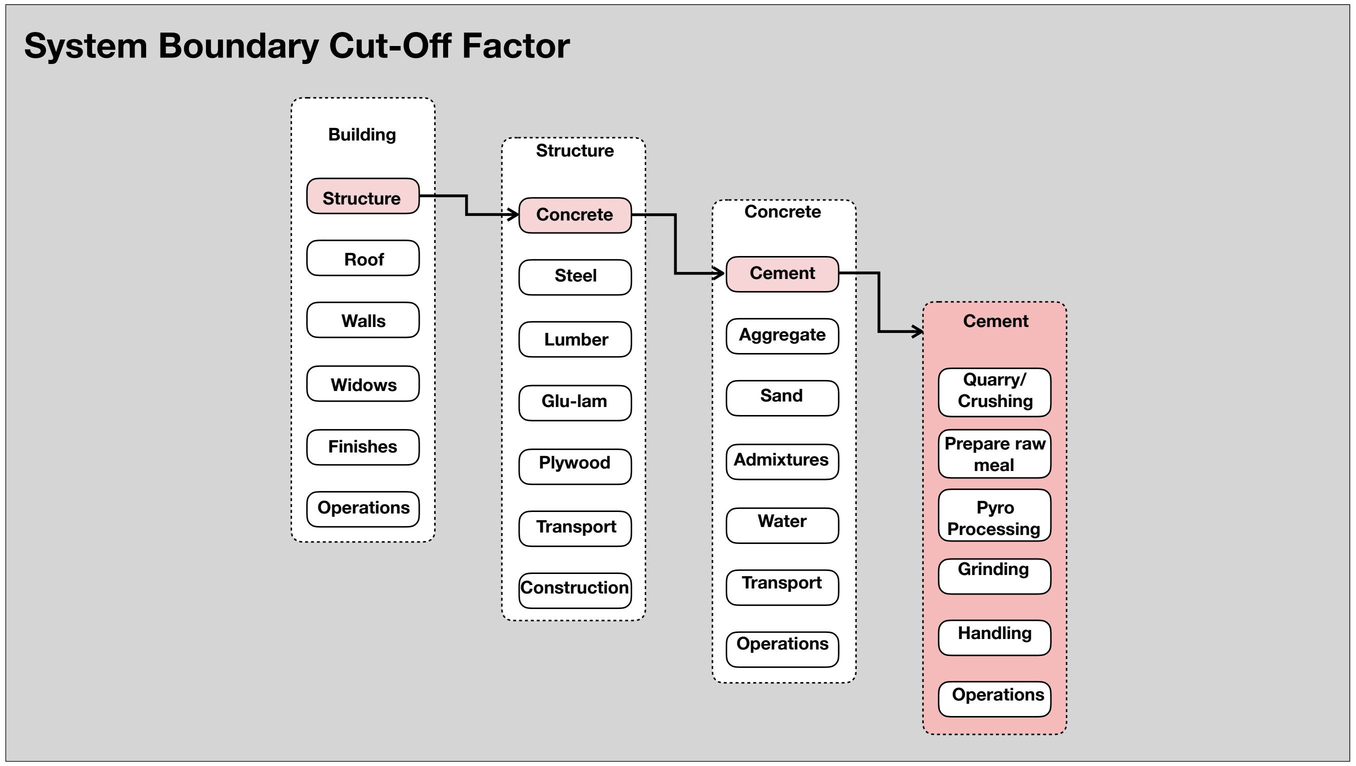
Construction Transportation [EN 15978 A4]:

- Transportation between the manufacturer and building site is included separately and can be modified by the modeler. Typically 4-8%
- Transport of people not included.

Construction / Installation [EN 15978 A5]

- Manufactured products are combined on site
- Operation of tools and machinery for construction
- Considerable amount of waste, off cuts, mistakes, etc
- Water usage and site degradation
- Ground works
- We don't have great data here, maybe 4.75%

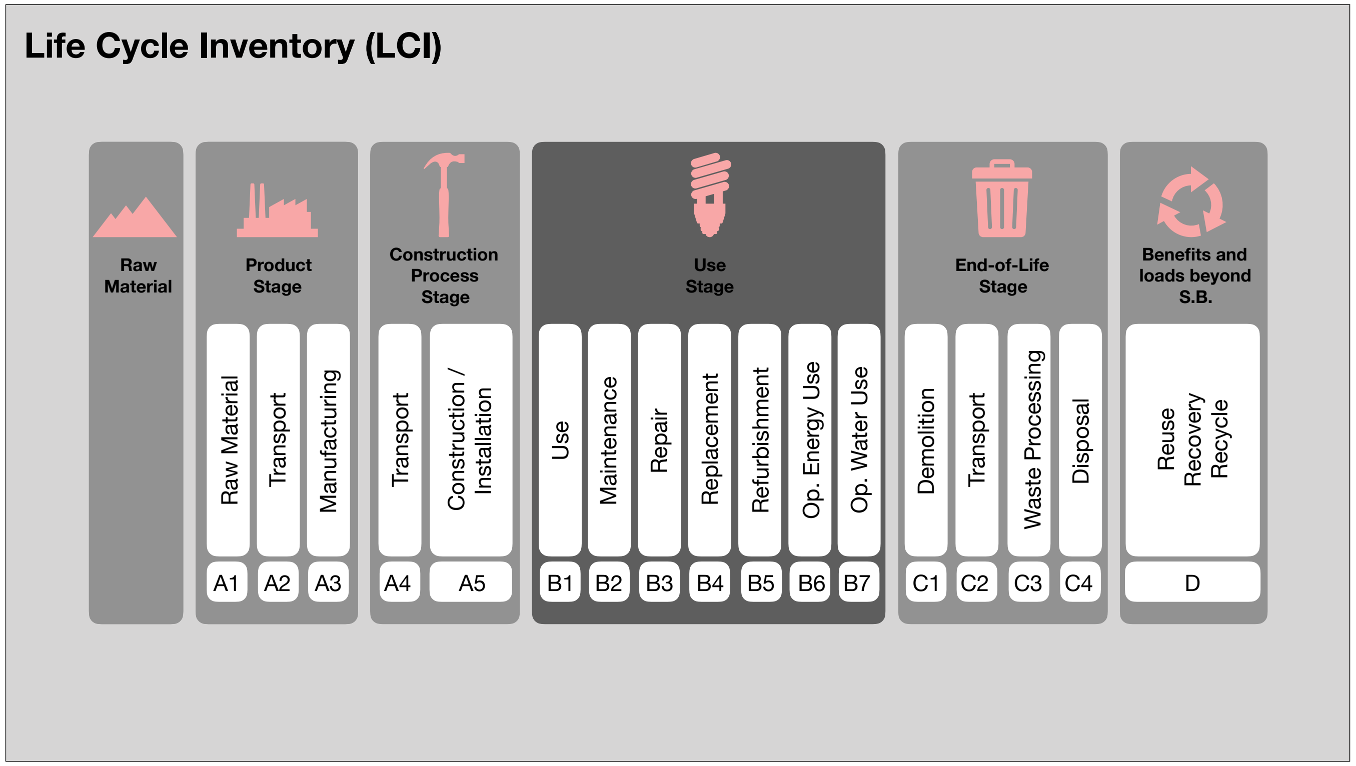
*construction site work, including demolition / clearance is not included under EN 15978



Several cut-off criteria are used in LCA practice to decide which inputs are to be included in the assessment, such as mass, energy and environmental significance.

What we include matters…the cut-off criteria shall be 1% of the total mass input of the building element category. The total of neglected material flows per information module shall be a maximum of 5% of the energy (carbon) usage by mass. The exception is if they have any of the following in which case they have to be included:

—significant effects or energy use in their manufacture, use or disposal (pains for example)
—are classed as hazardous waste



USE [EN 15978 B1]

- Any emissions to the environment during the normal use of the building. Including emissions from building elements (what about absorption?)

Maintenance, repair, refurbishment [EN 15978 B2-B6]

- Cleaning, period replacement of consumables, re-painting
- Common for building parts to have much shorter service life.
- Replacement of damaged or obsolete products (1.5 factor are applied [whole factors]).
- Refurbishment has similar inputs and outputs to construction.
- Replacement, Refurbishment (A1-3) Installation (A5) and disposal (C1-C4) factors can be used.

Operation and use [EN 15978 B6-7]

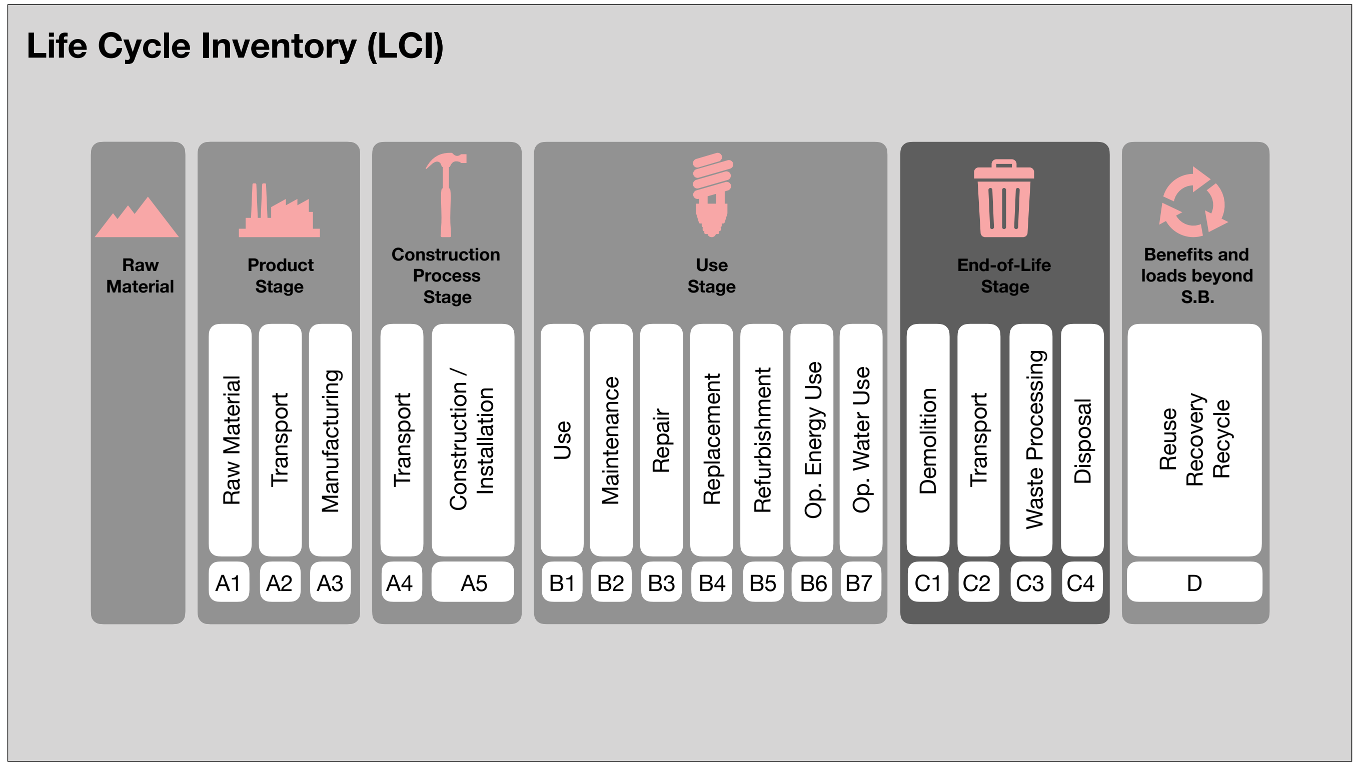
- Operational energy <u>AND exported energy</u> [MJ] —> carbon offset from renewable energy sources
- Operational water [kg]
- Does not include plug loads for appliances

Quick example for our guests:

- photovoltaic CO2 payback period = Ei/Eo (embodied CO2 emissions / operational CO2 emissions). PV's have an energy payback time of 2–6 years and expected life time of PV systems of 25–30 years.
- photovoltaic CO2 emissions might be about 0.03-0.23kg/kWh of energy created. In the UK the grid puts out about 0.4kg/kWh. Meaning every kWh of PV offsets 0.1kg of CO2 (over a 30 year period).

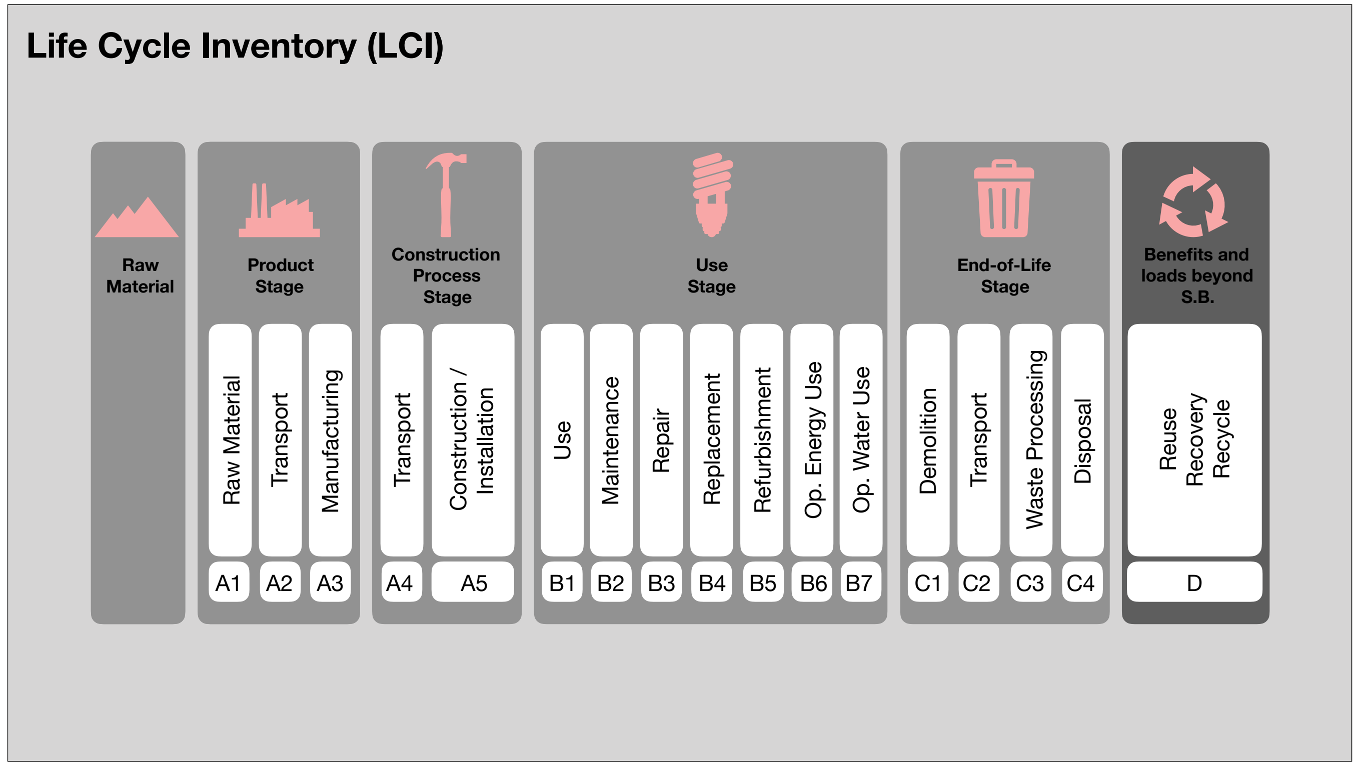
The next questions is how often are PV replaced in the building, again about 30 years. How does this impact the payback?

And, let's assume we make it to 2050 and achieve a near zero-emissions energy infrastructure. As the grid provides more electricity via renewables, an average CO2-factor of 0.2 kg/kWh might be reasonable by 2080, which is the end of the the building's service life. Tricky.



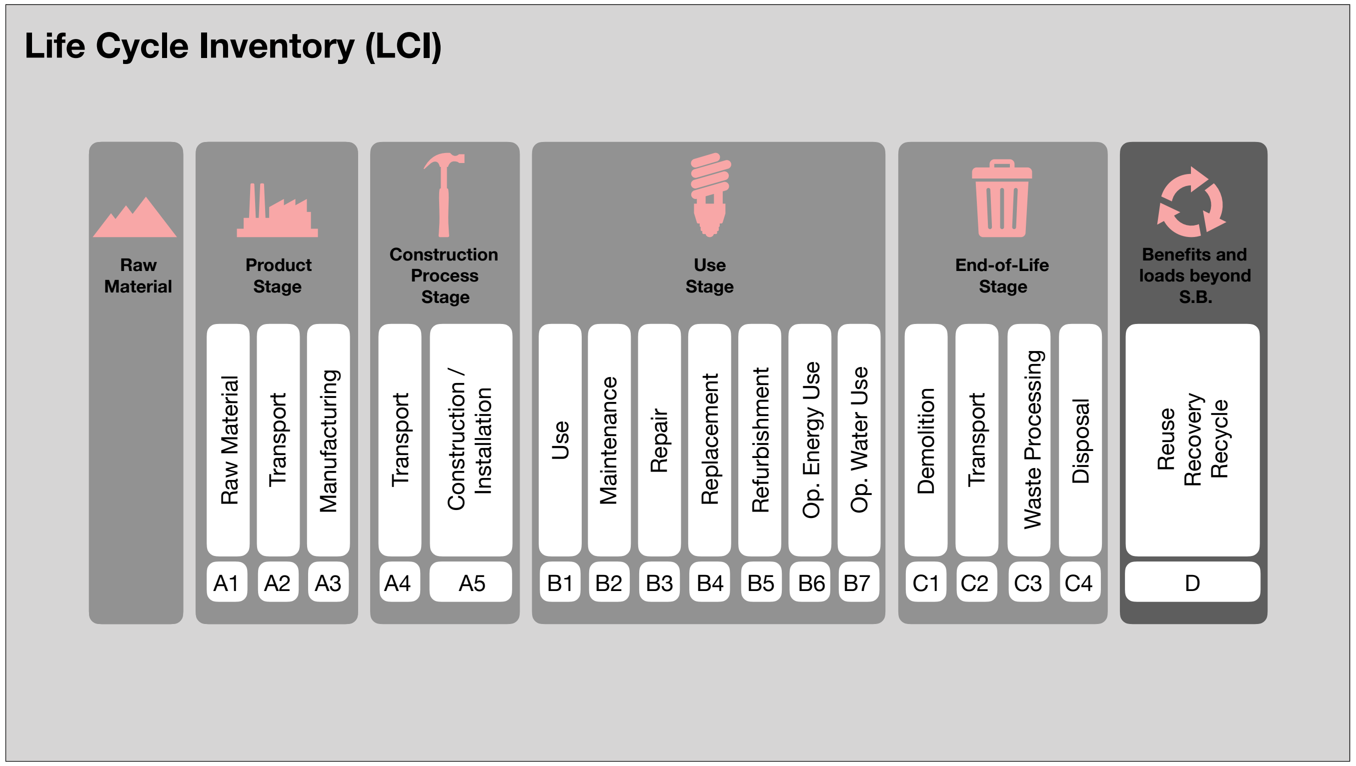
End-of-life (demo, transport, waste, disposal) [EN 15978 C1-C4]

- Includes the demolition or dismantling of buildings and subsequent disposal or reuse.
- We do not have great data for demolition and dismantling (some speculate dismantling to 130MJ/m2 or twice that)
- Stage C2 encompasses transportation from the construction site to end-of-life treatment based on national averages.
- Stages C3 and C4 account for waste processing and disposal such as impacts associated with landfilling or incineration.
- **Over-specification possible** (carpet, or operational payback. An example maybe PCM steel balls that require 10,200 GJ of energy to produce but only produce cooling is 280 GJ a year, energy payback is 36+ years…



Benefits and loads beyond the SB or Externalized Impacts [Reuse, Recovery, Recycle]) [D]

- Module D accounts for reuse and recycling potential that falls beyond the system boundary (beyond the LCA), such as energy recovery and recycling materials.
- Module D has a net impact on the calculation based on average existing tech or practice
- Recycling materials are modeled using an avoided burden approach.
- Avoided burden is an approach used in life-cycle assessment (LCA), especially in the context of allocating environmental burden in the presence of recycling or reuse. When determining the overall environmental impact of a product, the product is given "credit" for the potential recycled material included. For instance, PET bottles may be given environmental credit for the PET they contain, as this material will eventually be recycled back into further PET products.This credit is termed "avoided burden" because it refers to the impact of virgin material production that is avoided by the use of recycled material.
- Incineration of materials includes credit for average US energy recovery rates.



Benefits and loads beyond SB or Externalized Impacts [Reuse, Recovery, Recycle]) [D]

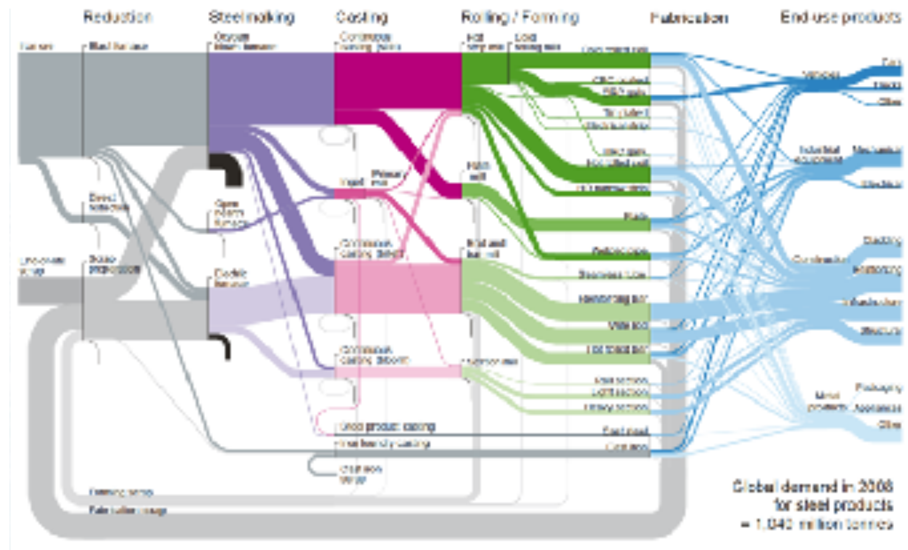
— reuse and recycling (as well as composting, energy recovery and other processes that can be assimilated to reuse/recycling) may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system;

— reuse and recycling may change the inherent properties of materials in subsequent use;

— specific care should be taken when defining system boundary with regard to recovery processes.

a) A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. However, the first use of virgin materials in applicable open loop product systems may follow an open-loop allocation procedure outlined in b). (steel to steel)

b) An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties. (tire to floor)



Allwood, Julian M. *Sustainable Materials with Both Eyes Open.* 2012.

http://www.withbotheyesopen.com/read.php

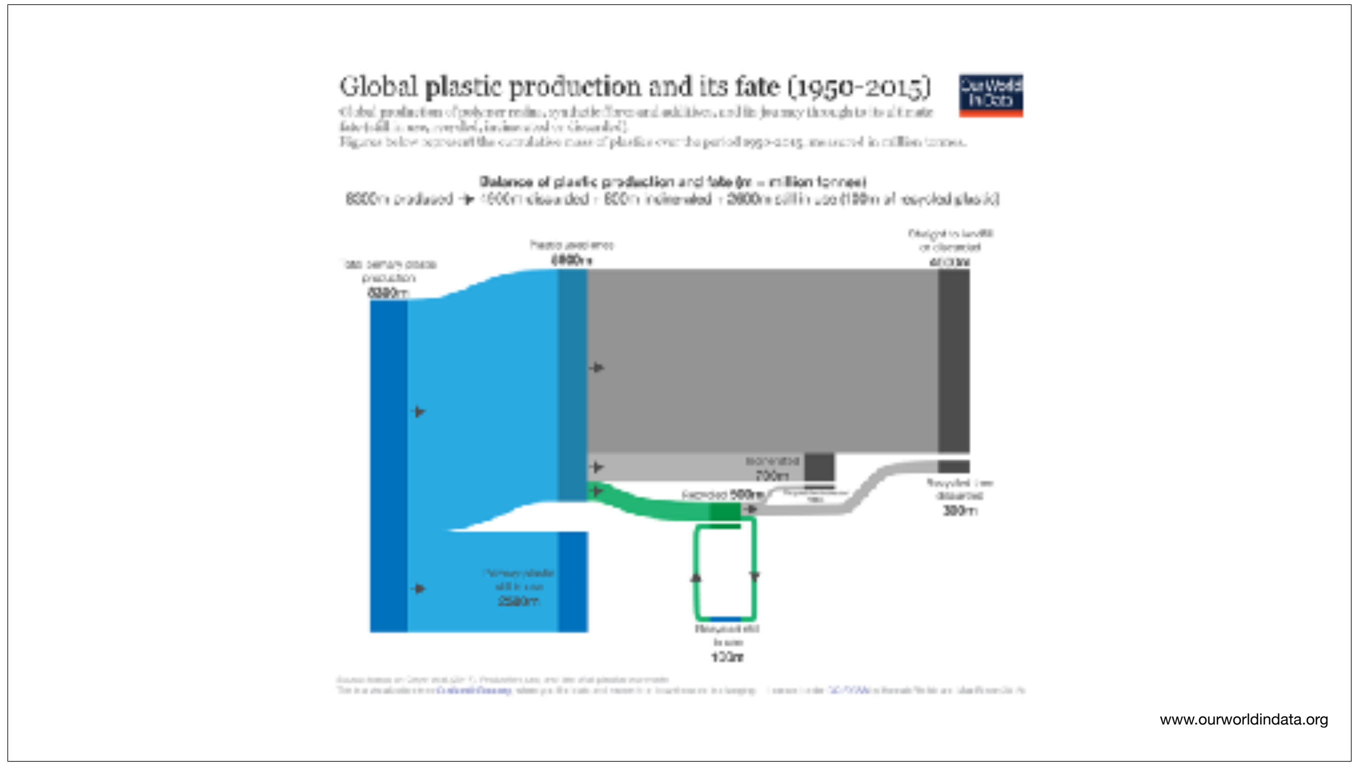
We saw some of this early. Steel retains an extremely high overall recycling rate, which in 2014, stood at 86 percent (Steel recycling insitute)

2/3 of the worlds steel is made from minded ore and 1/3 recycled scrap (makes sense as a blast furnace can only handle about 30% scrap).

1/5 of the scrap comes from within the industry
2/5 from product manufactures
2/5 from product and building end-of-life.

Most steel is produced oxygen blast furnaces, some in electric arc furnaces.

99% is rolled steel: 1/2 of the worlds steel is used in construction, of which 1/3 is reinforcing steel in concrete.



Plastic is closed and open.

In the figure we summarize global plastic production to final fate over the period 1950 to 2015

This is given in cumulative million tonnes.

- cumulative production of polymers, synthetic fibers and additives was 8300 million tonnes (8.3 billion tonnes);
- 2500 million tonnes (30 percent) of primary plastics was still in use in 2015;
- 4600 million tonnes (55 percent) went straight to landfill or was discarded;
- 700 million tonnes (8 percent) was incinerated;
- <u>500 million tonnes (6 percent) was recycled (100 million tonnes of recycled plastic was still in use; 100 million tonnes was later incinerated; and 300 million tonnes was later discarded or sent to landfill).</u>

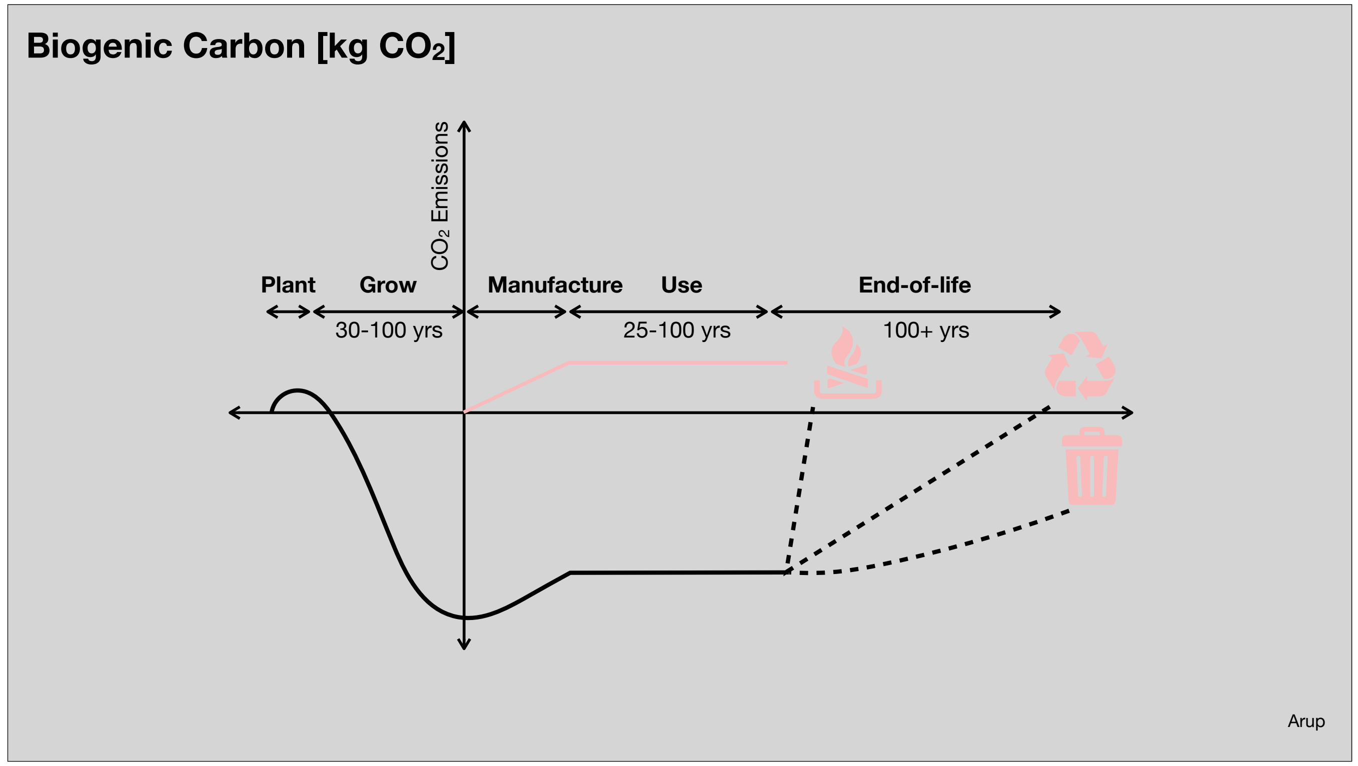
<u>Of the 5800 million tonnes of primary plastic no longer in use, only 9 percent has been recycled since 1950.</u>

Unlike steel plastic has little value, we live in a single use economy!

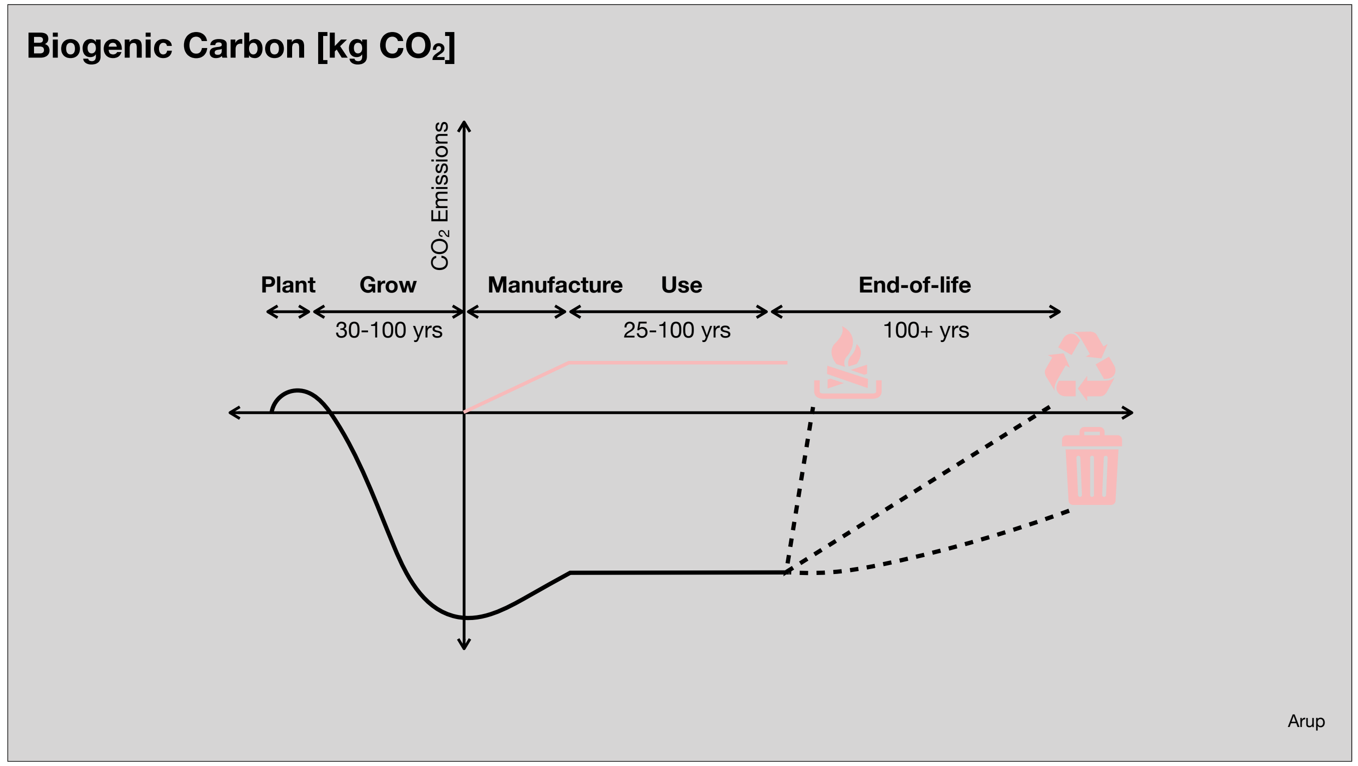
Accounting for Carbon Absorbed (carbonization of concrete put 43% of the CO2 emissions from production of cement)

ISO 21930:2017 Recommends accounting for biogenic carbon

ISO 21930:2017 Sustainability In Buildings And Civil Engineering Works - Core Rules For Environmental Product Declarations Of Construction Products And Services



- **Biogenic carbon** is the emissions related to the natural carbon cycle, as well as those resulting from the combustion, harvest, digestion, fermentation, decomposition or processing of biologically based materials.
- LCA does not account for biogenic carbon. Nor the fuel and fertilizer used in planting, management, harvesting. Nor does it capture environmental aspects, such as water, wild life, etc.
- A forest can act as carbon sink when the amount of carbon take in and stored by the soil, tress (and resulting timber products) and other vegetation is greater than the total amount of carbon dioxide emitted due to respiration, decay, disturbances (harvest or fire) and emissions due to wood processing.
- Natural wood is carbon neutral, but the emissions from manufacturing, transportation and other process are not.
- There are different methods for tracking long-term wood products
- Most methods report emissions from manufacturing, treating the absorbed and released biogenic carbon as net neutral.
- Carbon in trees is about 46 to 55 percent of total weight (500 kg CO2 for 1000kg of tree), the root mass for example is about 15 percent is considered carbon neutral as the rate of rot is the same as growth..
- A ballpark number for carbon uptake per tree per year is 22 kg CO2

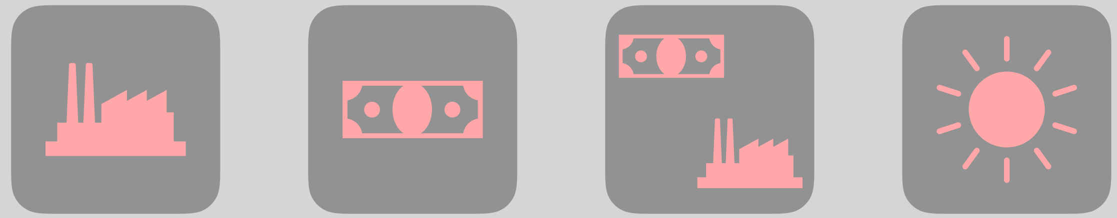


Biogenic carbon refers to carbon that is “produced in natural processes by living organisms but not fossilized or derived from fossil resources.”

- Report biogenic carbon emissions from each life cycle module for the three classifications of biogenic carbon per ISO 21930 (2017).
- Report the sequestration credit as a separate negative value (not added to the positive emissions values).
- If your biogenic material is wood, report the status of forest certification.

This great, but where do we get the data?

LCA Methods



Type	Process LCA	Economic Input Output LCA	Hybrid	ECO-LCA Emergy
Tool	Simpro, Gabi, Athena, Tally, etc.	CMU EIO	BIRDS	*
Inputs	Location, building element quantities	US $, Industry	Location, building type, stories	Building element mass, solar transformity
Quick Fact	Based on past studies and primary sources such as environmental product declarations.	Links environmental impacts to economic sectors (500 in US) EIO can be fast and identify hotspot using comprehensive supply chains, but cannot do comparative analysis	combines LCA and EIO (1) (Bottom up) start with process LCI and fill in gaps with EIO data (2) (Top down) start with EIO to find hot spot then refine with LCI	Address energy use further upstream within the building system
Impact	All, water, toxicity	All, water, toxicity	All, water, toxicity	Emergy
Unit	CO_2e/kg	$CO_2e/\$A1000$	$CO_2e/\$A1000$	seJ/g

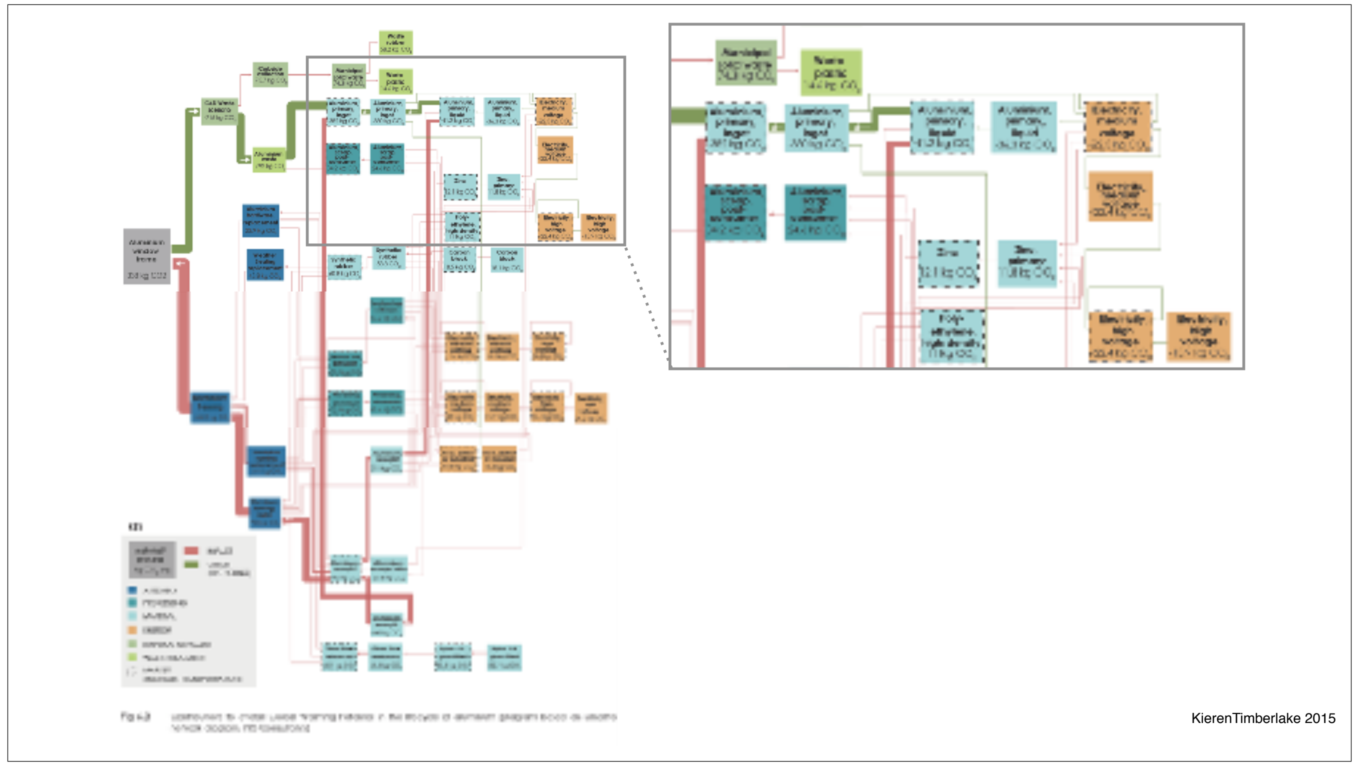
I highly recommend trying CMU's EIOLCA tool!
http://www.eiolca.net/

Building Industry Reporting and Design for Sustainability
https://ws680.nist.gov/birds

Other databases:
https://circularecology.com/embodied-carbon-footprint-database.html#.WjR0E0qnHIU

http://quartzproject.org/q

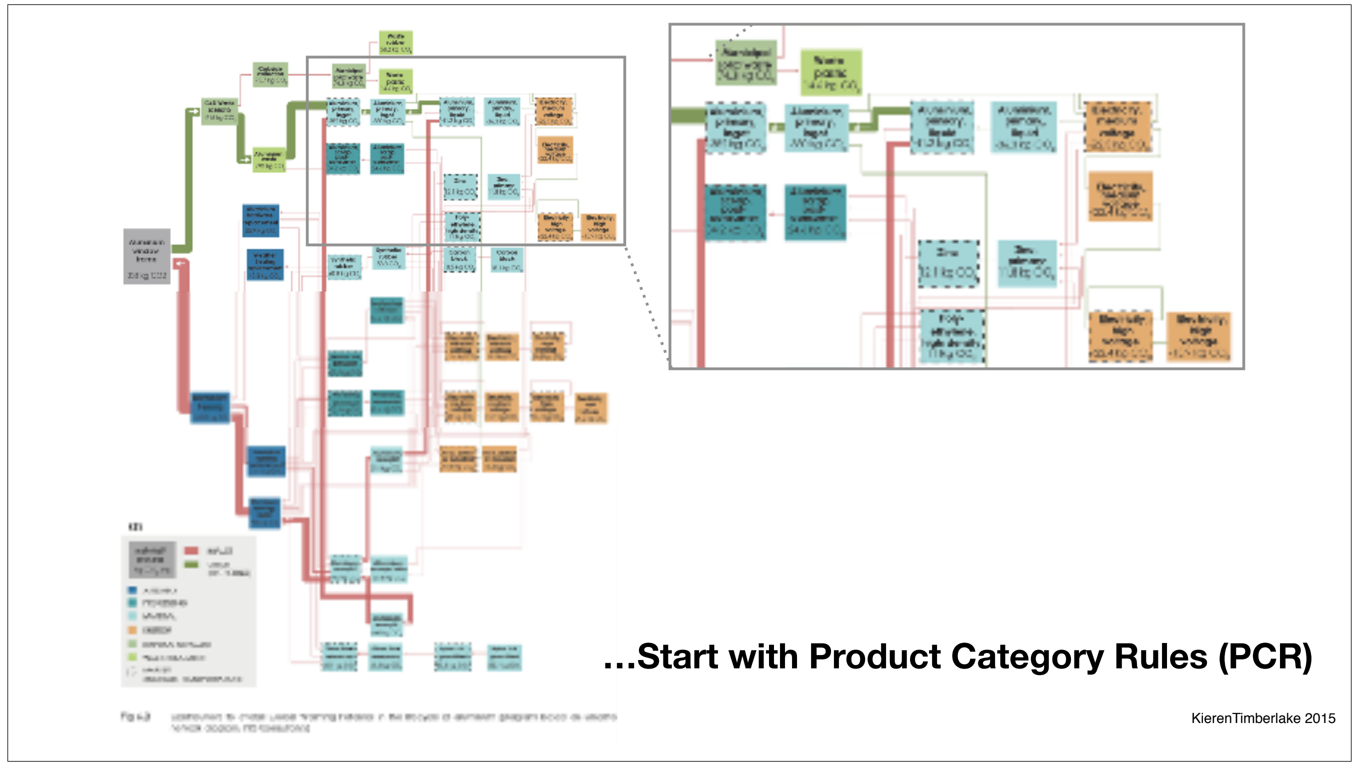
seJ/J = Transformity;
seJ/g = Specific emergy



Let’s return to KierenTimberlake’s “Aluminum and Life Cycle Thinking: Towards Sustainable Cities”

How do we calculate Embodied Energy or Carbon Footprint? One is tempted to do a full thermodynamic accounting. Extracting Aluminum requires free energy of oxidation to free aluminum from its oxide. This is an inefficient process <50%. Only part is usable, about 90%, the raw material has further embodied energy, transportation, and continual operation of the production plant (lights, heat, and services)….seems complicated.

Instead we can use and input/output analysis by measuring the energy used in a plant over a fixed period and just how much material comes out. This includes feed stocks like raw materials and energy (oil).



https://www.astm.org/CERTIFICATION/EpdAndPCRs.html
https://www.environdec.com/

Product category rules (PCR) are defined in ISO 14025 as a set of specific rules, requirements, and guidelines, for developing environmental declarations for one or more products that can fulfill equivalent functions. PCR determine what information should be gathered and how that information should be evaluated for an environmental declaration.

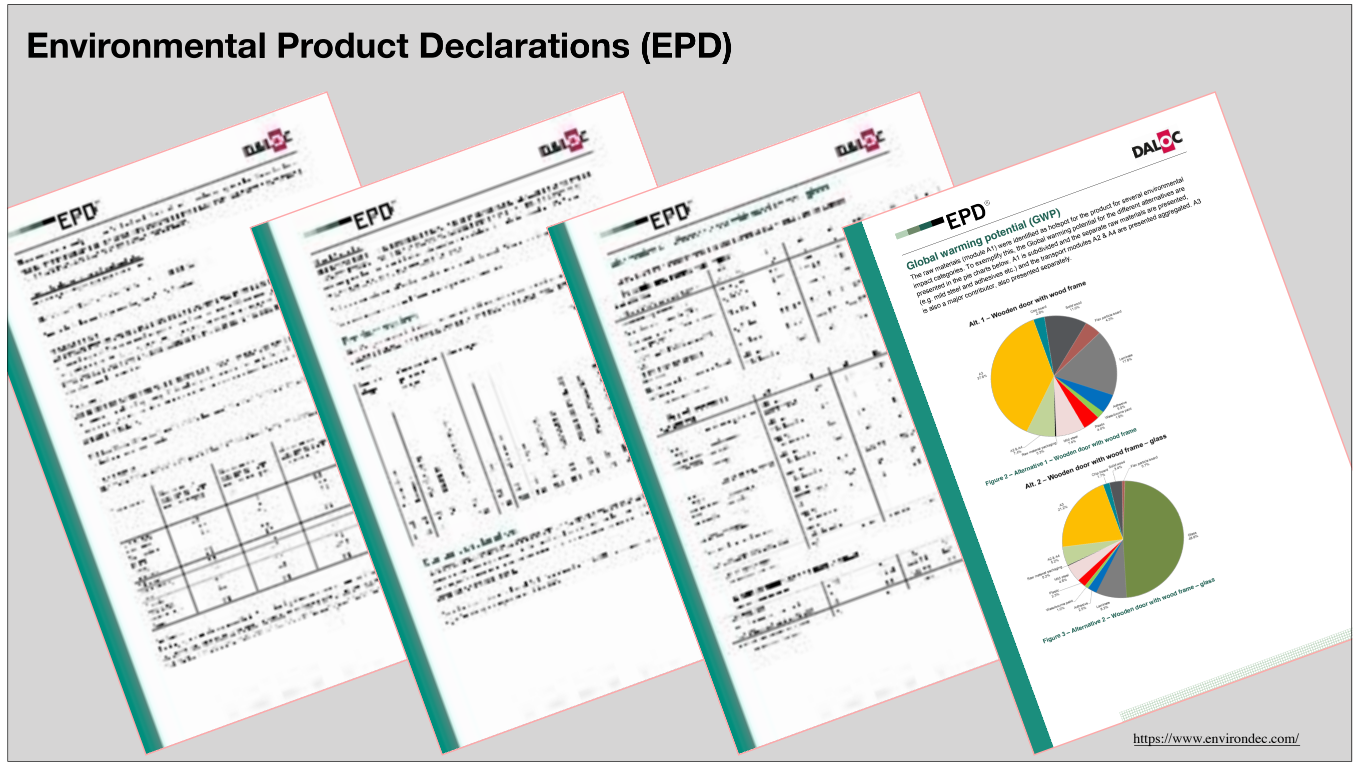
PCR are developed through the consultation of interested parties. In order to promote harmonization, existing PCR should be used and adapted prior to the development of a new PCR.

An LCA must be conducted to gather the necessary data in order to compile the environmental impact of the product across its life span from cradle to grave.

The manufacturer uses the PCR to compile the life cycle assessment data and other relevant environmental information to create the declaration.

The EPD must be verified by ASTM, a program operator, to ensure that the contents of the declaration conform to the requirements of the PCR, including the life cycle assessment.

EPDs are usually based on “functional units” rather than weight, and many will provide the carbon footprint of a specific product or set of products rather than a generic baseline.



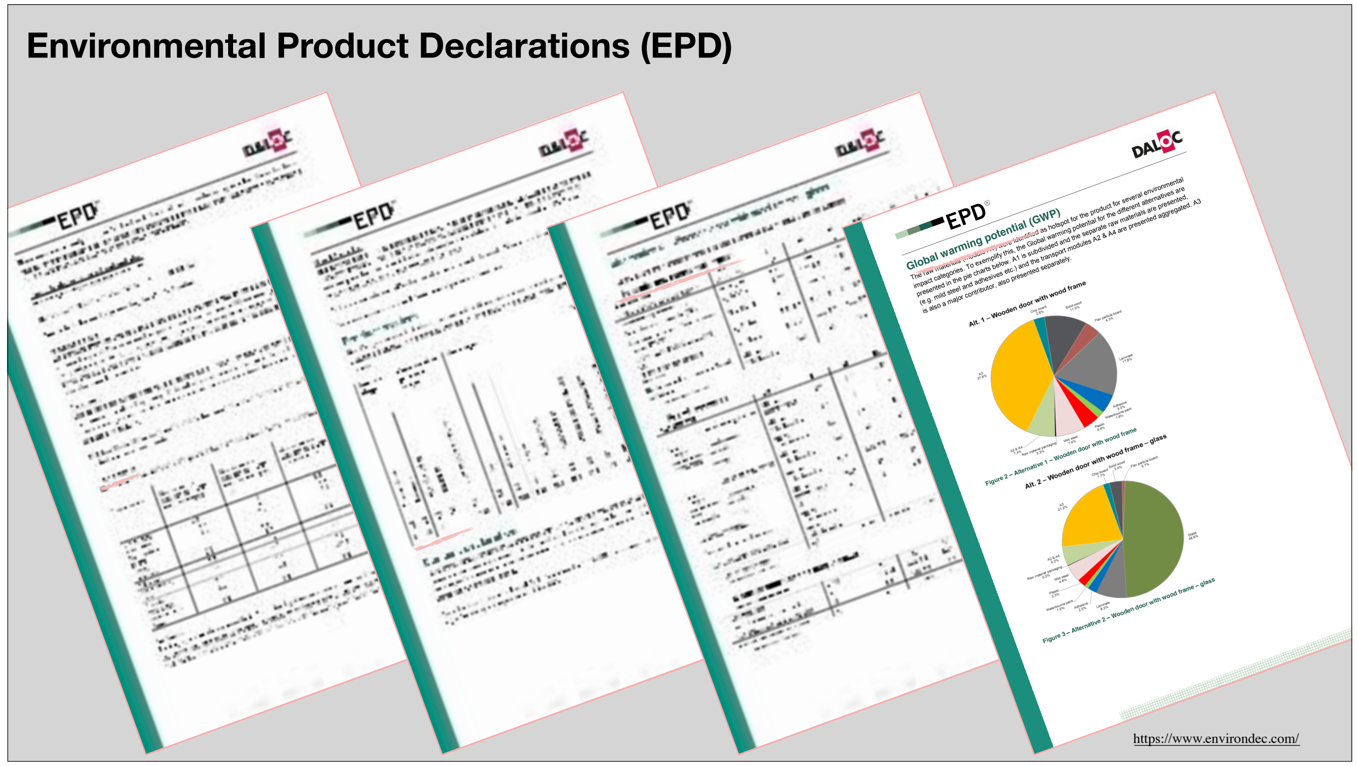
Environmental Product Declarations (EPD)

Critical components are:

- Based on LCA data developed in accordance with the International Organization for Standardization (ISO)
- Based on established Product category rules (PCR) for conducting LCA
- Verified by third party “program operator”
- Should be comparable*

<u>*EPDs are usually based on “functional units” rather than weight, and many will provide the carbon footprint of a specific product or set of products rather than a generic baseline.</u>

*Even within the same product category, EPD comparisons are not precise, <u>with uncertainties in the 20%-40% range quite common.</u>



Here we have an example for a standard wooden door with steel frame and glass window.

Note the system boundary is cradle to gate (A1-A4)

Note the format. There's no standard for machine readable EPDs (this is 4 of 17 pages).

North America
- FP Innovations - EPD Program on Wood Products (Canada)
- NSF International (U.S.)
- The Institute for Environmental Research & Education - Earthsure EPD (U.S.)The Sustainability Consortium (U.S.)
- UL Environment (U.S.)
- ASTM International (U.S.)
- Carbon Leadership Forum (U.S.)
- ICC Evaluation Services (U.S.)
- National Ready Mixed Concrete Association (U.S.)
- SGS Global Services (U.S.)

Asia
- Japan Environmental Management Association for Industry (Japan)
- Korean Environmental Industry & Technology Institute (Korea)
- Environment and Development Foundation (Taiwan)

All process LCA for industry (mostly envelop and structure, not MEP), most include location (electrical supply)

Most are methodologies are consistent with LCA standards ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011.

SimaPro
https://simapro.com/

Gabi
http://www.gabi-software.com/america/index/
https://sphera.com/

Granta CES —> CES database with simple and powerful interface
https://grantadesign.com/ [cradle to cradle]

*North America

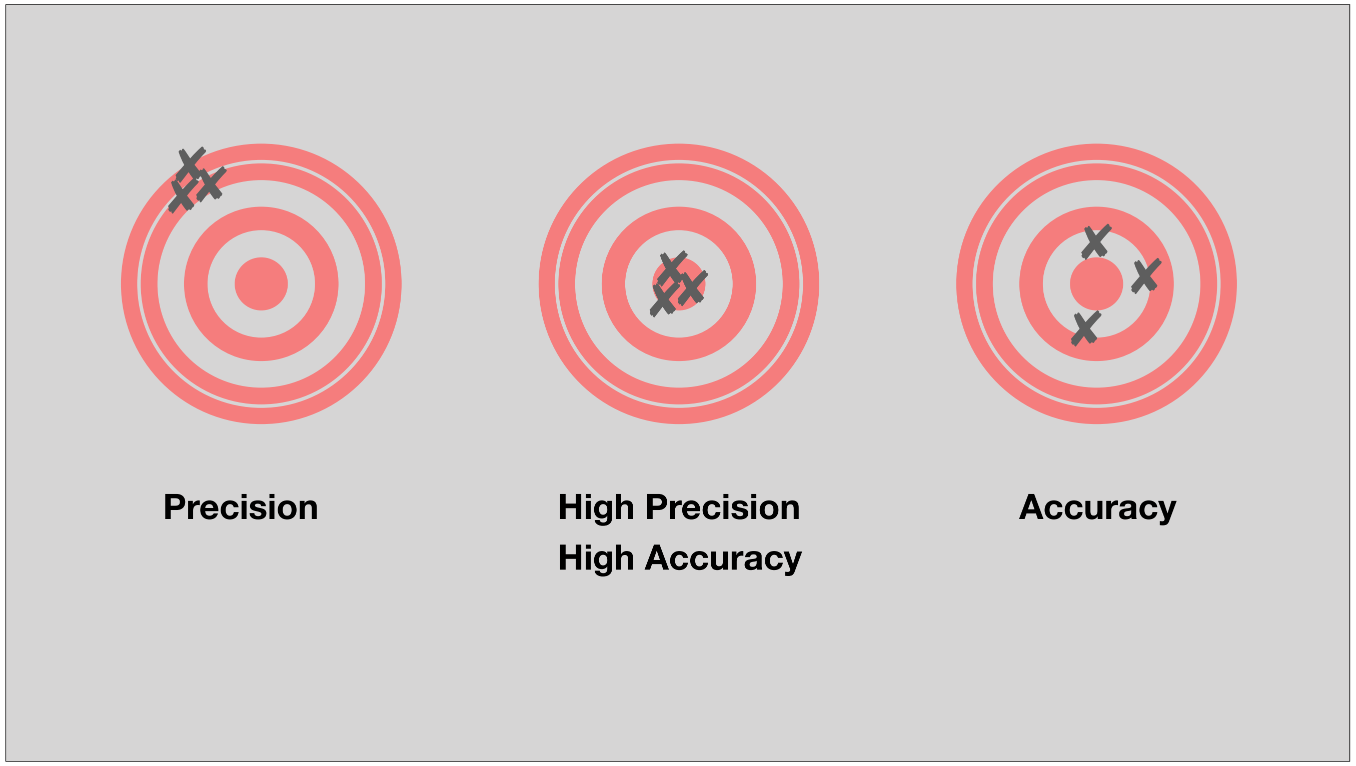
All process LCA for buildings (mostly envelop and structure, not MEP), most include location (electrical supply)

Most are methodologies are consistent with LCA standards ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011.

Athena independent database, user interface for architecture shells and structure, build out by building element type [cradle to cradle]
http://www.athenasmi.org/

Tally—> Revit application for GaBi Database, apply LCA to families and work groups for whole life cycle assessment, [cradle to cradle]
https://choosetally.com/

Embodied Carbon in Construction Calculator EC3 —> The EC3 tool utilizes building material quantities from construction estimates and/or BIM models and a database of digital, third-party verified Environmental Product Declarations (EPDs). EPDs have been expensive to publish, relatively small numbers, limited to variety of different EPD databases, unstructured print-only PDF files. EC3 provides a a free, open-access database to directly measure and compare embodied carbon in specific new buildings. Limited scope, just product phase A1-A3 (A4,5 WIP) [cradle to gate]

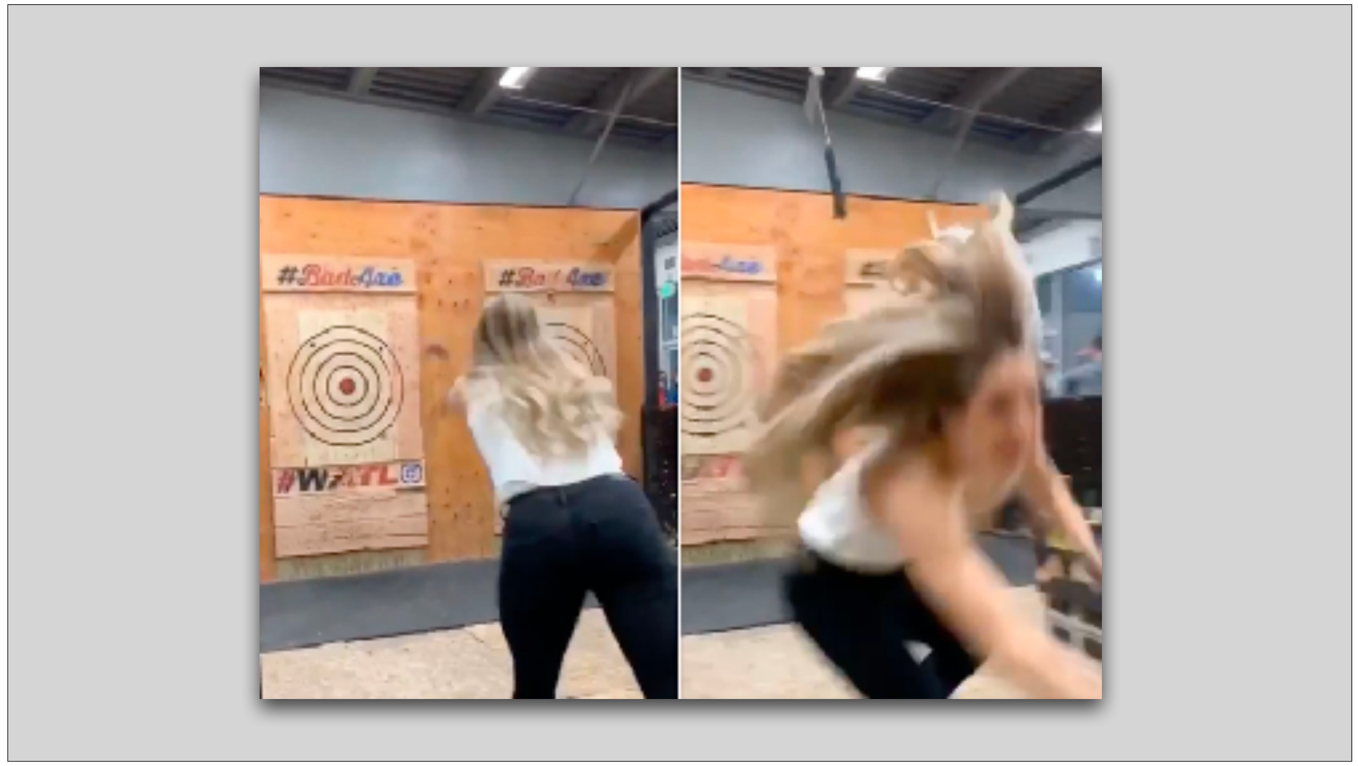


Accuracy refers to how close a measured value is to the standard or true value.

Precision refers to how close the measured values are to each other.

For example, the mean root error, which is similar to the standard deviation (but not the same) determine our standard uncertainty from a repeatable experiment and shows how much does the data deviate — typically in the form of linear regression

The root sum of squares is the way that combines the standard uncertainties of more than one contributor to provide our overall combined uncertainty.



Walker et al, *Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support,* 2003 distinguish three type of uncertainty: Location, level, nature. These are describe below.

Any attempt to measure the embodied carbon in buildings encounters numerous issues of uncertainty, both at the statistical and scenario levels.

Sources of statistical uncertainty are defined as those for which quantitative ranges can be determined. Sources of statistical uncertainty can be located in the model inputs because they relate to uncertainties in carbon factors or material and energy quantities or both (do you have the right embodied carbon and mass of a steel beam?)

Scenario uncertainty are characterized by multiple alternative options where the likelihood of each occurring is unknown or where the options are not subject to probabilities but represent subjective choices (will the steel beam be recycled at the E-O-L?).

There is also recognized ignorance, or ‘known unknowns,’ where ‘the scientific basis for developing scenarios is weak.”

Location specifies whether the uncertainty is the in the model input data (input uncertainty), in the models relationship or equations (model uncertainty) or assumptions or context on which the model is based (context uncertainty).

Level of uncertainty is a scale of how catering or uncertain something is (absolutely certain to absolutely uncertain). Between these extremes there is statical uncertainty, where probabilities can be estimated; scenario uncertainty, where different outcomes are anticipated but the likelihood of probability of each is not known; and recognized ignorance, or ‘known unknowns,’ where ‘the scientific baes for developing scenarios is weak.’

Nature further distinguishes between epistemic uncertainty that can be reduced through improved knowledge and uncertainty that are due to the natural variability of the system to be modeled.

Life Cycle Assessment Data Quality Analysis

Gravity analysis (e.g. Pareto analysis) is a statistical procedure that identifies those data having the greatest contribution to the indicator result. These items may then be investigated with increased priority to ensure that sound decisions are made.

Uncertainty analysis is a procedure to determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the LCIA.

Sensitivity analysis is a procedure to determine how changes in data and methodological choices affect the results of the LCIA.

During the interpretation phase additional techniques and information may be needed to understand better the significance, uncertainty and sensitivity of the LCIA results in order

— to help distinguish if significant differences are or are not present,
— to identify negligible LCI results, or
— to guide the iterative LCIA process.

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Reflecting the iterative nature of LCA, decisions regarding the data to be included shall be based on a sensitivity analysis to determine their significance.

The initial system boundary shall be revised, as appropriate, in accordance with the cut-off criteria established in the definition of the scope. The results of this refining process and the sensitivity analysis shall be documented.

The sensitivity analysis may result in:

— exclusion of life cycle stages or unit processes when lack of significance can be shown by the sensitivity analysis,

— exclusion of inputs and outputs that lack significance to the results of the study,

— inclusion of new unit processes, inputs and outputs that are shown to be significant in the sensitivity analysis.

Life Cycle Assessment Data Quality Analysis

Age of data - how current is the data and was it collected over an appropriate time?
Geographical coverage - do I have data for my location (big)?
Technology coverage - are we talking about the right tech?
Precision - does that data vary too much?
Completeness - how much is measure? how much is estimated?
Representativeness - does it reflect the scope of study?
Consistency - are we talking apples to apples?
Reproducibility - do methods and data allow the study to be repeated?
Sources - where did the data come from?
Uncertainty - what unknowns are tied to the data?
Missing data - state what is missing?

*When EPD are not available, proxies, generic material databases and peer-reviewed LCA studies can be used.

In many ways, you all experienced these issues
The data quality requirements should address the following:
a) time-related coverage: age of data and the minimum length of time over which data should be collected;
b) geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study;
c) technology coverage: specific technology or technology mix;
d) precision: measure of the variability of the data values for each data expressed (e.g. variance);
e) completeness: percentage of flow that is measured or estimated;
f) representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage);
g) consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;
h) reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;
i) sources of the data;
j) uncertainty of the information (e.g. data, models and assumptions).

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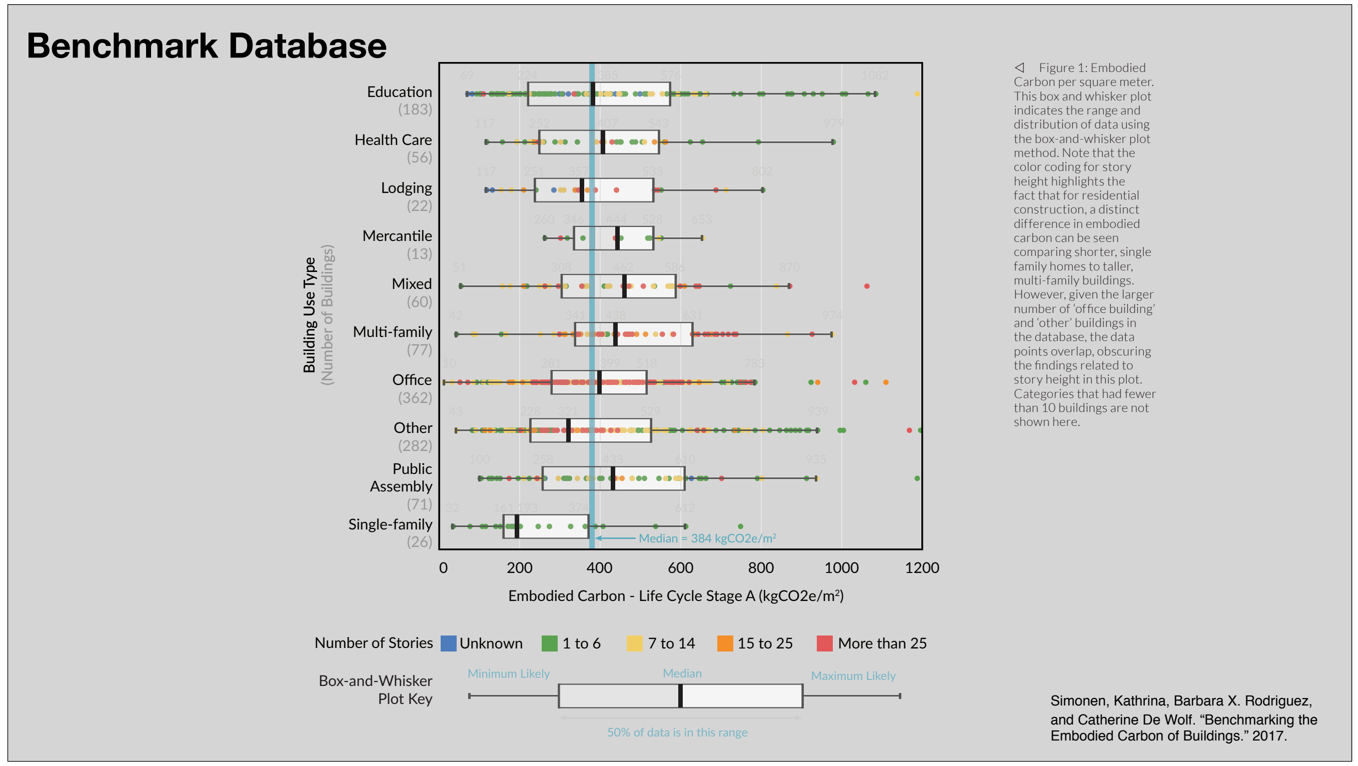
The treatment of missing data shall be documented.



The Benchmark database from the Carbon Leadership Forum is likely the best source to understand how much our buildings weigh, carbon-wise. It allows LCA studies that are comparative studies between two potential building designs.

This data has options for "building scope.Typically we use "structure, foundation, enclosure, interiors," but you'll see "structure and foundation" has similar results.

There is some question here as to whether the structure and an applied constant are enough to calculate the total embodied carbon (De Wolf's method).

It's worth reading "Benchmarking the Embodied Carbon of Buildings." This paper puts **offices at 281-518 kgCo2e/m2** with the overall building median of **384 kgCo2e/m2**. Or more broadly, commercial office buildings are on the range of **200-500 kgCo2e/m2** and the peak carbon is **1000kgCo2e/m2.** This paper also frames the conversation well.

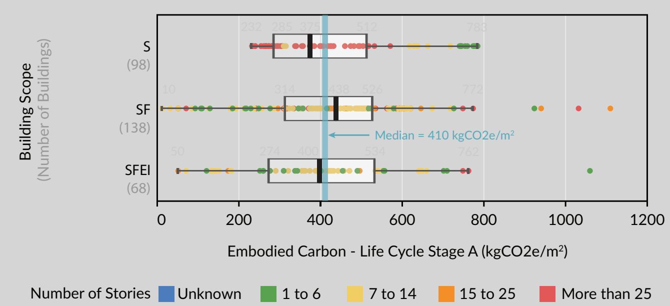
The Carbon Leadership Forum's benchmarking database uses Catherine De Wolf's deQo database and WRAP from the UK GBC. deQo has a similar data range for office buildings, **243-417 kgCo2e/m2.**

https://carbonleadershipforum.org/projects/embodied-carbon-benchmark-study-data-visualization/

Get the data (1200 bldg)
https://carbonleadershipforum.org/projects/embodied-carbon-benchmark-study/

https://www.carbondeqo.com/database/graph

Benchmark Database



◁ Figure 2: Embodied Carbon per m2 of Office Buildings Sorted by Building Scope. In this plot, the buildings are sorted based on the scope of building components included (S = Structure, SF = Structure/Foundation, SFEI = Structure/Foundation/Enclosure/Interiors). Buildings that did not have scopes defined (null), or had fewer than 10 buildings in the scope category are not shown here.

Simonen, Kathrina, Barbara X. Rodriguez, and Catherine De Wolf. "Benchmarking the Embodied Carbon of Buildings." 2017.

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Benchmarking Mechanical, Electrical, Plumbing and Tenant Improvements

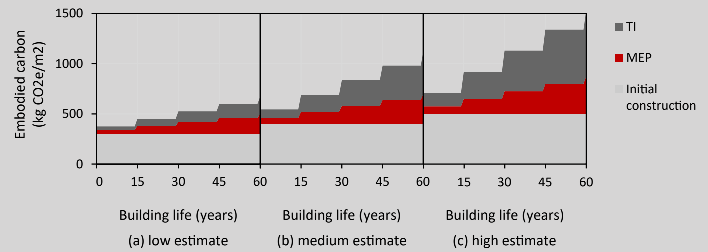

Figure 4. Cumulative embodied carbon impacts of initial construction, MEP, TI, and use (operational) at low, medium, and high estimate levels over 60 years.

Simonen et al. Estimates of Embodied Carbon for Mechanical, Electrical, Plumbing and Tenant Improvements 2019

CO2e for medium case

			0YR	15YR		30YR		45YR
Recurring MEP		60	120		180		240	
Recurring TI		90	180		270		360	
Initial Construction	400	400	400		400			
Initial Construction + MEP+TI	550	700	850		1000			

What do we get out of a life cycle impact assessment?

List LCI v LCA data

https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)

TRACI is an environmental impact assessment tool. It provides characterization factors for Life Cycle Impact Assessment (LCIA), industrial ecology, and sustainability metrics. Characterization factors quantify the potential impacts that inputs and releases have on specific impact categories in common equivalence units. Impact categories include:

ozone depletion,
climate change,
acidification,
eutrophication,
smog formation,
human health impacts, and
ecotoxicity.
Resource uses of fossil fuels are also characterized.

What Do We Get Out?

Life Cycle Inventory

Energy Consumption
Resource Use
Air Emissions
Water Emissions
Land Emissions
…

Life Cycle Inventory Assessment

Ozone depletion
Climate change
Acidification
Eutrophication
Smog formation
Human health impacts
Toxicity
Uses of fossil fuels
…

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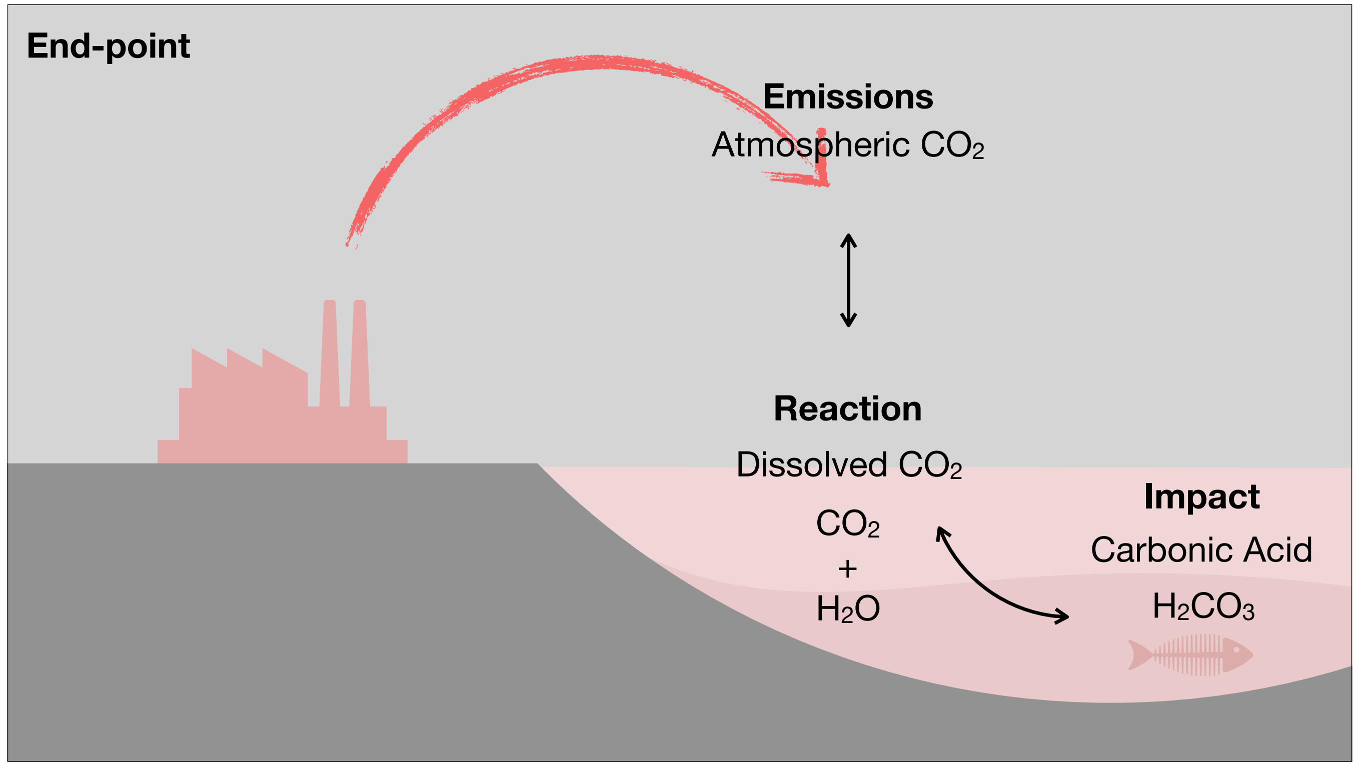
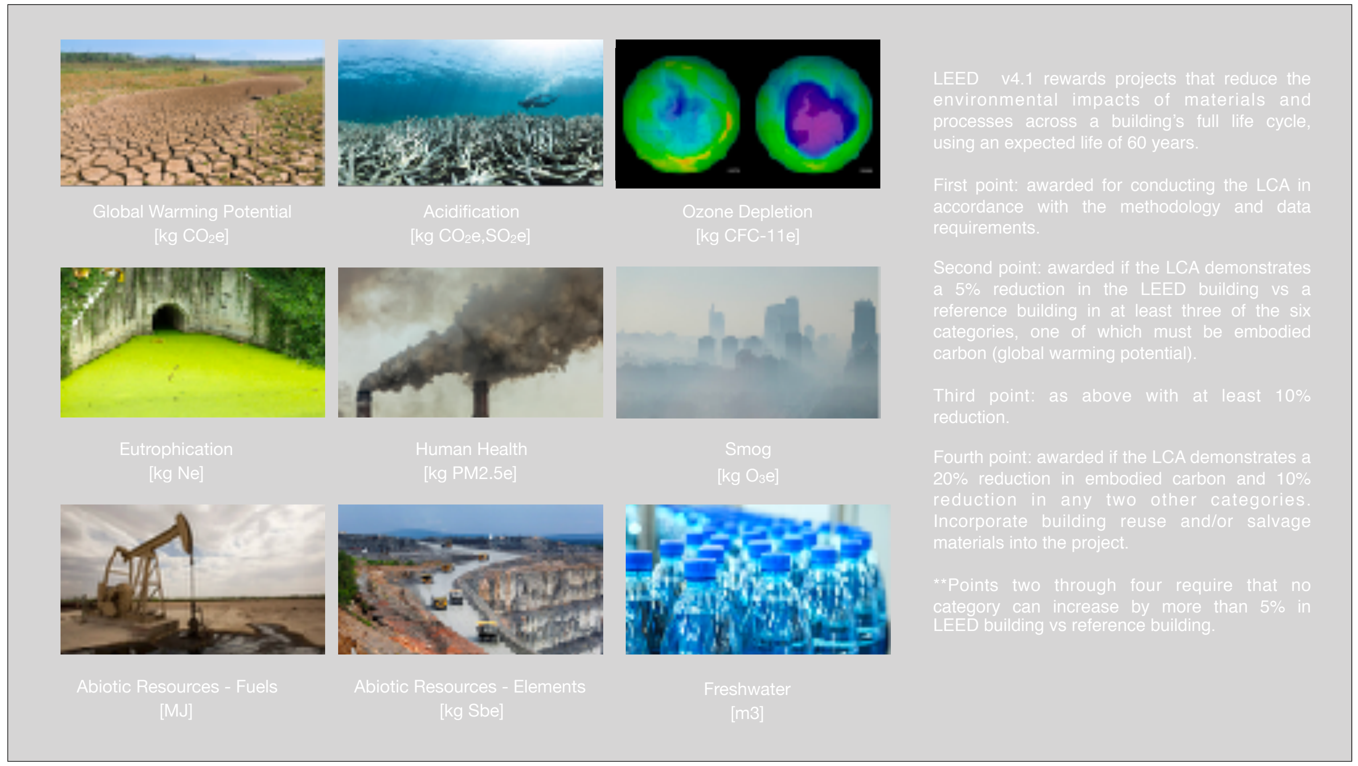


Chemical emissions (including sulfur dioxide and nitrogen oxides) from sources such as coal power plant are released into the air. These chemicals are transported in the air depending on wind and climate conditions (transport) and often carried to ground or water bodies via rain (fate). **The final, or "end-point" environmental impact** of acid rain includes a broad range of impacts ranging from corrosion of buildings to lack of productivity of soils.

Global —>GHG,
Regional—>Acidification
Local—>Smog.

Emissions and impacts are interconnected. Combustion of fossil fuels impacts acidification, climate change, eutrophication and ozone production. Carbon Dioxide causes both climate change and acidification. Eutrophication results in increased decomposition of organic matter that reduces oxygen and increased decomposition. **At the highest level, we are looking to protect human and ecosystem health .**



ISO 14044 recommends classifying the inventory data into four categories (1) inputs (energy, materials, etc) (2) products (including co-products and waste) (3) emissions (to air, water, and soil) and (4) other environmental aspects.

The results of an LCI report a compilation of quantities of resources consumed (from nature) and emissions (to nature). Quantities of material and energy must be quantified (ie amount of logs, resin for glue, and kilowatts of electricity consumed) as do the emission (kg of carbon dioxide per kilowatt of electricity generated).

Some policy-makers wish to have a single environmental performance "score" to enable them to rank choices. In order to do this, LCA results can be weighted by relative importance. The US National Institute of Standards and Technology provide a rating method in its LCA database and tool, BEES (NIST 2013) and permits users to over-ride this with their own priorities…There is no global consensus

Depletion of the earth's resources (Material and Energy) was introduced by The Limitss to Growth (1972) and concepts such as Peak Oil….See Pinker 'note on the bet' above.

- Non-renewable sources are those that cannot be replenished in life time
- Fossil fuels are generated by biological mechanisms of the conversion of decomposing plants and animals over millions of years
- The use of materials and energy resources are converted into units of energy, often termed 'embodied energy,' representing both the energy available within a product (what could be attained if the product were incinerated) and the energy used as fuel to manufacture the product.
- Heat released during combustion of a material can be characterized but the gross calorific value (GCV)
- Crude oil can be both energy (fuel) or material (plastic) with the same embodied energy.

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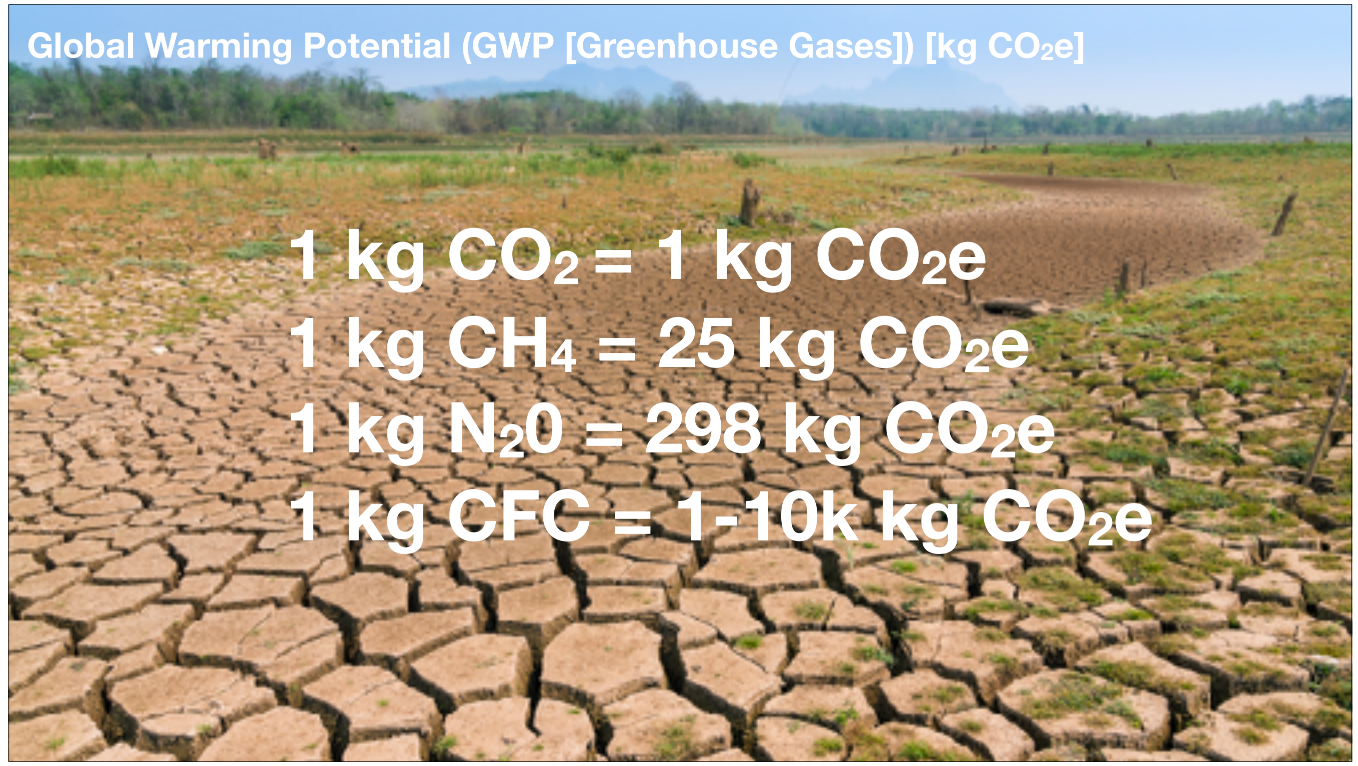
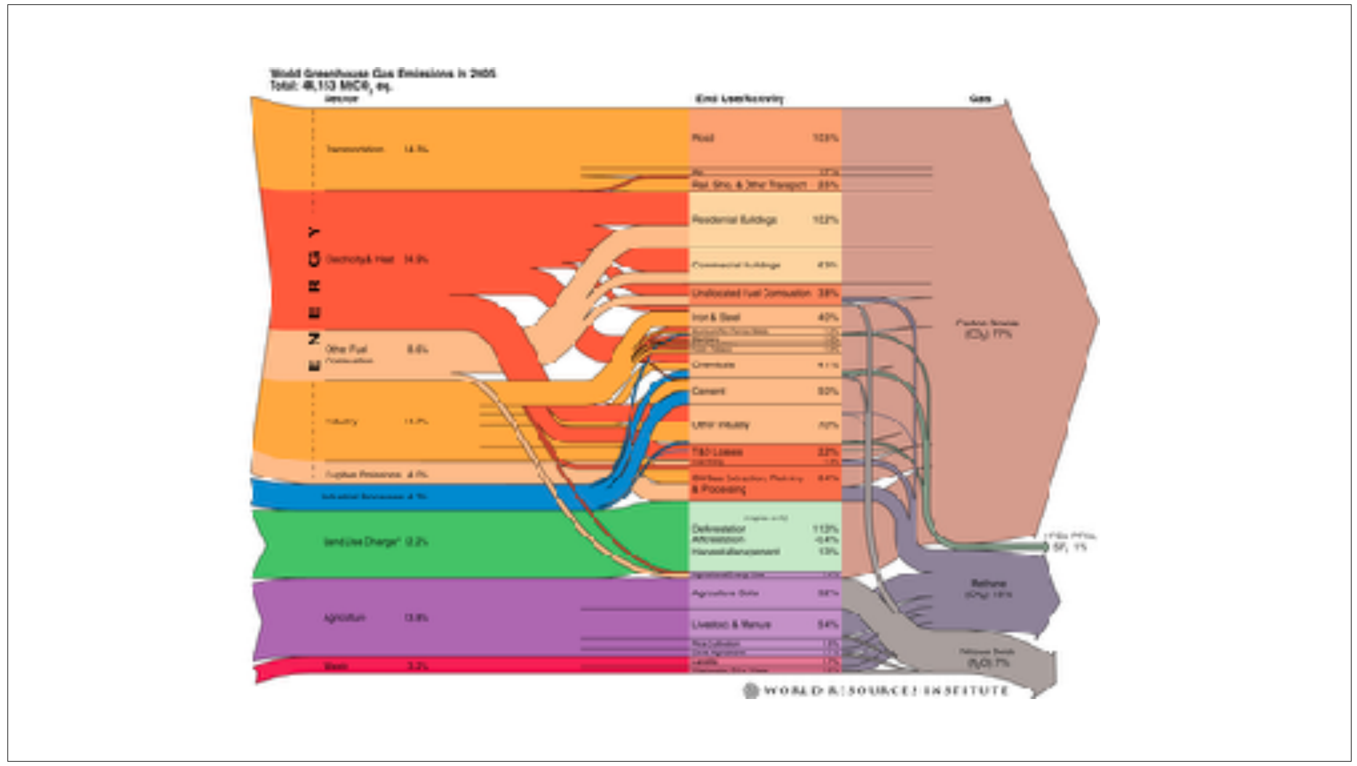


Climate change included impacts of global warming is the increase in global average temperature of the earth's surface and the associated changes to climate such as precipitation, wind, and other events over decades or longer. GHG absorb energy and trap heat (long wave radiation). GHG in buildings are produces through operation, production of materials. Process such as cement release CO2. Biological process such as plant growth absorb carbon, while decay releases carbon. Agricultural production produces GHG (Methane, Nitrous Oxide)

- LCA characterizes green house gasses as compared to equivalent mass of carbon dioxide (CO2)
- Global Warming Potential, Green House Gas, Climate Change Potential, Carbon Footprint, are all equivalent
- The most common greenhouse gases in earth's atmosphere are water vapor (H2O), carbon dioxide (CO2), methane (CH4), nitrous oxide (N20), Ozone (03), and chlorofluorocarbons (CFCs).
- CO2 has the highest concentration (growth from 280 ppm to 406ppm).
- While the global warming potential (GWP) of CO2 is less than methane (25x), nitrous oxide (298x).
- Nearly 100 other gases contribute…see TRACI



https://www.bbc.com/news/science-environment-35659947

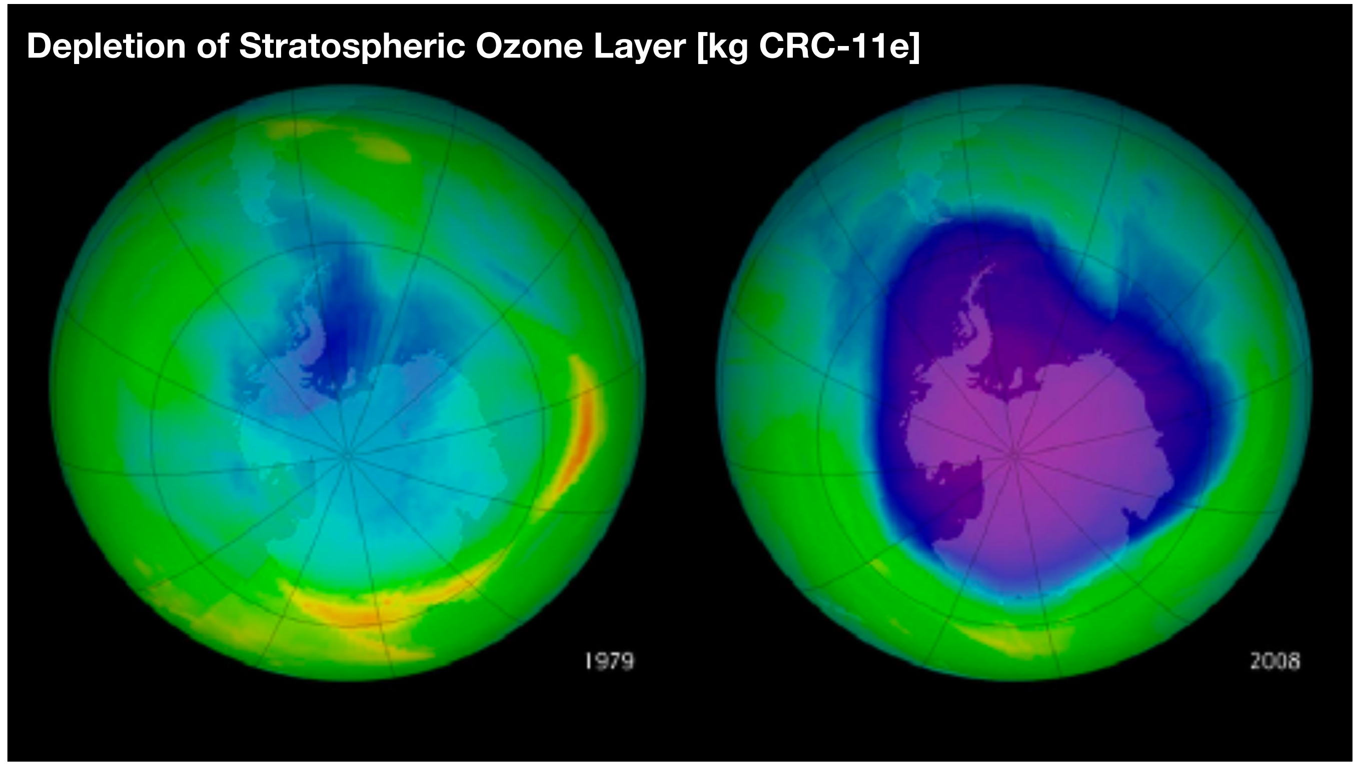
Material management accounts for more than half of greenhouse gas emissions (look at end us)

Acidification is a process of change the pH balance of water and soil. Flora and fauna have an optimal pH. One of several chemical reactions related to acidification is the combination of carbon dioxide, CO2, with water, H20, to form **carbonic acid**, H2C03. Hyrdocarbons release CO2, Sulfer and other chemicals. Other causes of acidification include Sulfur oxides (SO, SO2, SO3) Nitrous Oxides (NOx) and Ammonia (NH3). Chemicals can travel long distances before being deposited by rain, snow and fog, known as acid rain. SOx and NOx are most common for buildings (energy production/operation, manufacturing and transportation) Ammonia is common for agriculture.

Chemical emissions (including sulfur dioxide and nitrogen oxides) from sources such as coal power plant are released into the air. These chemicals are transported in the air depending on wind and climate conditions **(transport)** and often carried to ground or water bodies via rain **(fate)**. The final, or **"end-point"** environmental impact of **acid rain** includes a broad range of impacts ranging from corrosion of buildings to lack of productivity of soils. Global, GHG, Regional, Acidification, Local, Smog.

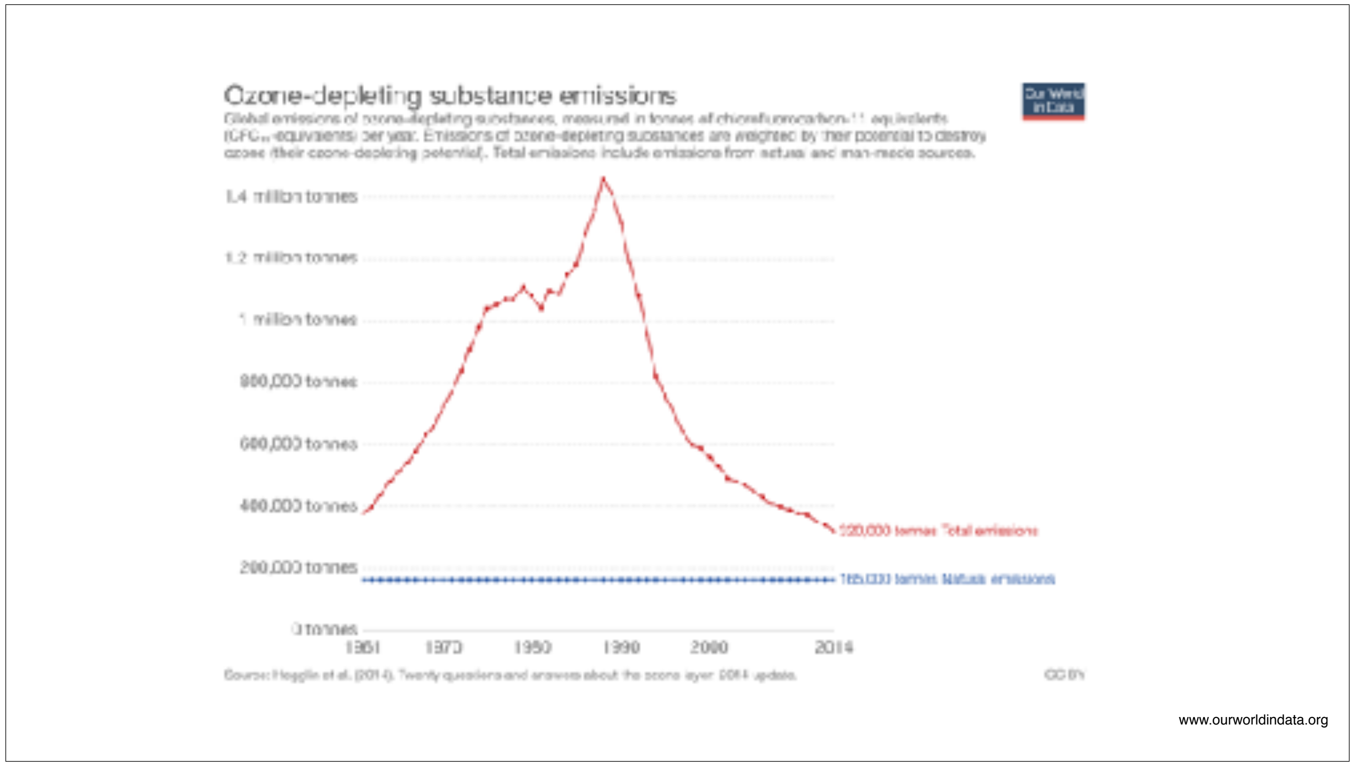
- Generally SO2 accounts for soil and water, CO2 for ocean acidification.
- LCA acidification is reported as emissions of the equivalent mass of sulfur dioxide (SO2).
- Steps for reduction include, reducing operational energy, switching from coal to natural gas, and reducing combustion from process such as cement production.

Eutrophication is excess of biological activity in an aquatic systems. Typically it is a result of the addition of nutrients, such as nitrogen. The excess plant growth, such as algae blooms, depletes available oxygen and create dead zones (and acidification)



Ozone is a gas that is present in the atmosphere and in constant flux, undergoing chemical reactions with other elements such as chlorine and oxygen. Ozone high in the atmosphere functions to protect the earth from the sun's UV Rays. Ozone low in the atmosphere is characterized as smog.

- Chlorofluorocarbons (CFCs) reacts (degrades) with energy of the sunlight and release chlorine. Chlorine breaks ozone down into oxygen.
- UN Montreal Protocol was ratified in 1987, by 2010 98 percent ozone depleting substances have been phased out.

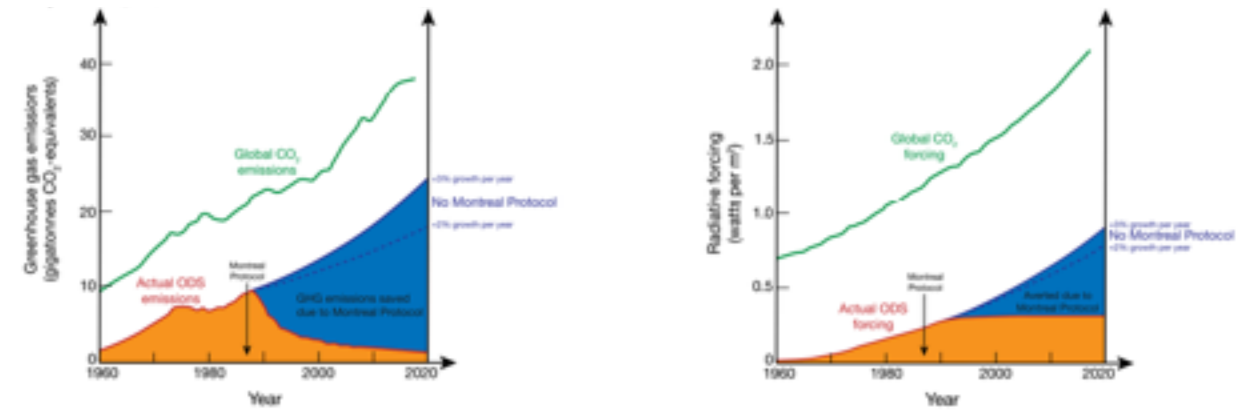


- Global emissions of ozone-depleting substances have declined by more than 98 percent since 1986 (the year before international action was agreed).
- The Montreal Protocol (and later amendments) was adopted in 1987 — since then all countries have signed on to the agreement, allowing for the dramatic decline in global ozone-depleting emissions.
- Ozone layer thickness declined, and the Antarctic ozone hole grew substantially from the 1980s through to the early 2000s. **Through the first decade this trend largely stabilized and we now see initial signs of recovery**.

- **Ozone layer depletion increases the amount of ultraviolet (UV) irradiation that reaches Earth's surface; this can increase the risk of skin cancer, particularly at higher latitudes.**

- **The global shift away from ozone-depleting substances has also had co-benefits on the reduction of greenhouse gas emissions.**

The Montreal Protocol



www.ourworldindata.org

The story of international cooperation and action on addressing ozone depletion is a positive one: the Vienna Convention was the first Convention to receive universal ratification. Over the last few decades we have seen a dramatic decline in emissions of ozone-depleting substances.

However, a 2018 study published in Nature reported "an unexpected and persistent increase in global emissions of ozone-depleting CFC-11".7 Montzka et al. (2018) reported that since 2012 there had been an unexpected increase in emissions of trichlorofluoromethane (CFC-11), a historically dominant source of ozone-depleting substances, since 2012.

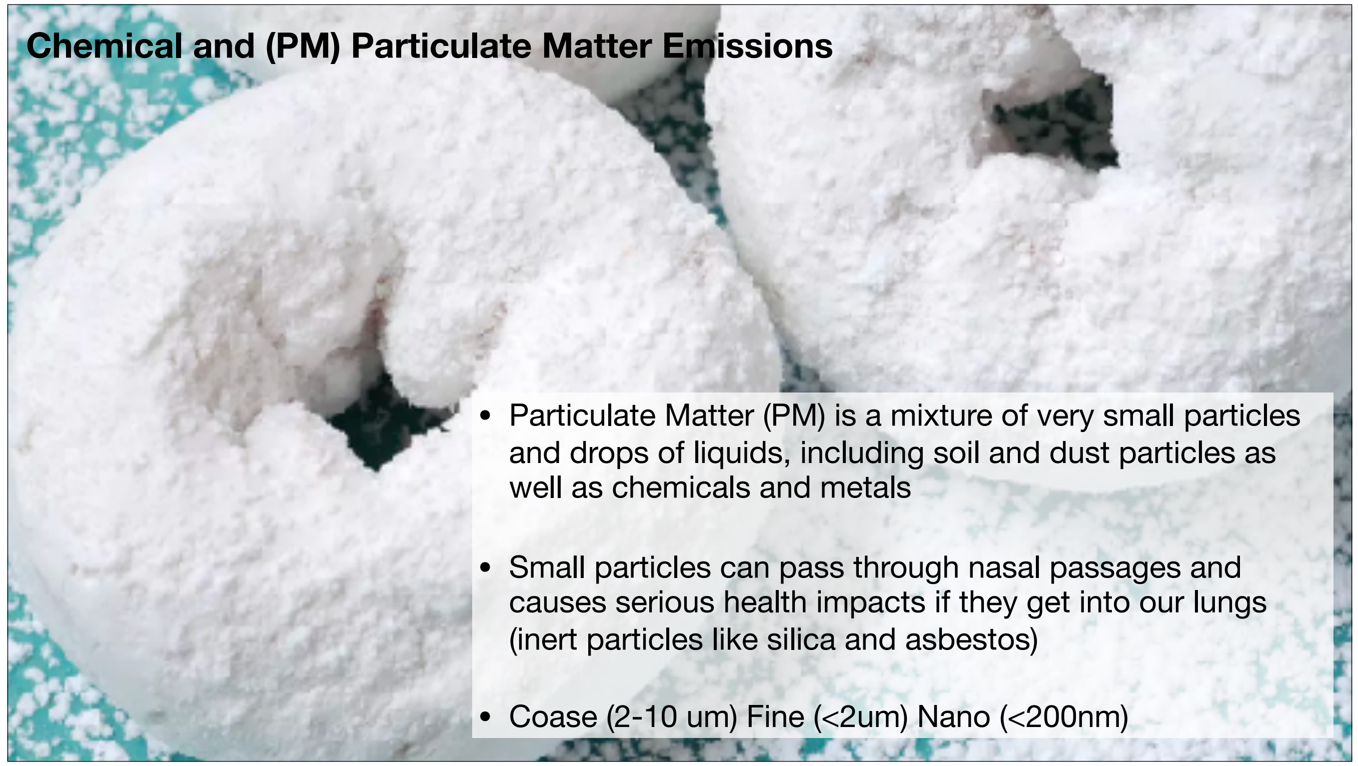
Every refrigerator and air conditioner contains chemical refrigerants that absorb and release heat to enable chilling. Refrigerants, specifically Chlorofluorocarbons (CFCs) and HCFCs, were once culprits in depleting the ozone layer. Thanks to the 1987 Montreal Protocol, they have been phased out. Hydrofluorocarbons (HFC), the primary replacement, spare the ozone layer, but have 1,000 to 10,000 times greater capacity to warm the atmosphere than carbon dioxide.

In October 2016, officials from more than 170 countries met in Kigali, Rwanda, to negotiate a deal to address this problem. Through an amendment to the Montreal Protocol, the world will phase out HFCs—starting with high-income countries in 2019, then some low-income countries in 2024 and others in 2028. Substitutes are already on the market, including natural refrigerants such as propane and ammonium.

Scientists estimate the Kigali accord will reduce global warming by nearly one degree Fahrenheit. Still, the bank of HFCs will grow substantially before all countries halt their use. Because 90 percent of refrigerant emissions happen at end of life, effective disposal of those currently in circulation is essential. After being carefully removed and stored, refrigerants can be purified for reuse or transformed into other chemicals that do not cause warming.

Ground level Ozone (Smog) is a significant threat to human health, causing irritation of respiratory systems, reduced lung function, aggravation of asthma, and potential long term lung damage.

- Major source of smog is SO2 and NO2 emissions related to fossil fuel combustion and the release of VOCs (Volatile Organic Chemicals)
- Volatile Organic Compounds, Volatile meaning they boil at room temperature, evaporate and become air born causing irritation to cancer.
- <u>Building materials such as paints and solvent and building maintenance products release VOCs</u>
- 1000 other gases contribute…
- Smog is a local condition, Why LA and Mexico City?



Canadian hockey and donuts around 2015

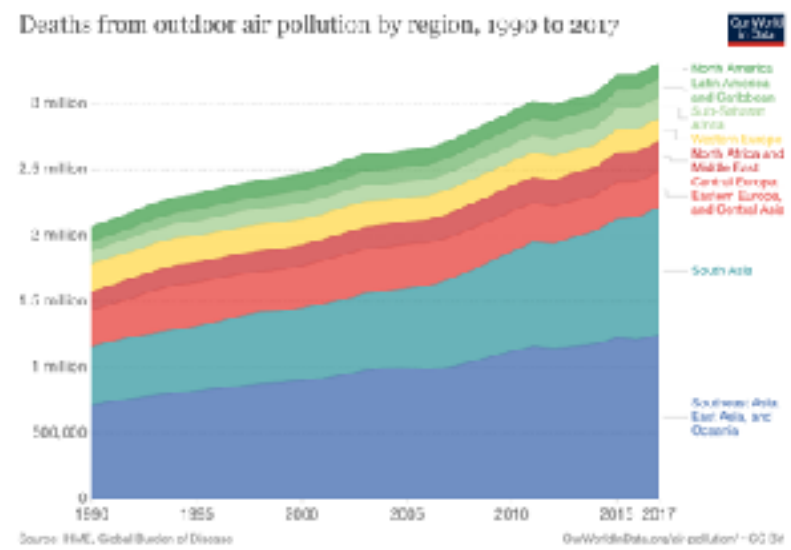
Titanium dioxide (which isn't the same thing as the metal titanium) is an inert, insoluble material that's used as a whitener in everything from paper and paint to plastics. It's the active ingredient in many mineral-based sunscreens. And as a pigment, is also used to make food products look more appealing.

And you've probably been consuming it for years without knowing. In the US, the Food and Drug Administration allows food products to contain up to 1% food-grade titanium dioxide without the need to include it on the ingredient label. Help yourself to a slice of bread, a bar of chocolate, a spoonful of mayonnaise or a donut, and chances are you'll be eating a small amount of the substance.

For some years now, researchers have recognized that some powders become more toxic the smaller the individual particles are, and titanium dioxide is no exception. Pigment grade titanium dioxide – the stuff typically used in consumer products and food – contains particles around 200 nanometers in diameter, or around one five hundredth the width of a human hair. Inhale large quantities of these titanium dioxide particles and your lungs would begin to feel it…

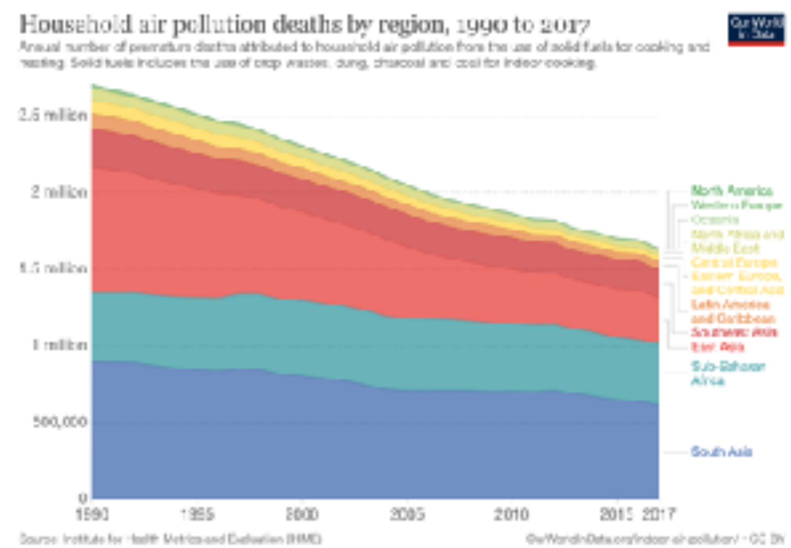
Dunkin' donuts pulled Titanium Dioxide from its products…but the jury is still out on its true health effects… https://theconversation.com/dunkin-donuts-ditches-titanium-dioxide-but-is-it-actually-harmful-38627

Chemical and (PM) Particulate Matter Emissions



Air pollution: An estimated **five million people die prematurely every year** as a result of air pollution; fossil fuels and biomass burning are responsible for most of those deaths (respiratory, pulmonary, cardiovascular, etc)

Chemical and (PM) Particulate Matter Emissions



Air pollution: An estimated **five million people die prematurely every year** as a result of air pollution; fossil fuels and biomass burning are responsible for most of those deaths (respiratory, pulmonary, cardiovascular, etc).

Why 3 billion people continue to cook over open biomass burning fires.

2-5% of global greenhouse gas emissions

Global Alliance for Clean Cookstoves

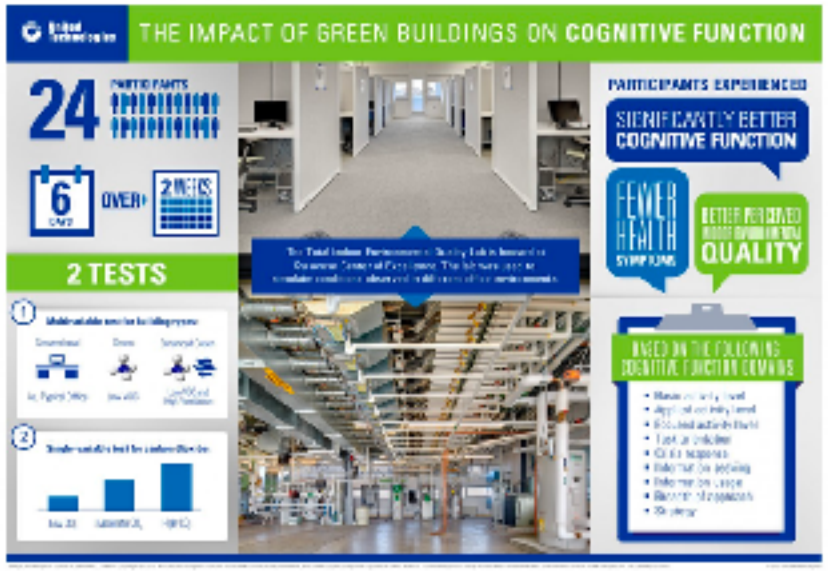
Chemical and (PM) Particulate Matter Emissions can have wide ranging impacts on human health, causing and aggravating diseases such as asthma, heart disease, low birth rate and cancer.

- Particulate Matter (PM) is a mixture of very small particles and drops of liquids, including soil and dust particles as well as chemicals and metals
- Small particles can pass through nasal paddles and causes serious health impacts if they get into our lungs (inert particles like silica and asbestos)
- Coase (2-10 um) fine (<2um)
- Methodologies are being developed to classify and quantify UNEP and SETAC developed Comparative Toxic Units (CTUh), which is equal to disease cases per kg emitted.
- There is large uncertainty on predicting health risks and little consensus on which material should be included on list of ‘chemicals of concern’
- Two orgs. Living Building Challenge and Health Product Declaration (HPD) Collaborative have developed methods for transparency.
- LBC has the ‘red list’ of chemicals that should be avoided for building products, HPD has the ‘priority Hazard list’
- https://living-future.org/declare/declare-about/red-list/#red-list-cas-guide

Volatile organic compounds (VOCs) are organic chemicals that have a high vapor pressure at ordinary room temperature. Their high vapor pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air, a trait known as volatility. For example, formaldehyde, which evaporates from paint and releases from materials like resin, has a boiling point of only –19 °C (–2 °F).

These can cause:
Astham
Itchy Eye
Sneezing and Runny Nose
Headaches
Kidney Damage
Elevated Blood Pressure

CO_2 and Cognitive Health



Allen JG, et al. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. Environ Health Perspect 2016.

Joe Allen HSPH

We simulated indoor environmental quality (IEQ) conditions in “Green” and “Conventional” buildings and evaluated the impacts on an objective measure of human performance: higher-order cognitive function.

Twenty-four participants spent 6 full work days (0900–1700 hours) in an environmentally controlled office space, blinded to test conditions. On different days, they were exposed to IEQ conditions representative of Conventional [high concentrations of volatile organic compounds (VOCs)] and Green (low concentrations of VOCs) office buildings in the United States. Additional conditions simulated a Green building with a high outdoor air ventilation rate (labeled Green+) and artificially elevated carbon dioxide (CO2) levels independent of ventilation.

For example, High levels of CO2 were 1400 ppm, Middle were 900ppm, and low where 400-500ppm (lethal at 100,000ppm)

On average, cognitive scores were 61% higher on the Green building days (low VOC) and 101% higher on Green+ building days (low VOC and low CO2) than on the Conventional building day ($p < 0.0001$). VOCs and CO2 were independently associated with cognitive scores.

Consumption of Freshwater can be tracked as an inventory with LCA or developed as a "water footprint."

- Only 2.5% of water is 'fresh' and much of this water is tied up in ice and ground water
- Local scarcity is not included in both assessments.
- Water footprint divides water into blue (fresh surface or ground water), green (precipitation on land), and grey (volume required to dilute pollutants).
- **LCA reports blue water consumption (1) water evaporates (2) is incorporating into products (3) not returned to source (4) not returned during the same period, dry to wet season.**
- Building consume water for irrigation, groundwater or utility water use during manufacturing, incorporated into products (concrete) and operational (blue, grey, black)
- **LCA does a poor job on water,** not all LCA include water for energy production (boiler), desalination, etc.
- Some methods suggest weighted reporting based on scarcity, but this is subjective and not static.
- Other methods suggest evaluating damage to human health, ecosystem quality, and resources.

Waste generation, evaluating environmental impact maybe uncertain, but calculating quantities of waste is straight forward (kg)

- Waste is reported as non-hazardous, hazardous, or radioactive.
- Not perfectly clear, fly ash is produced by the combustion of coal, it can be a waste product or by product…Ashphalt is by product of refining petroleum
- Radioactive materials…coal, oil and gas industries, metal mining and smelting, mineral sands, fertilizer industry, buildings (granite) recycling and naturally occurring such as Radon.
- Energy recovery are materials that have reached the end-of-waste state and are used in an energy recover process with an energy efficiency rate higher than 60%.
- Combustion has limited efficiency, about 50%, then 35% for making electricity, plus the environmental impacts.

A stream is no longer waste when:
- It is (commonly) used for a purpose
- There is an existing market or demand
- It fulfills technical requirements and standards
- It will not lead to adverse effects

Re-use and Recycling capture quantities (kg) of materials available for complete life cycle products compare to waste.

- Re-use may include crushed concrete for railroad beds with lower performance **(down cycle)**
- Recycle may include scrap metal for rebar manufacturing with higher performance **(up cycle)**
- Metals are easy to separate and therefore easy to recycle (density, magnetic and electrical properties, color)
- Polymers not so much…only about 60% the value of virgin materials.
- <u>LCA needs to be what is actually recycled not the potential…</u>
- Recycling can be closed loop or open loop.
- **Closed loop** recycling can be a closed loop within a manufacture, recycling scrap, or open loop, steel being recycled to steel. This may also be referred to as pre-consumer.
- **Open loop** occurs when materials properties change for the next application (tires to floors) This may also be referred to as post-consumer.
- **Recycle Content Method** focuses benefit on the use of recycled material in products stage (again, pre-consumer).
- **End-of-life Approach** Focuses on how much material can be recycled at the end of a product cycle and thus replaces the need for the production of primary material. (again, post-consumer).

Recycle content method

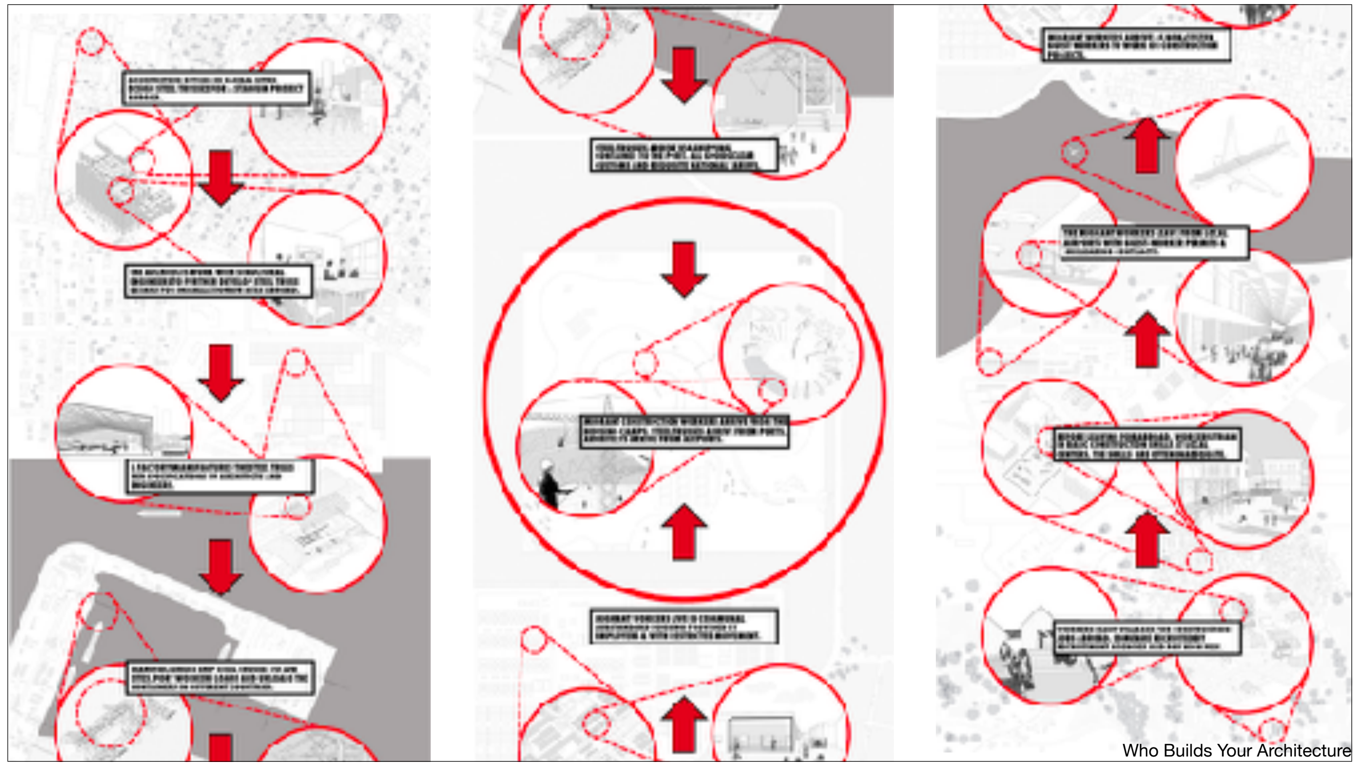
- **focuses benefit on the use of recycled material in products stage**
- Assigns impacts from extraction, refining, manufacturing, and demolition of the recycled material to the first use of the material.
- The impact from transportation, processing and re-use of the recycle material are assigned to the second product.
- Recycling at end of life is not modeled as the end-of-life impacts of disposing materials are negligible and no credit is given for the amount of metal recycled.
- Thus the recycling rates of a product will not impact the LCA results.
- The recycle material is outside the system boundary of the next product.
- **This method would favor the use of recycled material and would to a focus on increasing these of recycle materials and would useful in promoting recycled materials.**
- **Mining and metals states that metal recycling is economical and the market is mature and thus a policy to reward recycling is not necessary and might not result in improved performance.**

End-of-life Approach

- **Focuses on how much material can be recycled at the end of a product cycle and thus replaces the need for the production of primary material.**
- The avoided production of primary material is then credited to the system at the end-of-life stage for products that result in recyclable material.
- This expands the system boundary to include the avoided production processes to credit the process creates the recycled materials.
- **This would reward highly recyclable materials and not directly incentives the use of recycled material.**
- **Mining and metals states that it encourages manufactures, policy-makers and other decision-makers to evaluate real performance and improve the design and management of products including their disposal and recycling**

Scrap has economic value: No need to create demand;
Quantity recycled is driven by end-of-life recycling rates:
Demand for scrap exceeds the availability

*Only 9 percent of the total plastic we produce has been recycled


Who Builds Your Architecture

<u>Not just "how much does your building weigh" but "who builds your architecture"</u>

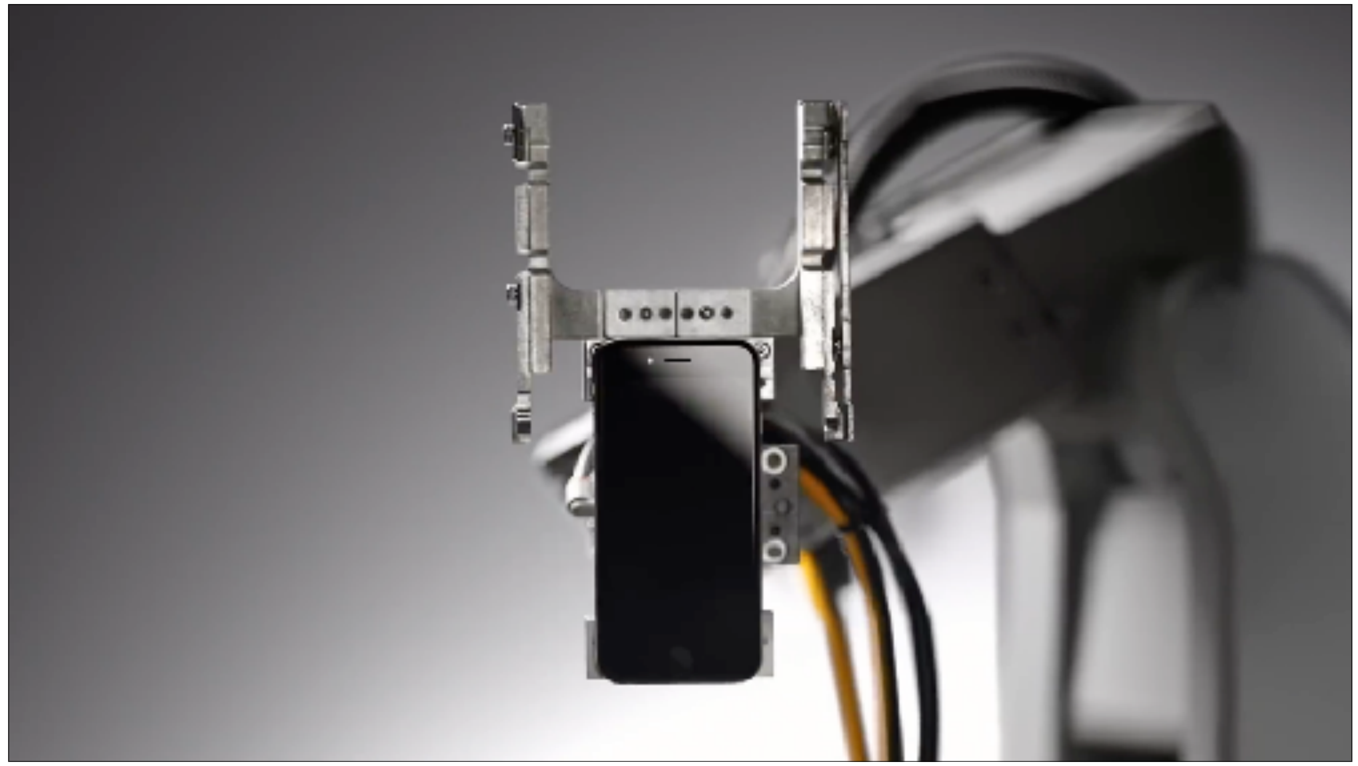
LCA does not factor human impact….does architecture?

Social LCA does

Who Builds Your Architecture? http://whobuilds.org/

From WBYA…

"WBYA? is a coalition of architects, activists, scholars, and educators that tackles the pressing question: who builds your architecture? to examine the links between labor, architecture and the global networks that form around building buildings. **As major architectural projects unfold in the Middle East, Asia, Africa and around the globe, and as architects from the US increasingly work abroad, we explore the ethical, social and political questions that emerge under these relatively new circumstances**. From workers' rights to construction practices to design processes to new technologies WBYA? investigates the role of architecture and architects: what it is and what it could be.



Rapid turnover in products, single use, and laminate design are all recent phenomenon. Products where once passed on, furniture, wristwatch, pens.

Today, imagine the gift of getting your mothers old IPhone.

But life span is more involved. Life span is based on the physical life, functional life, technological life, economical life, legal life, and loss of desirability…and fashion (fashion drove abidance of cotton in the industrial revolution, why stop now).

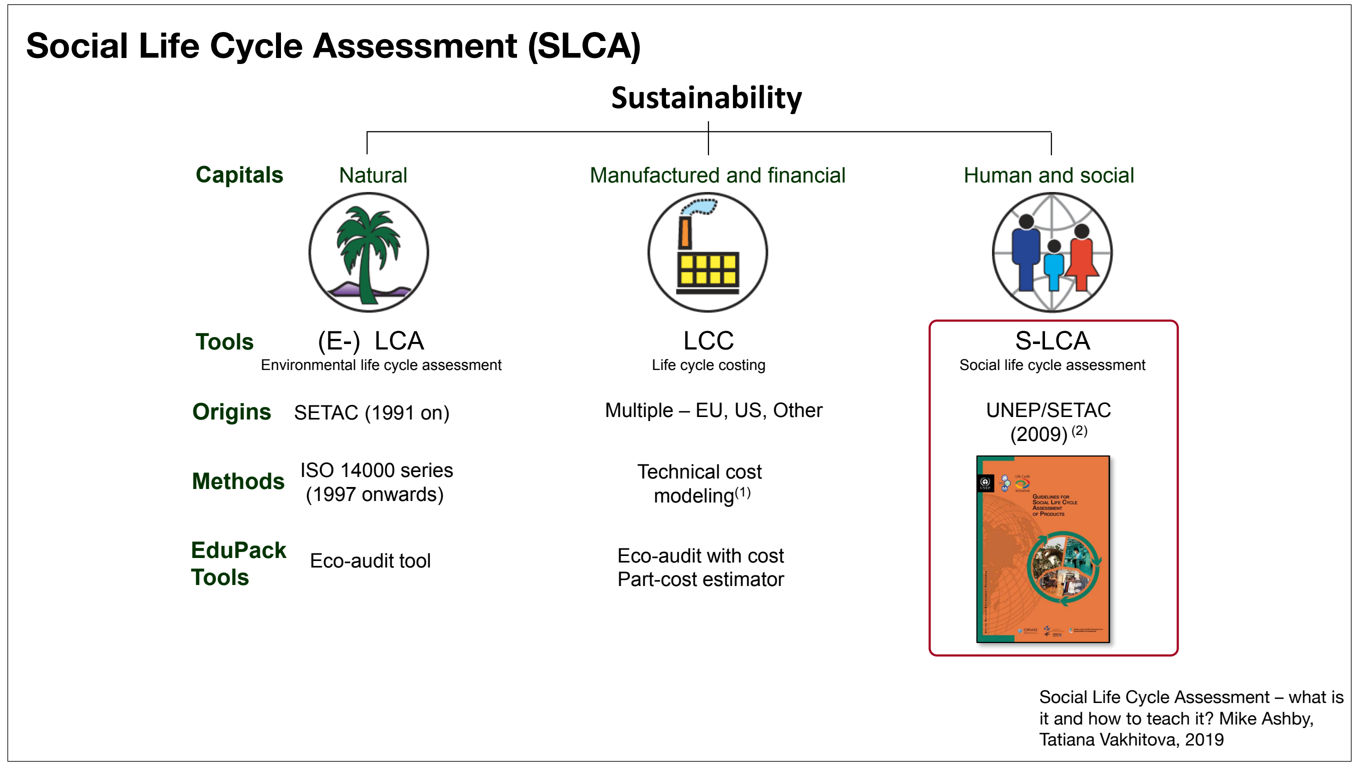
Green washing?

Environmental Justice

End-of-life has incredible environmental, social and health impacts.

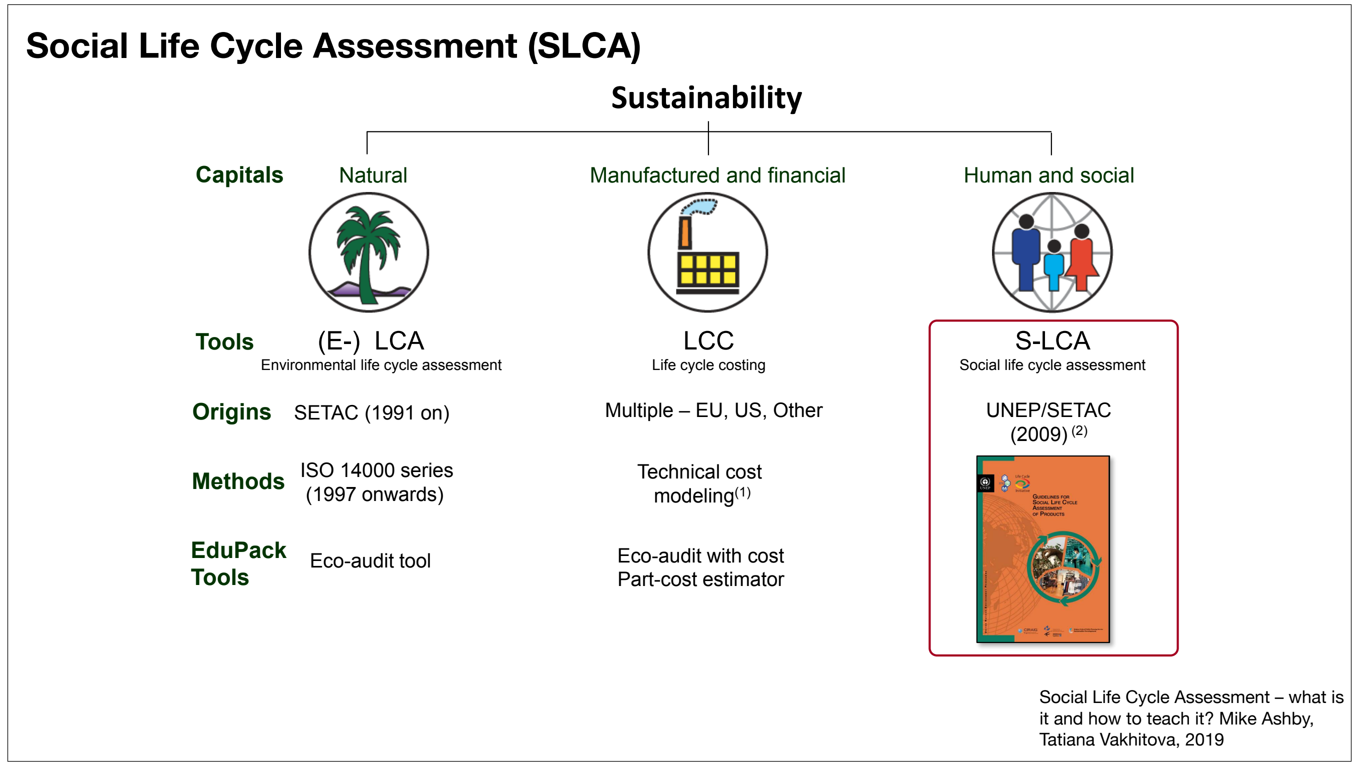
The global north is extremely efficient at exporting waste.

Your product is not done in the dumpster!



From Granta: Products provide practical utility: shelter, transport, protection and comfort, for example. They also carry social utility: prestige, status, convenience, cultural associations and reassurance. But product development processes can also be environmentally and economically damaging and can harm human well-being through unfair practices, poor working conditions and failure to respect human rights. **Social life-cycle assessment (S-LCA) aims to assess the possible social impacts of products over their life.** Materials play a big part in this. **Ores and feedstock are frequently sourced from resource-rich but economically poor nations. Manufacture may take place under conditions that could be made socially more acceptable. Disposal at the end of life may disadvantage communities that lack proper facilities to deal with it.**

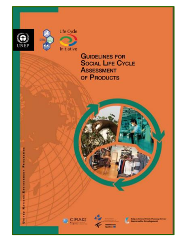
The UN Environment Program (UNEP) / Society of Environmental Toxicology and Chemistry (SETEC) Report [1] “Guidelines for Social Life Cycle Assessment of Products” lays out a widely-accepted framework for S-LCA. Our tool introduces students to the method and provides the data needed to carry out assessments. The sources of all the data are via links within the tool. The output is a list of Social hotspots.



S-LCA is a management tool. **It draws attention to aspects of product life that might potentially harm human welfare and prompts interventions which might improve the well-being of the individuals and communities.** Proponents see it as contributing to the following activities:

- Understanding the social aspects of material choice
- Providing an overview for due diligence in setting up supply chains or manufacturing routes
- Informing decision-making in product development and establishing material supply chains
- Funnelling social investment in community projects
- Comparison of different options for products and services
- Comparison and bench-marking of suppliers
- As a basis for certification and labelling
- As input to Corporate Sustainability Reporting
- Marketing and communication

Social Life Cycle Assessment (SLCA)



S-LCA adapts
LCA methods

- **Five Stakeholder groups**
  - S1 Workers
  - S2 Consumers
  - S3 Local community
  - S4 Society
  - S5 Value-chain actors
- **31 Impact categories - *examples***
  - Human rights, equity
  - Health and safety
  - Social support / Benefits
  - *(more)*
- **Data inventory**
  - At National level – national statistics
  - At Enterprise level – requires on-site data-gathering
- **Impact assessment**
  - Identify "social hot-spots"
  - Options for actions

Where can do something?

Social Life Cycle Assessment – what is it and how to teach it? Mike Ashby, Tatiana Vakhitova, 2019

Goal of SLCA: To improve social conditions and socio-economic performance associated with a product throughout its life.

Social Hotspot: Point of contact between stakeholders and aspects of the materials, manufacture, distribution and use of the product that may, potentially, be damaging or could be influenced in a positive way.

As far back as 1991, Imperial Oil the Canadian arm of Exxon Mobil Corp.'s empire anticipated that a high tax on carbon emissions would be necessary to maintain a stable climate, newly released documents show….

An April 1991 memo that then-chief executive A.R. Haynes signed showed it would take a tax of "\$55 per tonne of CO2" for Canada "to stabilize CO2 emissions," roughly the equivalent of \$88.50 in today's Canadian dollars. In United States dollars, that translates to about \$41 per metric ton in 1991, or \$78 per metric ton in 2019 — far higher than anything either country has considered.

Compare that to the leading carbon tax proposal in the 1990s, which called for a price of about \$2.5 per ton. The \$78 per ton tax was even higher than the roughly \$40 per ton carbon price the Obama administration considered and that Exxon Mobil endorsed as part of an ill-fated effort led by a handful of Republican elder statesmen in 2017.

Today…A bill backed by dozens of Democrats and one Republican in Congress would impose a \$15 per ton carbon tax that increases by between \$10 and \$15 each year and could top \$100 per ton by 2030.

Other proposals project the need for a much higher price. In October, the International Monetary Fund called for a \$75 per ton carbon tax by 2030. That same month, Wagner published a study in the Proceedings of the National Academy of Sciences that pegged the price at something closer to \$100 per ton, and probably more.

The median value of carbon dioxide emissions' cost to society in a September 2018 paper published in Nature was **\$400 per ton.**

https://www.huffpost.com/entry/exxon-imperial-oil-carbon-tax_n_5de5b57de4b0913e6f84120f

Thoughts?

LCA Strengths

Quantifiable: Quantifiable method to evaluate environmental impacts: LCA standards provide guidance on how to develop comprehensive and systematic evaluation

Comparable: If framed correctly LCA results can be used to compare design options

Comprehensive: LCA can track impacts thought the supply chain and whole building life cycle

Indicative: provides insight to manufactures and consumer looking for improvements and to identify trade-offs

Motivational: Quantifiable data provide motive to manufactures and consumers to improve

Avoids Green-Washing: Quantifiable data minimizing claims such as greener or low impact

New: LCA is emerging discipline and its integration into building design, construction, and manufacturing practices is likely to develop quickly in the near future.

LCA Weaknesses

Time-consuming: LCA Requires knowledge of the product and processes, time to assemble the data, access to LCI database and expertise in evaluating results. Little research has been done on establishing a cost-benefit ratio for LCA.

Incomplete: Global and regional impacts related to emission from fuel combustion are easier to track than local impacts such as habitat disruption or indoor air quality…Social and economic impacts of sustainability are not yet considered or standardized

Incomplete Data: Data sets exist for certain locations, when data is missing proxy data is used.

Requires Judgement: Many aspects of LCA require human judgment: What to include, what data to use, how to model recycling, etc.

Uncertain: Full cradle-to-grave LCA requires developing scenarios to outline the use and end of life phases—we don't actually know what will happen in the future.

Faulty Precision: Data is based on industry averages, yet report data to four decimal points. Users can be misled to believe that the results are precise. LCA studies are best used to compare within consistently structured analysis and less relevant when comparing across studies with different assumptions, different data sources and different methods

Disguises Green-Washing: LCA can be reported based on undocumented or unusual methods.

That’s a lot of work. Can’t we just learn from these studies and…

Focus on CO_2

Consume less operational energy

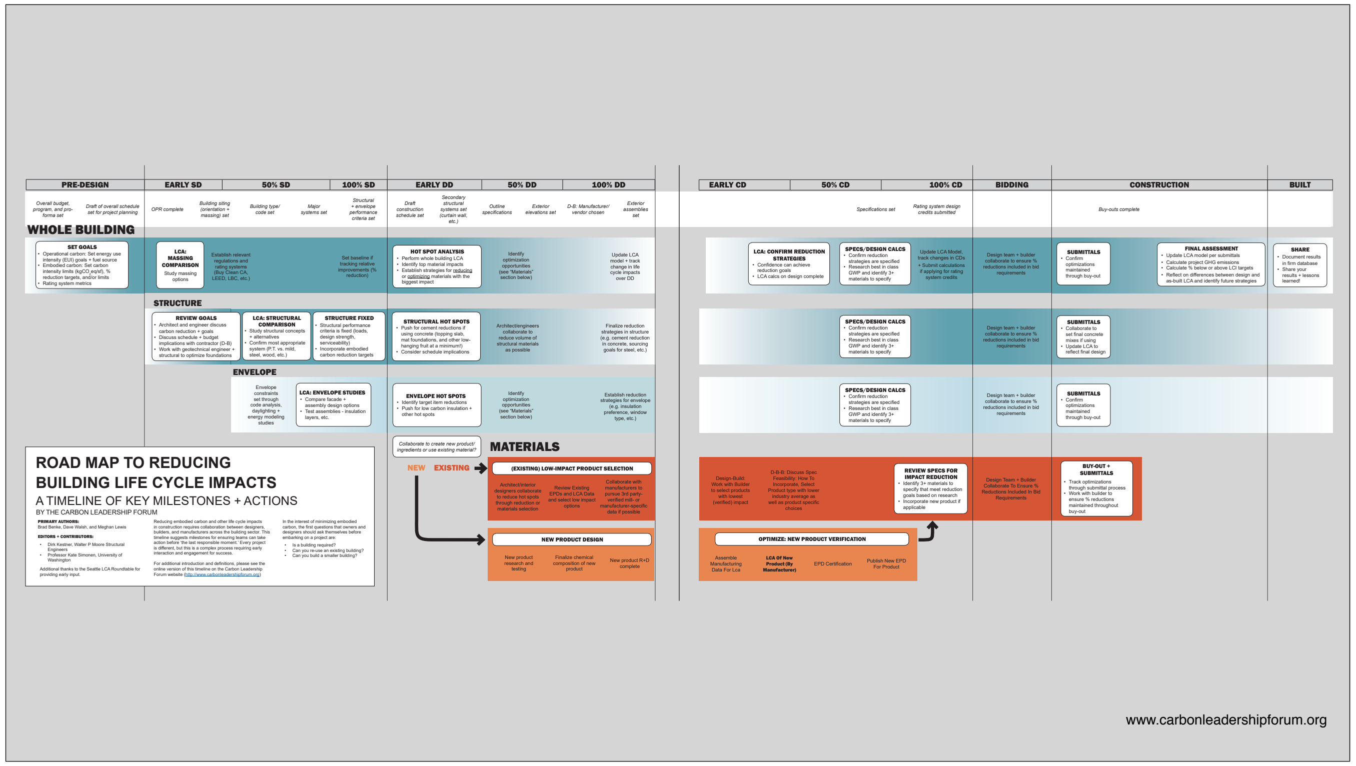
Build smaller buildings

Re-use existing buildings and materials (We build only 1-3% a year, think about the other 99%)

Design efficient structural systems

Design for the right longevity of materials and buildings, this mean short pulses too!

Design buildings as carbon sinks, such as wood products from sustainably managed forests



More resources at Carbon leadership forum

https://carbonleadershipforum.org/projects/lca-practice-guide/