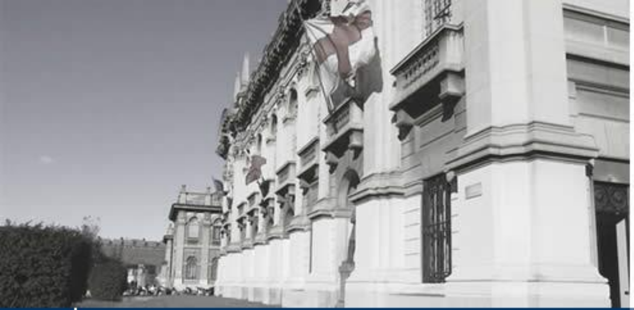


School of Industrial and Information Engineering

Course 096125 (095857)

Introduction to Green and Sustainable Chemistry

POLITECNICO DI MILANO

Sustainability of Human Activities.

Prof. Attilio Citterio

Dipartimento CMIC “Giulio Natta”

https://iscamapweb.chem.polimi.it/citterio/it/education/course-topics/

Sustainability is a crucial parte of present and future technology:

'… *Sustainable development seeks to meet the needs and aspirations of the present, without compromising the ability to meet those of the future*.'

Brundtland Commission, UN Earth Summit 1992
Rio de Janeiro, Brazil

- Materials from the earths crust (e.g. heavy metals) must not systematically increase in nature
- Persistent substances produced by society (DDT, CFC's) must not systematically increase
- The physical basis for earth's productive natural cycles must not be systematically deteriorated
- There must be fair and efficient use of resources with respect to meeting human needs

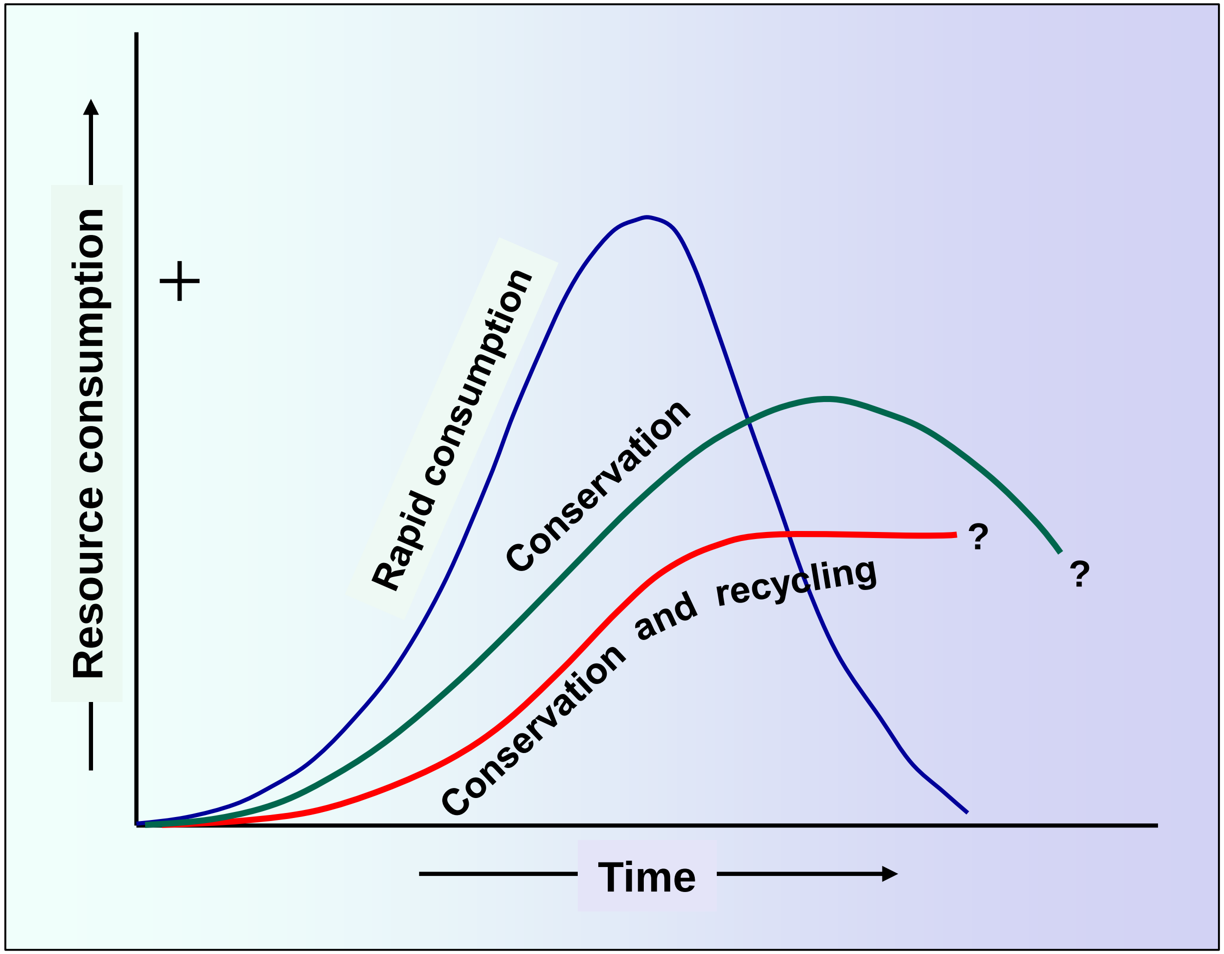
The Natural Step (Sweden)

Resources: Definitions.

- A ***resource*** is a naturally occurring substance which is currently, or potentially, economically extractable
- An ***ore*** is an economically recoverable mineral deposit.
- A ***reserve*** is the total amount of known ore.
- A **biomass** is any biological organism (living or dead)

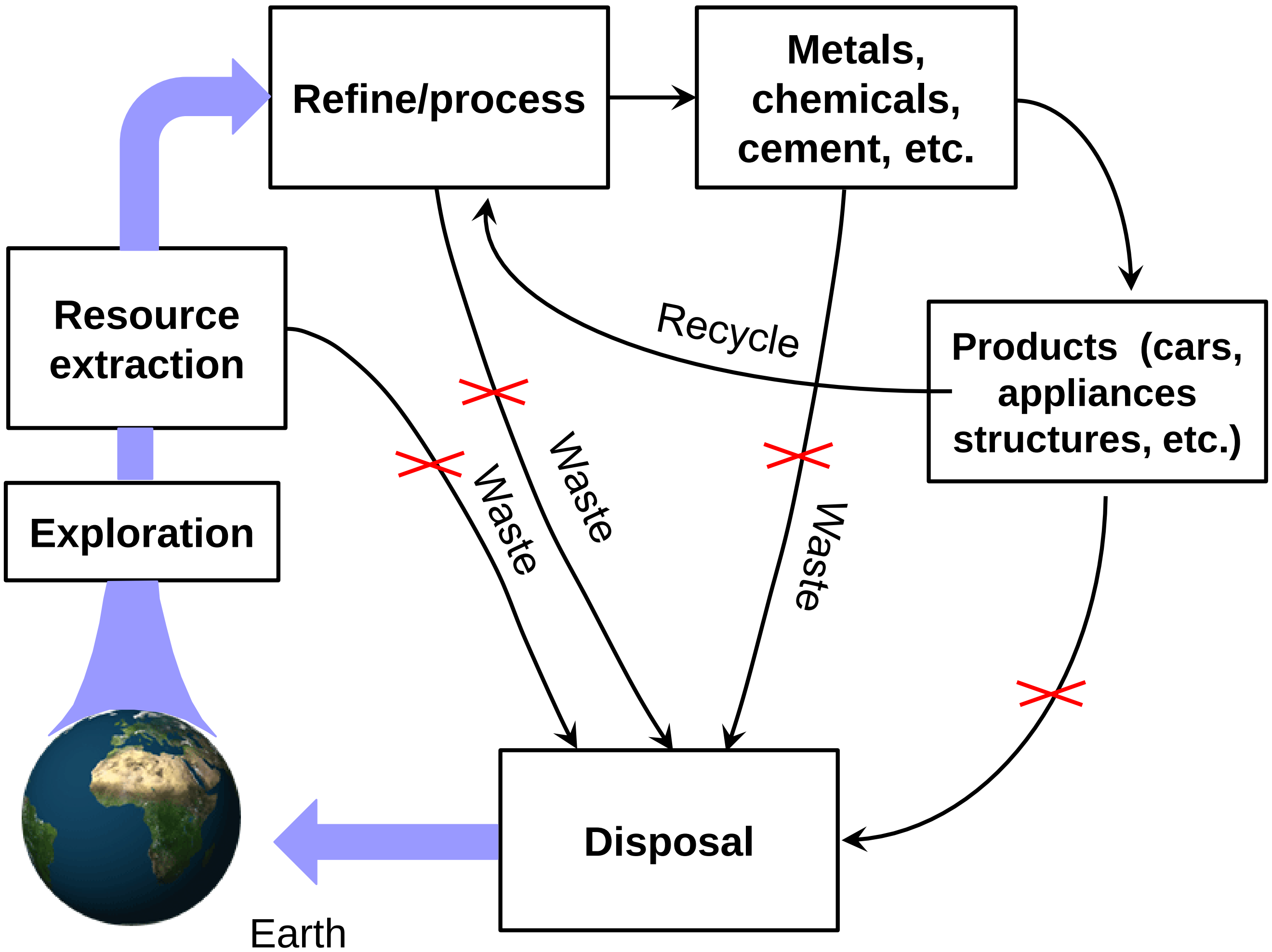
- ***Non-renewable*** refers to substances that are available in fixed quantities that are not naturally replenished on short timescales (from the anthropogenic perspective)
  - Minerals and Metals
  - Fossil Fuels (coal, natural gas, oil)

Resource Consumption Curves.



Resource consumption can be sustainable

Resource Cycle.



The Tragedy of Commons.

G. Hardin (Univ. California, S. Barbara) published (1968) in *Science* the Article: *The Tragedy of Commons*

- "perfect freedom of action in activities that adversely influenced commons properties was eventually doomed to failure".

Local commons

- Example 1: free pasture area where each herdsman, seeking to maximize his financial well-being, independently conclude that he should add animals to his herd. This will destroy the pasture by overgrazing and disaster will strikes all.
- Example 2: At low level of traffic density, the convenience for all individuals to drive private automobiles, At some critical densities, however, the road network of commons is incapable of dealing with the traffic and a smallest disruption dooms drivers to idleness.

Global commons

- Example 3: Local alteration of hydrosphere and atmosphere are easily reversible, but a global alteration can injure all. *Much of society's functions are embodied in human actions (industry) involving the transformation of materials and energy (common-pool resources).*

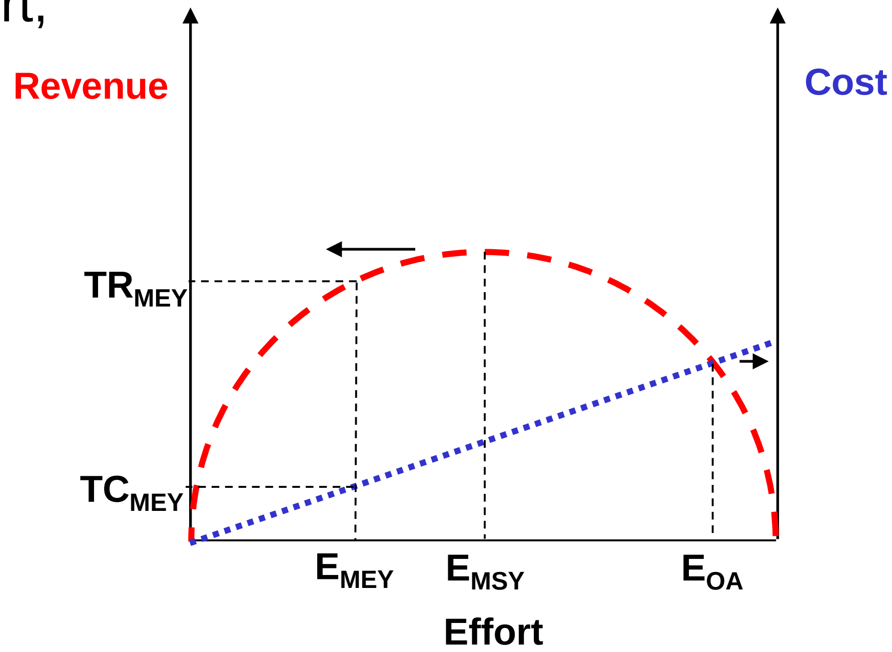
Concerns for Common Resources.

The common (global) resources are object of attention in the *industrial ecology* and in *sustainable engineering* because the limited availability of these resources can adversely influence the progresses due to modern technology.

Example:

The relationship among fishing effort, cost, and revenues.

- TR = total revenue
- E = level of fishing effort
- MEY = max. economic yield
- MSY = max. sustainable yield
- OA = open access



"The Question of the Commons" B.J. McCay and J.A. Acheson Eds. Tucson , 311-326, 1987

Global Sustainable Limiting Rate of Land Productivity.

Land type	Equivalence factor	Biocapacity 1 (hectare/person)	Biocapacity 2 (acre/person)
Arable (crops)	2.2	0.51	1.31
Pasture	0.5	0.26	0.67
Forest	1.3	0.83	2.12
Built-up	2.2	0.10	0.25
Sea	0.4	0.15	0.35
	Total:	1.84 hectares per person	4.7 acres per person

If we divide the total productive surface on the earth by the population, we arrive at about 1.84 hectares per person. Anybody who uses more is either depriving someone else or contributing to irreversible damage on Earth.

Footprints of individuals, groups and even nations have been calculated. A finding is that the wealthier the group, the larger the footprint. This is because wealth and consumption are closely related. The general rule is that people in industrialized nations consume 5 to 10 times more than people in poor countries.

Note that human creativity could be taken into account by adjustment of the equivalence factors: An invention that increases productivity raises the corresponding factor.

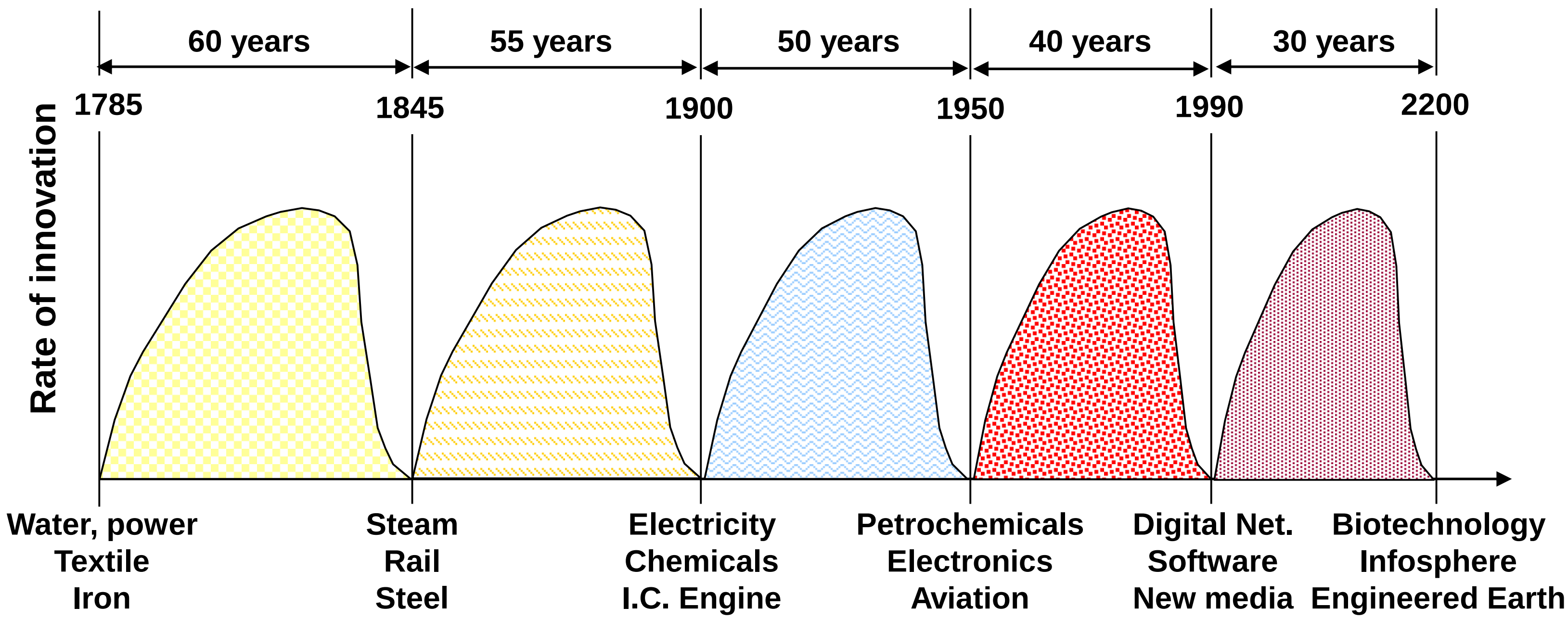
Use of Energy and Materials under Socio-Ecological Regimes in World History.

	per capita annual use Energy	 Material
Basic human metabolism (biomass intake by nutrition)	3.5 GJ	1 t
Hunter-gatherers (uncontrolled solar energy use)	10-20 GJ	2-3 t
Agrarian societies (controlled solar energy use)	60-80 GJ	4-5 t
Industrial/Technological society (fossil energy use)	250 GJ	20-22 t

Technological Evolution.

Technological evolution proceeds generally cyclically in two ways:

1) Incremental, marked by small improvements and changes in existing products or systems that improve the quality of life without changing economic, cultural and natural systems
2) Transformative, new “transformative technologies” change profoundly the technological landscape.



The Fundamental Equation.

An useful way to focus the most efficient answer that society con provide to environmental safety and to social stress is to examine the main factors involved in the generation of those stress.

Fundamental Equation: ***(IPAT = C·r·a$_p$)***

$$\text{Environmnetal Impact} = \text{Population} \times \frac{\text{GDP}}{\text{person}} \times \frac{\text{Environmental Impact}}{\text{GDP unit}}$$

Population dimension

(persons N°)

Average Pro-capite consumption

(Res. unit/ persons)

Resource consumed per unit of consumption

(Pol. unit/ Res. unit)

GDP = gross national product (measures the economic and industrial activity)

Trend vs. Time of Resources/Population/Food/Pollution.

Control of decay:

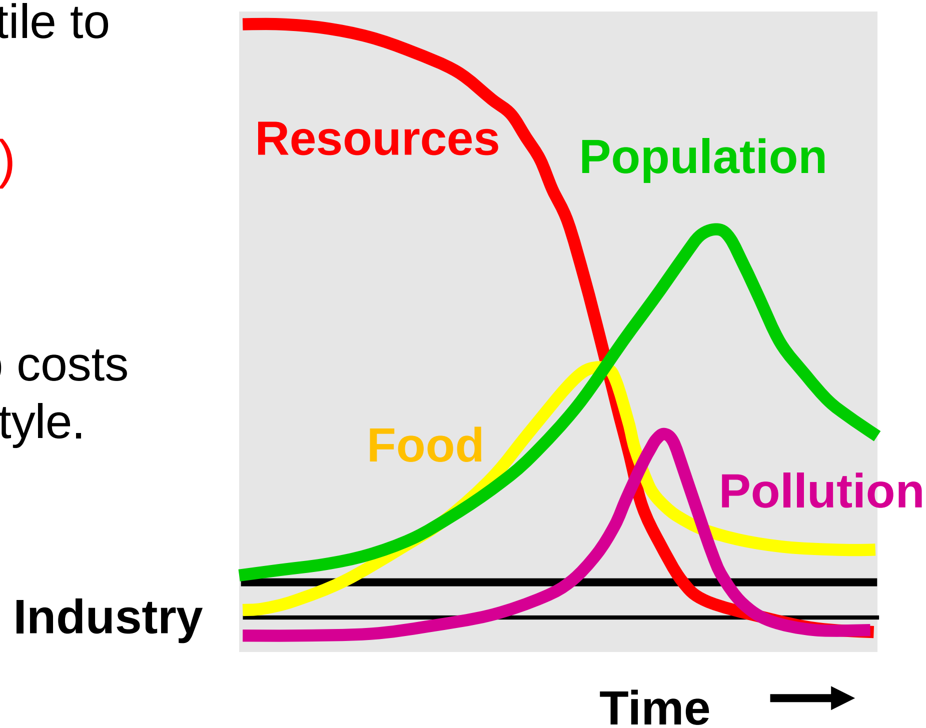
- Reduce the population (C ↓)
  - "Relocate or die"
- Reduce the consumption (r ↓)
  - But! People is normally hostile to change its life style
- Increase the efficiency (a_p ↓)
  - Obtained with technological improvements
  - People can agree to adsorb costs in order to maintain its life style.

(*IPAT* = $C \cdot r \cdot a_p$)

$$P = P_0 e^{Rt}$$ Population growth*

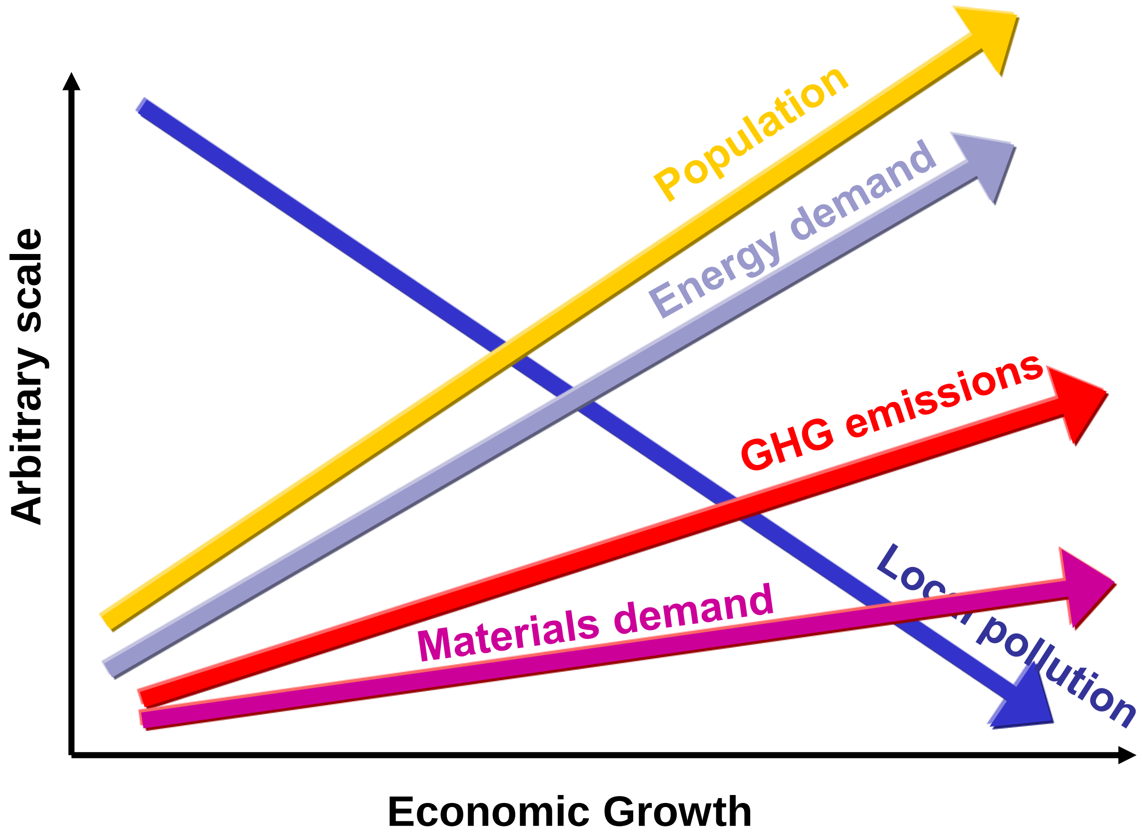
$$R = [R_b - R_d] + [R_i - R_e]$$

Subscripts refer to birth, death, immigration and emigration



*Model: exponential growth/decay

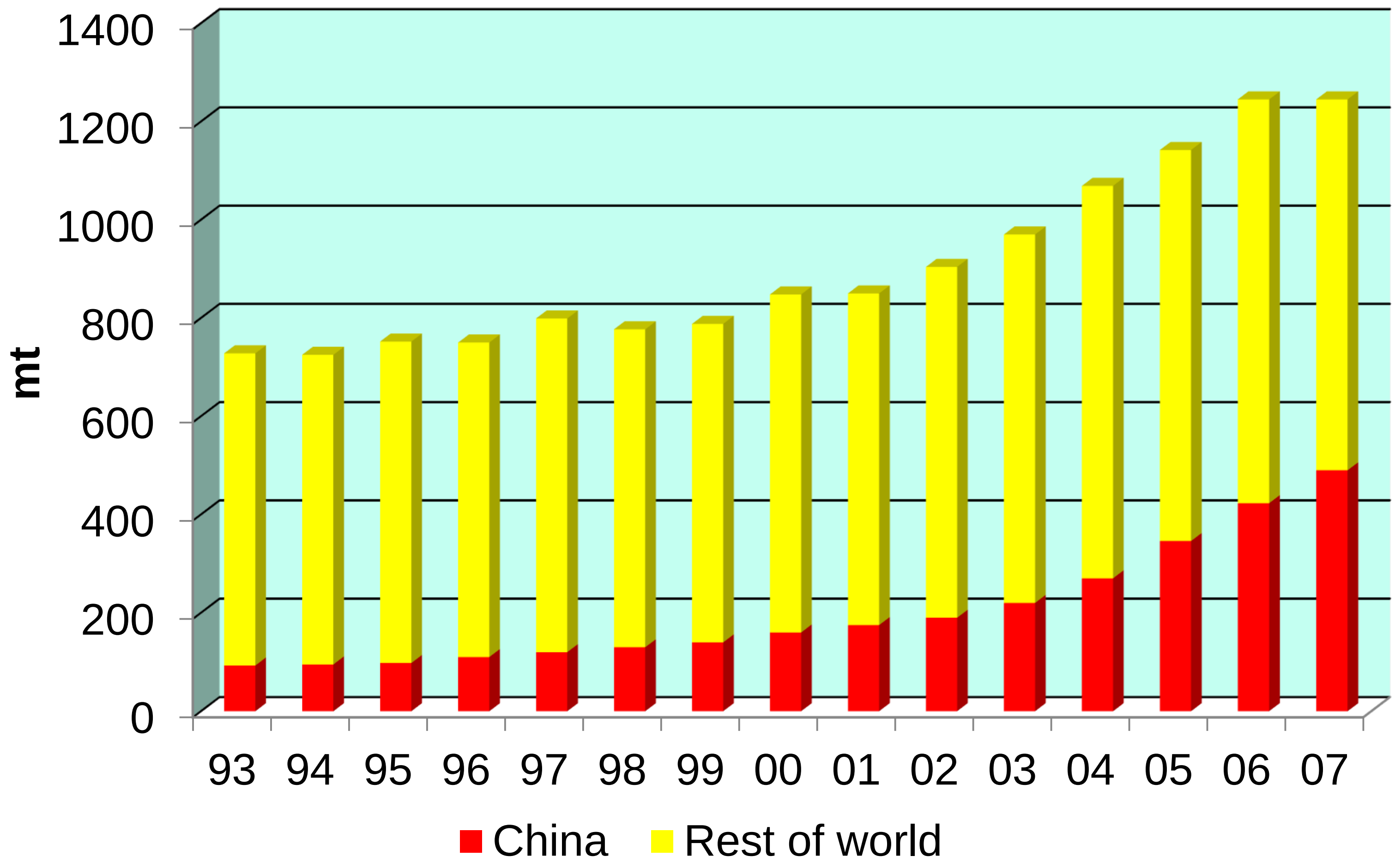
Qualitative Trends of Development.



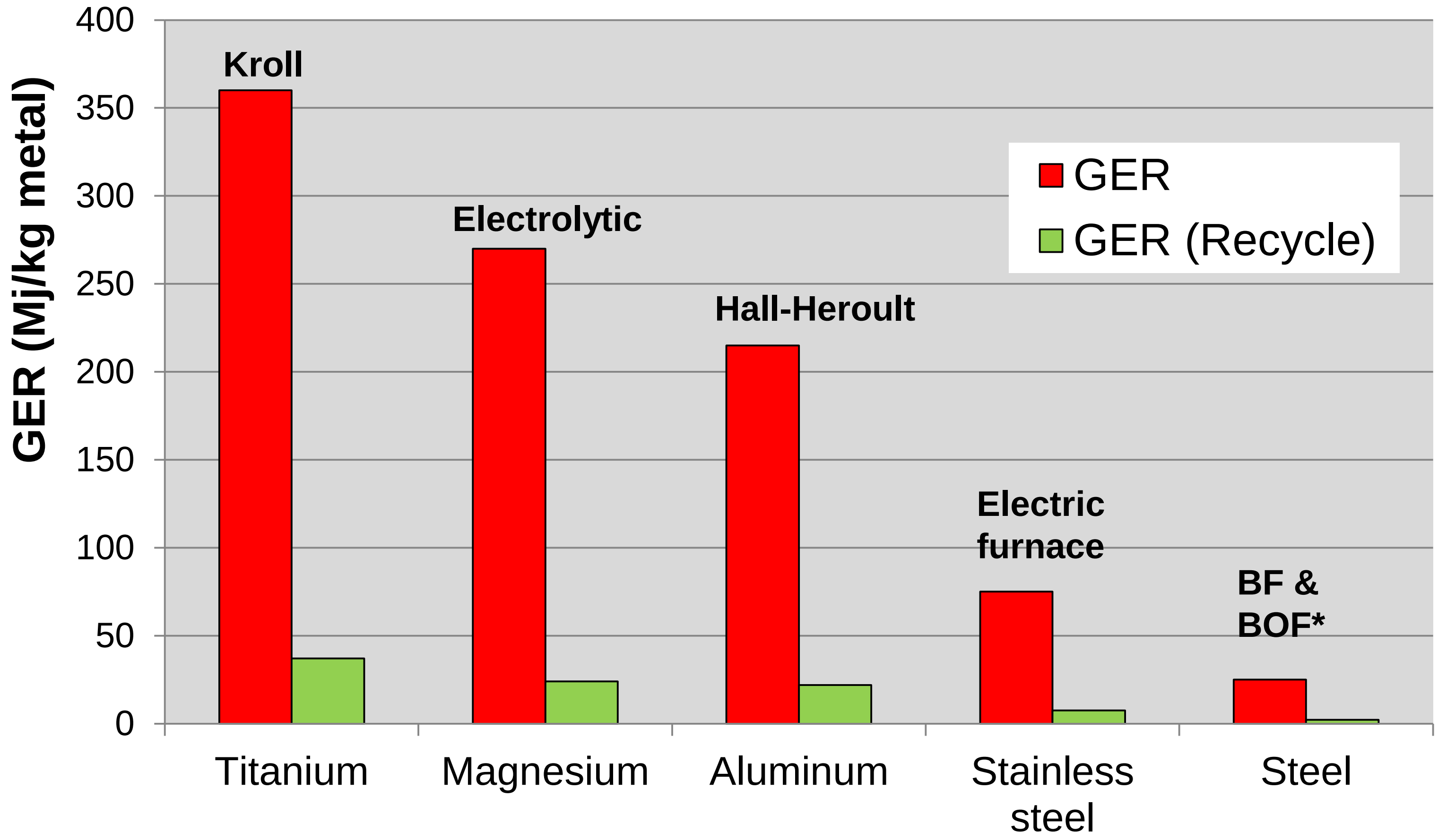
Definition of carrying capacity:
"The maximum rate of resource consumption and waste discharge that can be sustained indefinitely in a given region without progressively impairing the functional integrity and productivity of the relevant ecosystems."

Physical Restrictions.

World Crude Steel Production 1993-2007.



Greenhouse Impact of Metal Production.



***blast furnace (BF) iron-making followed by basic oxygen furnace (BOF)**

GER - Gross Energy Requirement
GER (Recycle) = GER for metal recycle

Norgate et al., Green Processing 2004, AusIMM

Quantifying Sustainability.

Realistic and defensible goals for sustainability and their implementation will not be easily to establish in practice, but the principles by which one could proceed are reasonably straightforward. They are:

- Establish the limiting rate of use of the environmental, economic, or equity component;
- Allocate the allowable limit by some appropriate method to those who are influenced by that limit;
- Compare the current situation with the permitted allocation;
- Consider potential corrective actions.

In a number of cases it will be necessary to select a time horizon over which sustainability is to be evaluated. Generally a 50 year (i.e. roughly two human generations) is considered as a reasonable period for assessment.

Preliminary Measure of Sustainability.

Once a resource of interest is chosen, four basic steps are taken:

1. **Establish the virgin material supply limit** by calculating the amount of resource that can be useful per year if that resource is to last for 50 years, knowing the quantity of resource available. For a non renewable resource, the amount often used is the "reserve base", defined as the one extracted at a profit plus some other known but presently not economically viable.
2. **Allocate the virgin material supply** according to a reasonable formula.
3. **Establish the regional "re-captureable" resource base**, which is the known quantity in stockpiles, landfill, etc., where it might reasonably be accessed.
4. **Compare the current consumption rate** to the sustainable limiting rate for that resource within the region being assessed.

Example: Sustainable Supply of Zinc – Calculations.

1. **Virgin material supply limit**: for zinc, the reserve base as of 2009 was 430 Tg, so the virgin material supply limit over 50 years is 430 Tg/50 years = 8.5 Tg/yr. [50% of zinc is to make galvanized steel].
2. **Allocation of virgin material**: allocating the available zinc equally among all the world's population gives (8.6 Tg/yr)/(7.5 billion people) = 1.15 kg/(person·year).
3. **Regional "re-captured" resource base**: Assuming a 30% recycling rate, each person in the region actually has 1.15 + (0.3)·(1.15 kg/person·year) = 1.5 kg/(person·year).
4. **Current consumption rate vs. sustainable limiting rate**: For instance in U.S. zinc consumption in 2009 was 1.6 Tg for a population of 260 million people (per capita zinc use in U.S. is 6.2 kg/year). In Netherland in 1990 the value was 26.5 Gg/15 million people (per capita zinc use in NL is 1.9 kg/year). The NL is close to its global sustainable allocation for zinc but the value of U.S. is unsustainable.

Graedel, T.E., Allenby B.R. Industrial Ecology and Sustainable Engineering, Pearson (2010)

Sustainable Supply of Germanium – Calculations.

1. **Virgin material supply limit**: for germanium, the reserve base as of 1999 in U.S. was 500 Mg, so the virgin material supply limit over 50 years is 500 Mg/50 years = 10 Mg/yr. [75% of Ge is for optical fibers].
2. **Allocation of virgin material**: allocating the available germanium equally among all the world's population gives (10 Mg/yr)/(7.5 billion people) = 1.3 mg/(person·year).
3. **Regional "re-captured" resource base**: Assuming a 25% recycling rate, each person in the region actually has 1.3 + (0.25)·(1.3 mg/person·year) = 1.6 mg/(person·year).
4. **Current consumption rate vs. sustainable limiting rate**: in U.S. germanium consumption in 1999 was 20 Mg for a population of 260 million people (per capita germanium use is 77 mg/(person·year)). The U.S. clearly exceeds its global sustainable allocation of germanium per person.

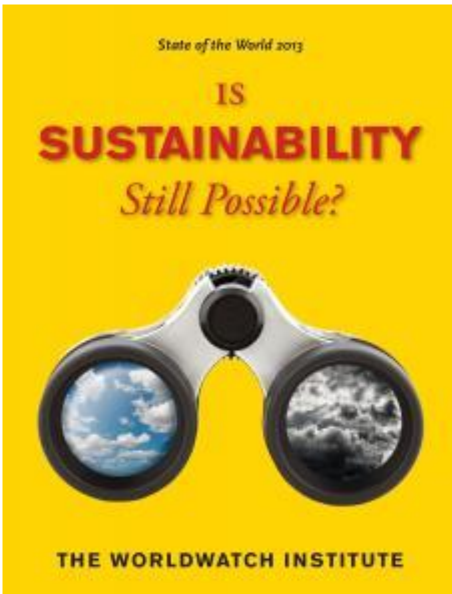
Graedel, T.E., Allenby B.R. Industrial Ecology and Sustainable Engineering, Pearson (2010)

Global Sustainable Limiting Rate of CO_2 Production.

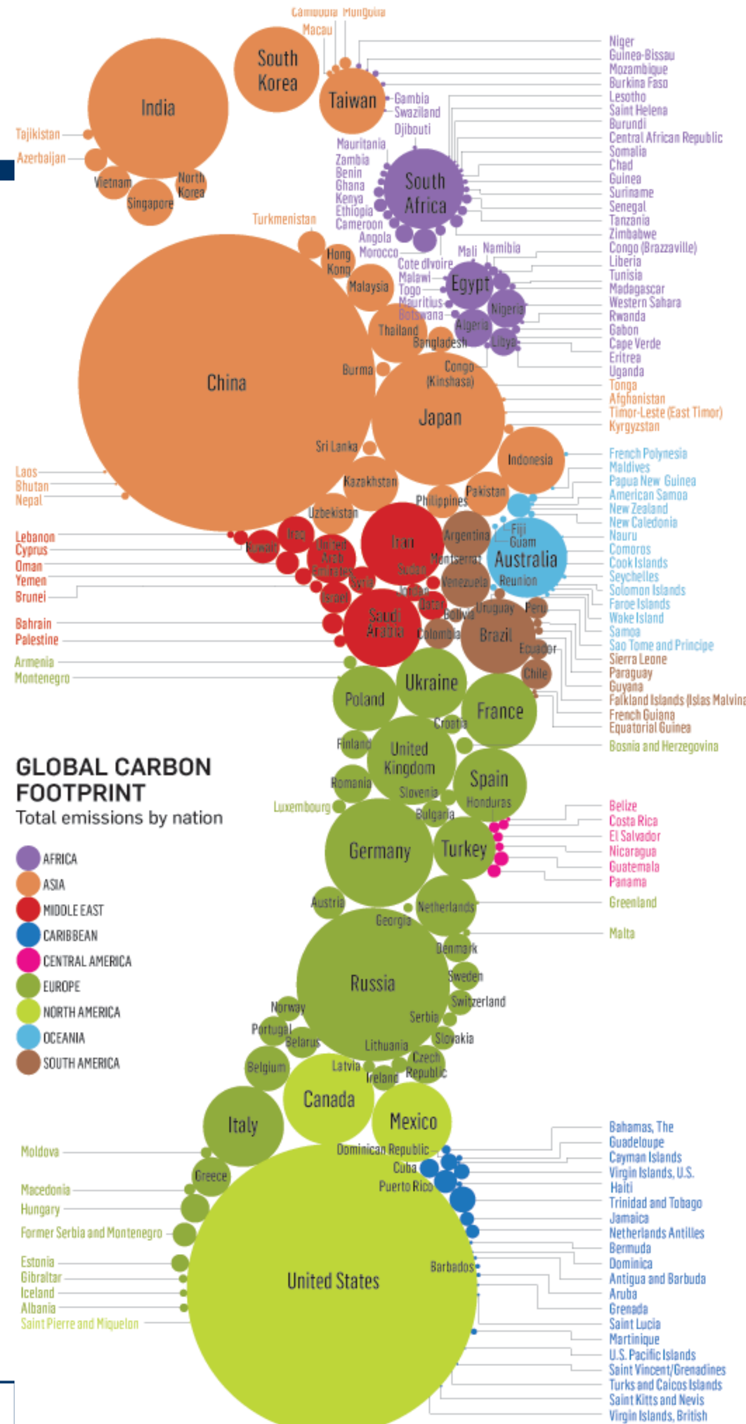
1. **Virgin material supply limit:** the IPCC indicate that in order to level off atmospheric CO_2 concentration below a doubling from the preindustrial level (550 ppmv by 2100) global anthropogenic emissions must be limited to -7/-8 Pg of carbon per year.
2. **Allocation of virgin material:** allocating an equal share of CO_2 emissions among the world's population in 50 years gives roughly 1 metric ton of carbon per person per year.
3. **Regional "re-captured" resource base:** Recycling of carbon in the form of permanent o semi-permanent sequestration may eventually be possible through controversial techniques. Value at present unknown.
4. **Current consumption rate vs. sustainable limiting rate:** U.S. actually produces 6.6 metric ton of carbon equivalent per person, well beyond the global sustainable allocation rate of 1 metric ton of carbon per person. In Switzerland the value is 2, near the limit.

Graedel, T.E., Allenby B.R. Industrial Ecology and Sustainable Engineering, Pearson (2010)

Global Carbon Footprint.



State of the World 2013:
Is Sustainability Still Possible?
ISBN: 978-1-61091-449-9



Issues in Quantifying Sustainability.

1) Simplicity vs. Complexity Issues

- Simple metrics do not yet handle the inherent complexity of global environmental system. Holes and unintended effects can be present.
- Increase the recycling of a resource may have negative effects on energy consumption and greenhouse gas production.
- Simplified sustainability measurements offer a perspective on the challenges ahead.

2) The Property Rights Issues

In calculating preliminary values for sustainability of resources on an individual basis, equivalent allocation for each human was made. But resources are not equally distributed on a geographical basis and they owned by a variety of entities, including nations, corporations and individuals. Some alternative approaches are used:

a) The global extraction rate is dictated, but allocation left to market

b) Regional total extraction rate is dictated, resident allocated more

c) Regional allocations is based on both local virgin and secondary resources.

Linking Industrial Ecology Activity to Sustainability: the Grand Objectives.

Many of the sustainable dialogs involve environmental perturbations and it is useful to consider how such issues might be prioritized. From recent analyses a reasonable exposition of the Grand Objectives is the following

- Ω_1 : Maintaining the existence of human species
- Ω_2 : Maintaining the capacity for sustainable development and the stability of human systems
- Ω_3 : Maintaining the diversity of life
- Ω_4 : Maintaining the aesthetic richness of the planet.

If it is granted that these objectives are universal, there are certain basic societal requirements that must be satisfied if the objectives are to be met. In the case of Ω_1 these are the minimization of environmental toxicity and the provision of basic needs, For Ω_2 the requirements are a dependable energy supply, the availability of suitable material resources. For Ω_3 to maintain a suitable amount of natural areas and biological diversity. For Ω_4 to control wastes of various kinds, and, in general, degradation of the visible world.

Linking the Grand Objectives to Environmental Science (and to Green Chemistry/Engineering).

Objectives and related environmental issues are easily linked:

Global Objectives	Environmental concerns
Ω_1 : Human species existence	1. Global climate change
	2. Human organism damage
	3. Water availability and quality
	4. Resource depletion: fossil fuels
	5. Radionuclides
Ω_2 : Sustainable development	3. Water availability and quality
	4. Resource depletion: fossil fuels
	6. Resource depletion: non fossil fuels
	7. Landfill exhaustion
Ω_3 : Biodiversity	3. Water availability and quality
	8. Loss of biodiversity
	9. Stratospheric ozone depletion
	10 Acid deposition
	11. Thermal pollution
	12. Land use patterns
Ω_4 : Aesthetic Richness	13. Smog
	14. Aesthetic degradation
	15. Oil spills, pollution
	16. Odor

Linking the Grand Objectives to Environmental Science.

The particular difficulty of identifying the best actions of society is that activities related to environment inevitably involve trade-off.

i.e.:
- wetland preservation versus job creation,
- the lack of greenhouse gas emissions of nuclear power reactors versus the chance of nuclear accident,
- preservation and reuse of clothing versus the energy costs for cleaning

To enable choices to be made, many have proposed that environmental resources (raw materials, plant species, the oceans, etc.) be assigned economic value, so that decisions could be market driven. The concept has proven difficult to put into practice, further confounded by the fact that the scientific understanding of many of the issues is itself evolving and impacts need continuous evaluation.

Given this uncertain, it is believed that sustainability ultimately requires:

- Not using renewable resources faster than they are replenished
- Not using nonrenewable non abundant resources faster than renewable substitutes can be found for them.
- Not significantly depleting the diversity of life on the planet
- Not releasing pollutants faster than the planet can assimilate them.

Targeted Activities in Connection with Crucial Environmental Concerns (1):

The mitigation of the environmental impacts of human activities follows, at least in principle, a logical sequence, including (though are not limited to) the following targeted activities:

Environmental concern	Targeted activity for examination
1. Global climate change	1.1 Fossil fuel combustion
	1.2 Cement manufacture
	1.3 Rice cultivation
	1.4 Coal mining
	1.5 Ruminant population
	1.6 Waste treatment
	1.7 Biomass burning
	1.8 Emission of CFCs, HCFCs, N_2O, greenhouse gases
2. Loss of biodiversity	2.1 Loss of habitat
	2.2 Fragmentation of habitat
	2.3 Herbicide and pesticide use
	2.4 Discharge of toxins to surface waters
	2.5 Reduction of dissolved oxygen in surface waters
	2.6 Oil spills
	2.7 Depletion of water resource
	2.8 Industrial development in fragile ecosystems

Targeted Activities in Connection with Crucial Environmental Concerns (2):

Environmental concern	Targeted activity for examination
3. Atmospheric ozone depletion	3.1 Emission of CFCs
	3.2 Emission of HCFCs
	3.3 Emission of halons
	3.4 Emission of nitrous oxide
4. Human organism damage	4.1 Emission of toxins to air
	4.2 Emission of toxins to water
	4.3 Emission of carcinogens to air
	4.4 Emission of carcinogens to water
	4.5 Emission of mutagens to air
	4.6 Emission of mutagens to water
	4.7 Emission of radioactive materials to air
	4.8 Emission of radioactive materials to water
	4.9 Disposition of toxins in landfills
	4.10 Disposition of carcinogens in landfills
	4.11 Disposition of mutagens in landfills
	4.12 Disposition of radioactive materials in landfills
	4.13 Depletion of water resources
5. Resource depletion: fossil fuels	5.1 Use of fossil fuels for energy
	5.2 Use of fossil fuels as feed stocks

Targeted Activities in Connection with Crucial Environmental Concerns (3):

Environmental concern	Targeted activity for examination
6. Water availability and quality	6.1 Use of pesticides and herbicides
	6.2 Use of agricultural fertilizers
	6.3 Discharge of toxins to surface waters
	6.4 Discharge of carcinogens to surface waters
	6.5 Discharge of mutagens to surface waters
	6.6 Discharge of radioactive materials to surface waters
	6.7 Discharge of toxics to groundwaters
	6.8 Discharge of carcinogens to groundwaters
	6.9 Discharge of mutagens to groundwaters
	6.10 Discharge of radioactive materials to groundwaters
	6.11 Depletion of water resources
7. Land use patterns	7.1 Urban sprawl
	7.2 Agricultural disruption of sensitive ecosystems

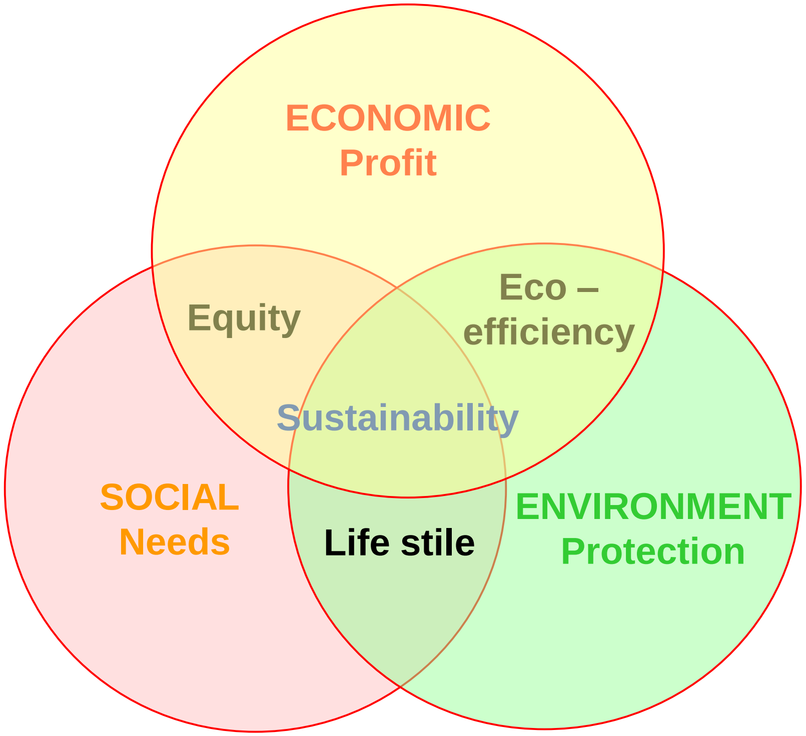
Sustainable Development = Balance between Three Primary Issues.

The three pillars of sustainability :

Needs of society **(the social objective)**;

Efficient use of scarce resources **(the economical objective)**;

Need to reduce the burden on eco-system to maintain the natural bases for life **(the environmental objective)**.



In the business community sustainability is coined **“the triple bottom line”**

Dimensions of Sustainability.

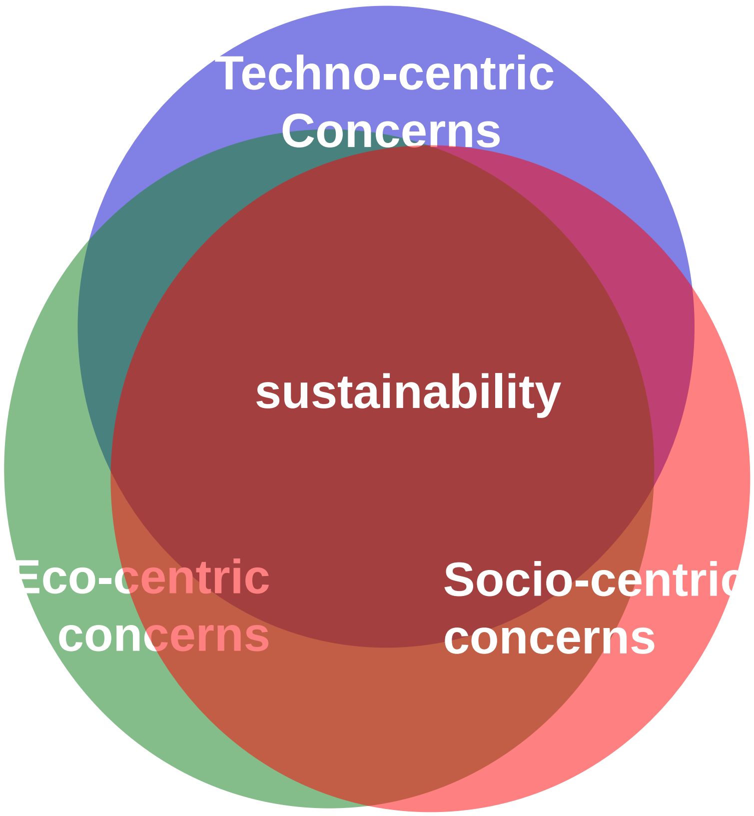
What is important?

Environmental	Resources	Material Intensity Energy Intensity Water Usage Land Use
	Pollutants Waste	Products / Processes / Services Manufacturing Operations Buildings / Sites Effects: Ecosystems / Human Health
Economic	Internal	Eco-Efficiency Costs Revenue Opportunities Access to capital / Access to insurance Shareholder value
	External	Cost of externalities Benefits to local community Benefits to society
Societal	Workplace	Workplace conditions Employee health / safety / well-being Security Human capital development (ed/train)
	Community	Social impacts Stakeholder engagement Quality of Life in community Human rights

High Sustainability Means Minimum of Concerns!

The field of sustainability developed immensely over the past few decades. The awareness and action that precipitated this progress has accomplished a great deal, however one difficult aspect of sustainable improvement is that it can be hard to measure and quantify. However these measurements are still extremely important; they can validate actions taken, reveal areas in which methods have been ineffective, and identify how our efforts can be improved into the future.

As the circles overlaps, sustainability is becoming more and more realizable!



Natural cycles provide reliable models for "long term" sustainability!

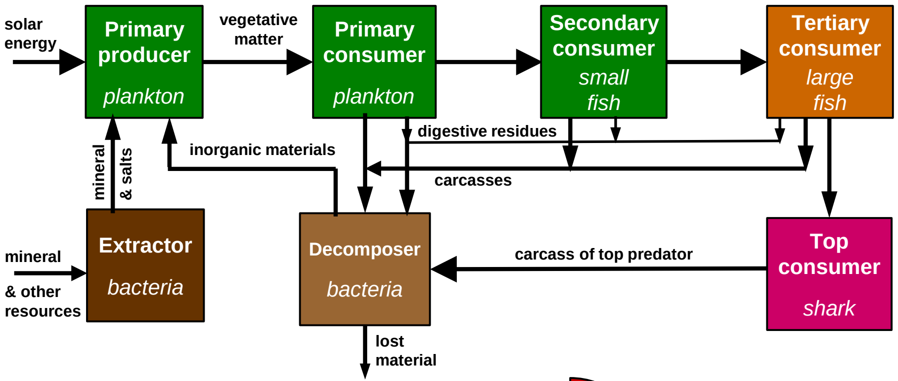
What Sustainable Development Entails.

Like sustainability, sustainable development can mean different things to different people.

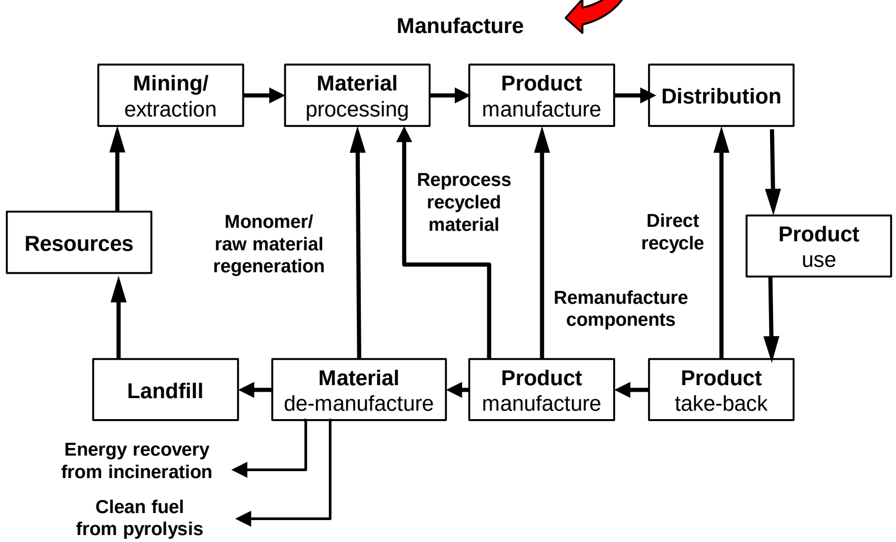
There is no universally accepted definition, but the following elements are regarded by essential by most people:

1. Systems view – Integrative approach
2. Environment alongside social welfare and economy (Triple Bottom Line)
3. Recognition of limits
4. Regenerative systems – Waste of a process to become food for another
5. Use of planetary resources at a rate below regeneration
6. Local production to the extent possible
7. Long-term view – Obligation to future generations
8. Precautionary approach
9. Respect of biological and cultural diversity
10. Social equity

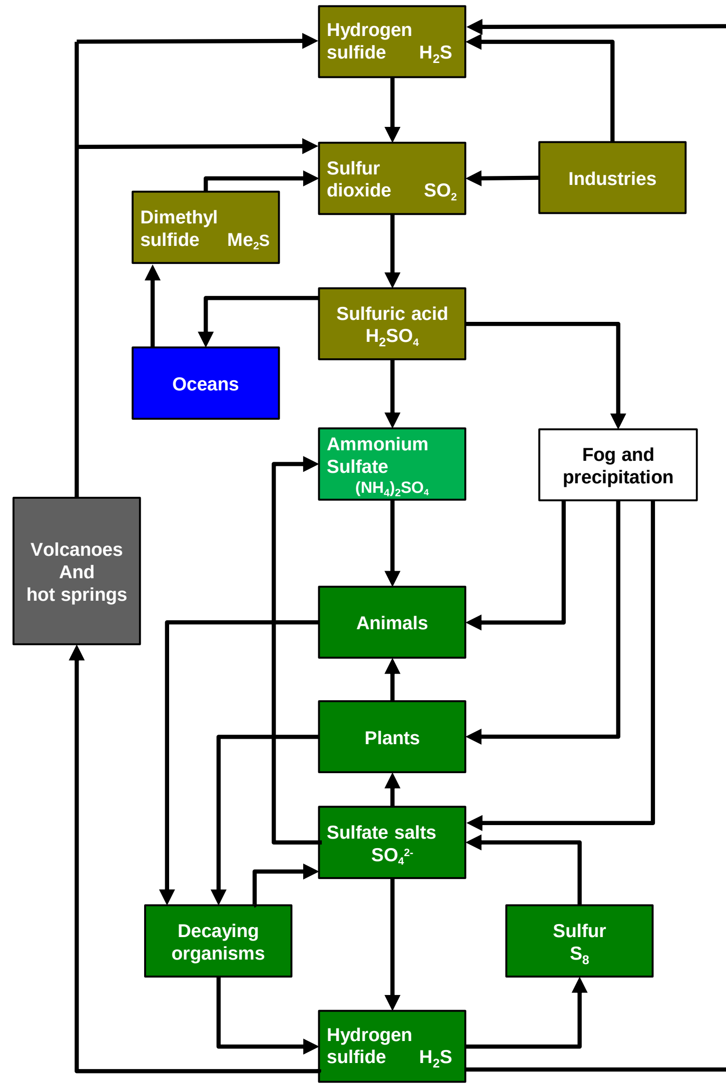
What Imitation of Nature Should Look Like.



Possible Imitation of Nature

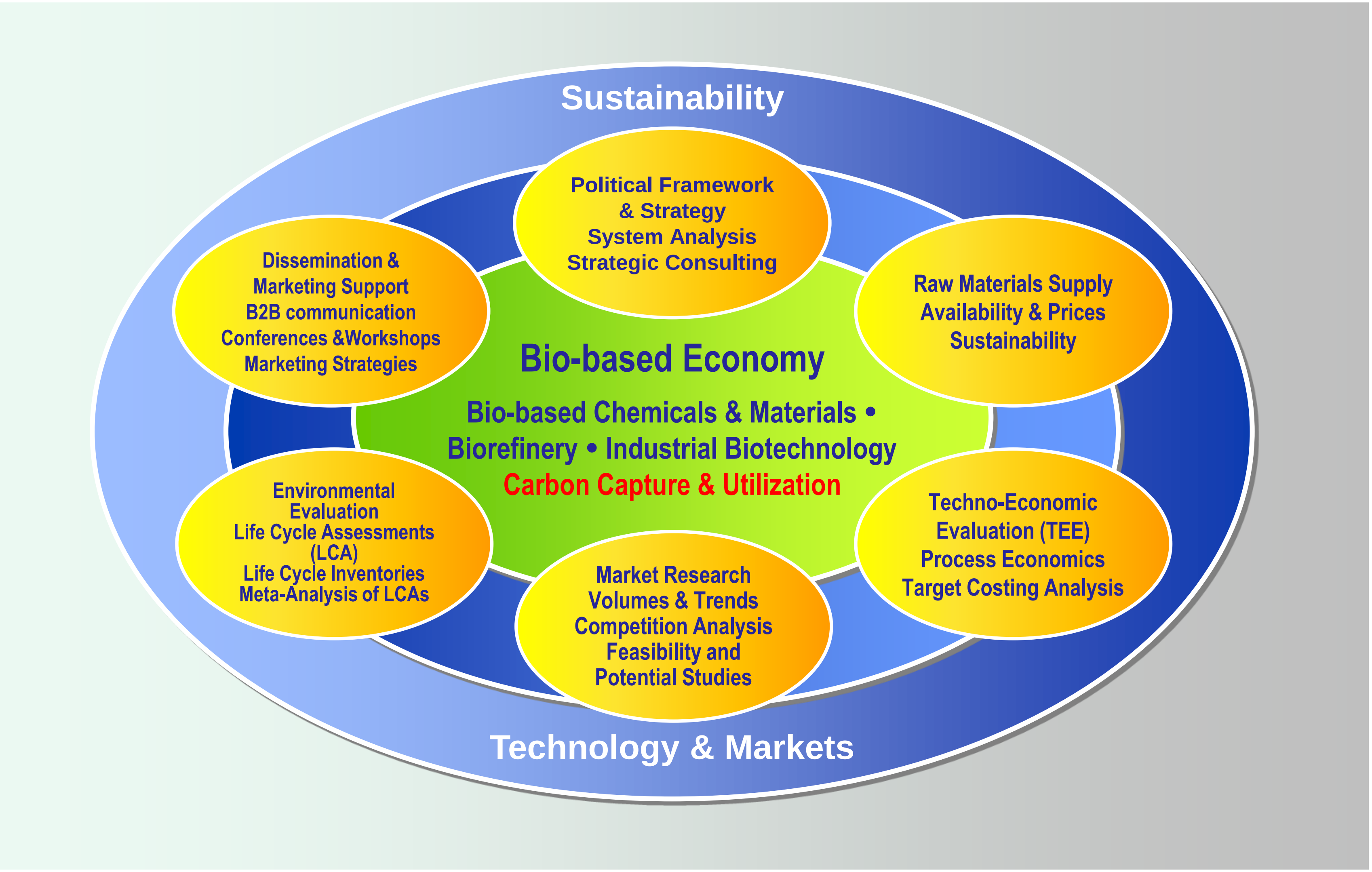


A product's life cycle cradle to reincarnation.



Coupled natural and industrial cycle of sulfur

Bio-based Economy and Sustainability.



In Conclusion:

Assembling the pieces, we see that the concept of Sustainability implicates:

- our actions,
- future generations,
- the environment,
- responsibility, and
- limits.

The challenge before us is to identify, and engage in, those responsible actions that make the environment an integral part of our economy and respect environmental limits, so that we and future generations can continue to live on this spaceship called Earth.

"Sustainability is the ultimate relation of action and consequence."

(Kirsten Childs, in *Sustainable Architecture - White Papers*, 2004)