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Modeling matter, energy and information flows through ecological and economic systems, within a “zero emission” framework

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An aerial view of Siena

The City Hall, the Torre del Mangia and Piazza del Campo

In this presentation...

- …we draw a parallel between self-organization in ecosystems for maximum success opportunity (Lotka-Odum’s Maximum Power Principle), and the needed reorganization of human societies for optimum use of natural resources and decreased load on environment (Zero-Emission Strategies).

- A combined use of Life Cycle Assessment and Emergy Synthesis is suggested, as a tool to evaluate and choose among alternative options.

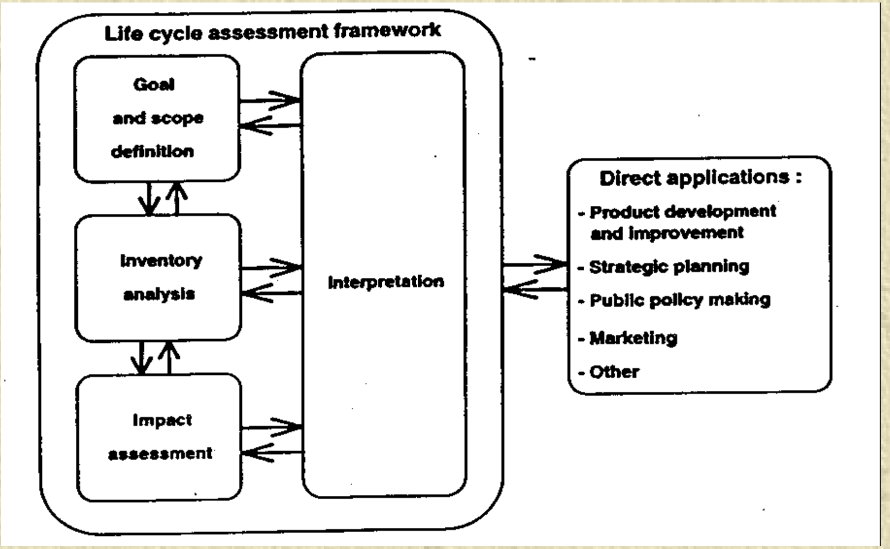
Life Cycle Assessment

Life Cycle Assessment is a methodology used to assess the environmental impacts of a product (or a service) from "cradle to grave" or better "from cradle to cradle", including recycle and reclamation of degraded environmental resources.

SETAC - Life Cycle Assessment Code of Practice, 1993; ISO norms: 14040/1997 to 14043/2000

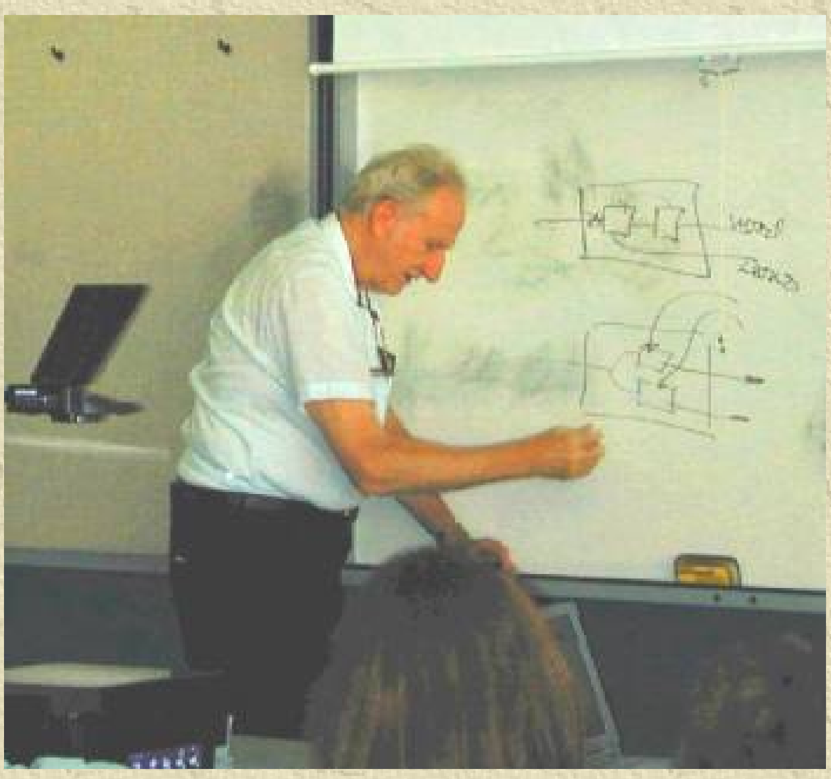
LCA Steps

- DEFINITION OF GOALS
- INVENTORY ANALYSIS
- IMPACT ASSESSMENT
- IMPROVEMENT ANALYSIS



The Emergy Synthesis approach

Emergy Synthesis
was originally developed by H.T. Odum to study eco-systems,
but it can be applied to any system, including human societies.



Howard T. Odum (1924 - 2002)

Emergy, transformity, empower

- Emergy (more often solar emergy) is defined as the total amount of available energy of one kind (usually solar), that is directly or indirectly required to make a given product or to support a given flow. (Odum, 1983).

- It measures the environmental support to a process. The unit is *solar equivalent joule* (seJ). By expressing all input flows in emergy units, they can be compared on the scale of the biosphere.

- The amount of emergy that it takes to make a unit of output flow or product is the solar transformity (seJ/J). A flow of emergy per unit of time is called empower (seJ/s; seJ/yr).

Emergy Accounting of Pine Plantation

TABLE 5.2. EMERGY **Evaluation of Pine Plantation in New Zealand. Annual Flows per Hectare (see Figure 5.1)**

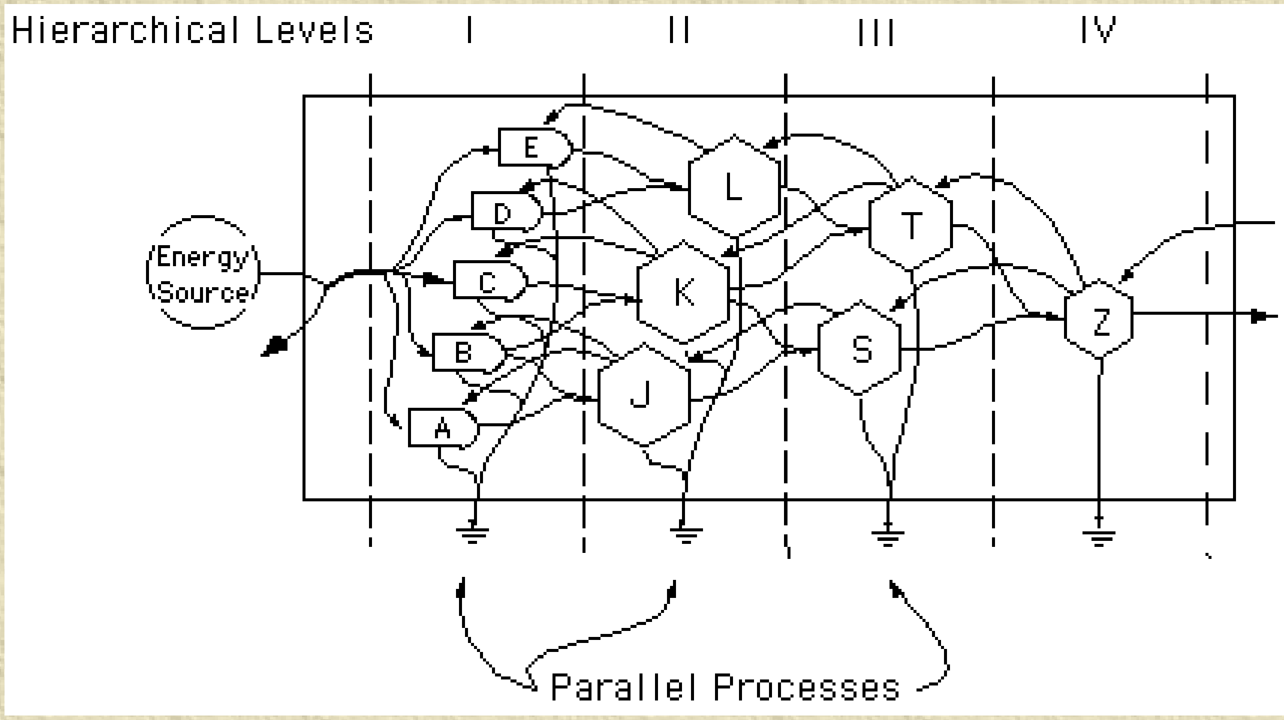
Note	Item	Data	EMERGY/unit (sej/unit)	Solar EMERGY ($\times 10^{12}$ sej)	Em\$* (1984 U.S.\$)
1	Sunlight	5.14×10^{13} J	1	51.4	23.
2	Rain transpired	3.16×10^{10} J	1.6×10^{4}/J	506	230.
3	Soil used	3.39×10^{9} J	6.3×10^{4}/J	214	97.
4	Phosphate added	4.84×10^{6} J	4.4×10^{7}/J	213	97.
5	Fuel used	1.79×10^{8} J	6.6×10^{4}/J	12	5.
6	Services	57 1978\$	4.6×10^{12}/\$	262	119.
7	Annual Yield	1.507×10^{11} J	8×10^{3}/J	1207	548

Solar Transformities

Wood standing in forest: $$\frac{(506 + 213 + 214 + 199) \times 10^{12}\ \text{sej/yr}}{1.507 \times 10^{11}\ \text{J}} = 7511\ \text{sej/J wood}$$

Harvested wood: $$\frac{(506 + 213 + 214 + 12 + 262) \times 10^{12}\ \text{sej/yr}}{1.507 \times 10^{11}\ \text{J wood/yr}} = 8009\ \text{sej/J wood}$$

Hierarchical levels



The energy flux becomes smaller and smaller from the lower to the higher levels, but the emergy flux remains the same or increases.

Transformities in terrestrial ecosystems

Table 2. Summary of transformities in terrestrial ecosystems.

Ecosystem	Transformity (seJ/J)	Reference
Gross primary production		
Subtropical mixed hardwood forest, Florida	1.03E+03	Orrel, 1998
Subtropical forest, Florida	1.13E+03	Orrel, 1998
Tropical dry savanna, Venezuela	3.15E+03	Prado-Jutar & Brown, 1997
Salt marsh, Florida	3.56E+03	Odum, 1996
Subtropical depressional forested wetland, Florida	7.04E+03	Bardi & Brown, 2001
Subtropical shrub-scrub wetland, Florida	7.14E+03	Bardi & Brown, 2001
Subtropical herbaceous wetland, Florida	7.24E+03	Bardi & Brown, 2001
Floodplain forest, Florida	9.16E+03	Weber, 1996
Net primary production		
Subtropical mixed hardwood forest, Florida	2.59E+03	Orrel, 1998
Subtropical forest, Florida	2.84E+03	Orrel, 1998
Temperate forest, North Carolina (Quercus spp)	7.88E+03	Tilley, 1999
Tropical dry savanna, Venezuela	1.67E+04	Prado-Jutar & Brown, 1997
Subtropical shrub-scrub wetland, Florida	4.05E+04	Bardi & Brown, 2001
Subtropical depressional forested wetland, Florida	5.29E+04	Bardi & Brown, 2001
Subtropical herbaceous wetland, Florida	6.19E+04	Bardi & Brown, 2001
Biomass		
Subtropical mixed hardwood forest, Florida	9.23E+03	Orrel, 1998
Salt marsh, Florida	1.17E+04	Odum, 1996
Tropical dry savanna, Venezuela	1.77E+04	Prado-Jutar & Brown, 1997
Subtropical forest, Florida	1.79E+04	Orrel, 1998
Tropical mangrove, Ecuador	2.47E+04	Odum & Arding, 1991
Subtropical shrub-scrub wetland, Florida	6.91E+04	Bardi & Brown, 2001
Subtropical depressional forested wetland, Florida	7.32E+04	Bardi & Brown, 2001
Subtropical herbaceous wetland, Florida	7.34E+04	Bardi & Brown, 2001
Wood		
Boreal silviculture, Sweden (Picea abes, Pinus silvestris)	8.27E+03	Doherty, 1995
Subtropical silviculture, Florida (Pinus elliotti)	9.78E+03	Doherty, 1995
Subtropical plantation, Florida (Eucalyptus & Malaleuca spp.)	1.89E+04	Doherty, 1995
Temperate forest, North Carolina (Quercus spp)	2.68E+04	Tilley, 1999
Peat		
Salt marsh, Florida	5.89E+03	Odum, 1996
Subtropical depressional forested wetland	2.52E+05	Bardi & Brown, 2001
Subtropical shrub-scrub wetland	2.87E+05	Bardi & Brown, 2001
Subtropical wetland	3.09E+05	Bardi & Brown, 2001

Lotka's Maximum Power Principle:

Designs are reinforced that maximize power output possible from the resource available. The system can then draw in more resources, produce more and out-compete alternative patterns that reinforce less (Lotka, 1922a,b).

Odum's Maximum (em)power Principle:

In self-organization patterns, systems develop those parts, processes, and relationships that maximize useful empower. Designs that do not maximize useful empower are displaced.

Complexity

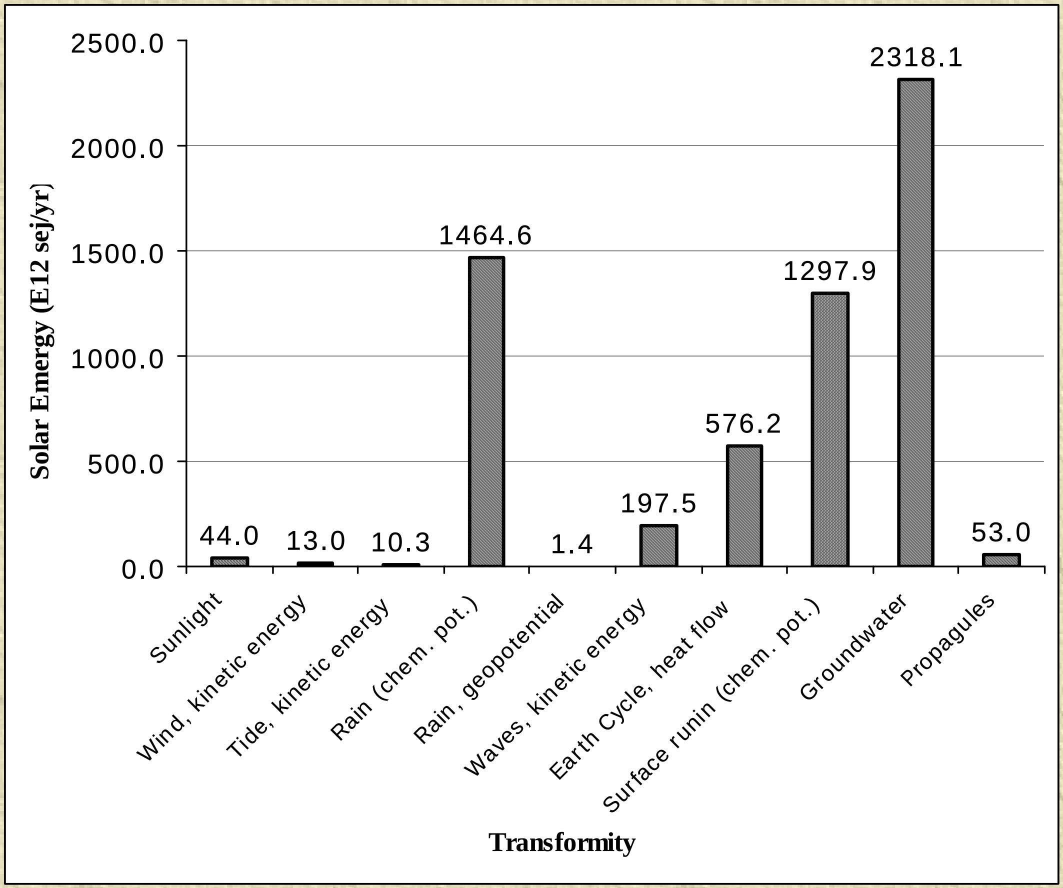
- Self-organization for maximum empower requires complexity:
  - the largest possible number of components
  - the largest possible number of (onward and feedback) connections
  - the largest possible number of patterns for resource use and exchange
  - information (DNA, exergy, landscape,…)

  consistent with available resources.

  Complexity is generated and constrained by the driving forces supporting the system.

What drives complexity?

The Emergy "signature" of a Mangrove Ecosystem

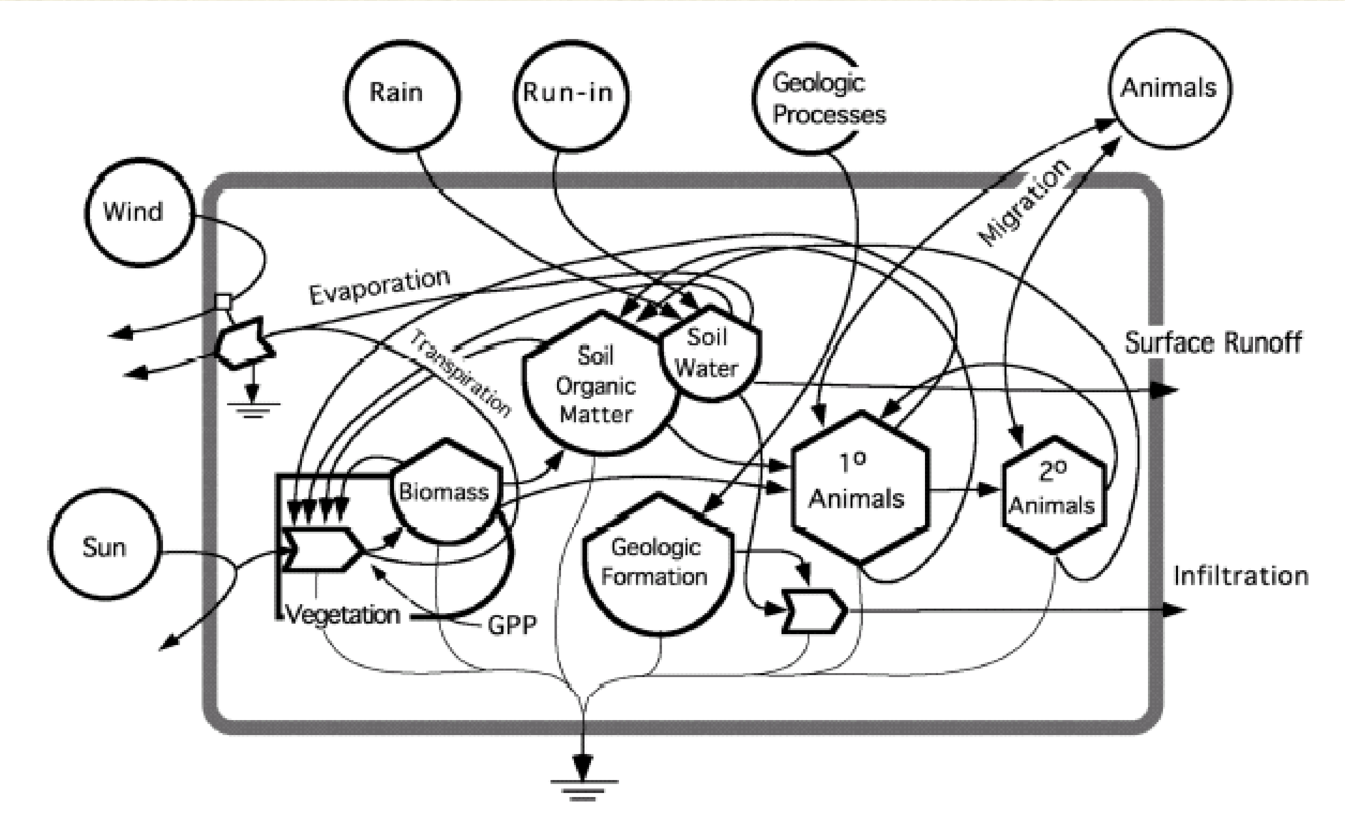


Ecosystems

- Ecosystems circulate materials, transform energy, support populations, join components in network interactions, organize hierarchies and spatial centers, evolve and replicate information, and maintain structure in pulsing oscillations.

- Each energy and matter flow has an emergy cost, i.e. it is supported by the work performed by the environmental driving forces of sun, wind, rain, deep heat, etc. The cost is assigned to the product (in this case: biomass, stored exergy, DNA, environmental services,...)

A Typical Ecosystem Diagram



Generic ecosystem diagram showing driving energies, production, cycling, and the hierarchy of ecological components

The detritus chain...

The *Scarabaeus Semipunctatus*, typical insect of sandy littorals rolls balls of excrements, transports them, and then buries them in sand so they do not dehydrate.

The excrements provide the insect with nourisment, and a growing place for its larvae.
In so doing, the Scarabaeus contributes to the complex and multi-component chain of detritus mineralization.

Environmental metabolism: networks for maximum empower

- Ecosystems recycle every kind of waste. The concept itself of “waste” is no longer appropriate for ecosystems. The products from one component or compartment are always a useful resource for another component or compartment.

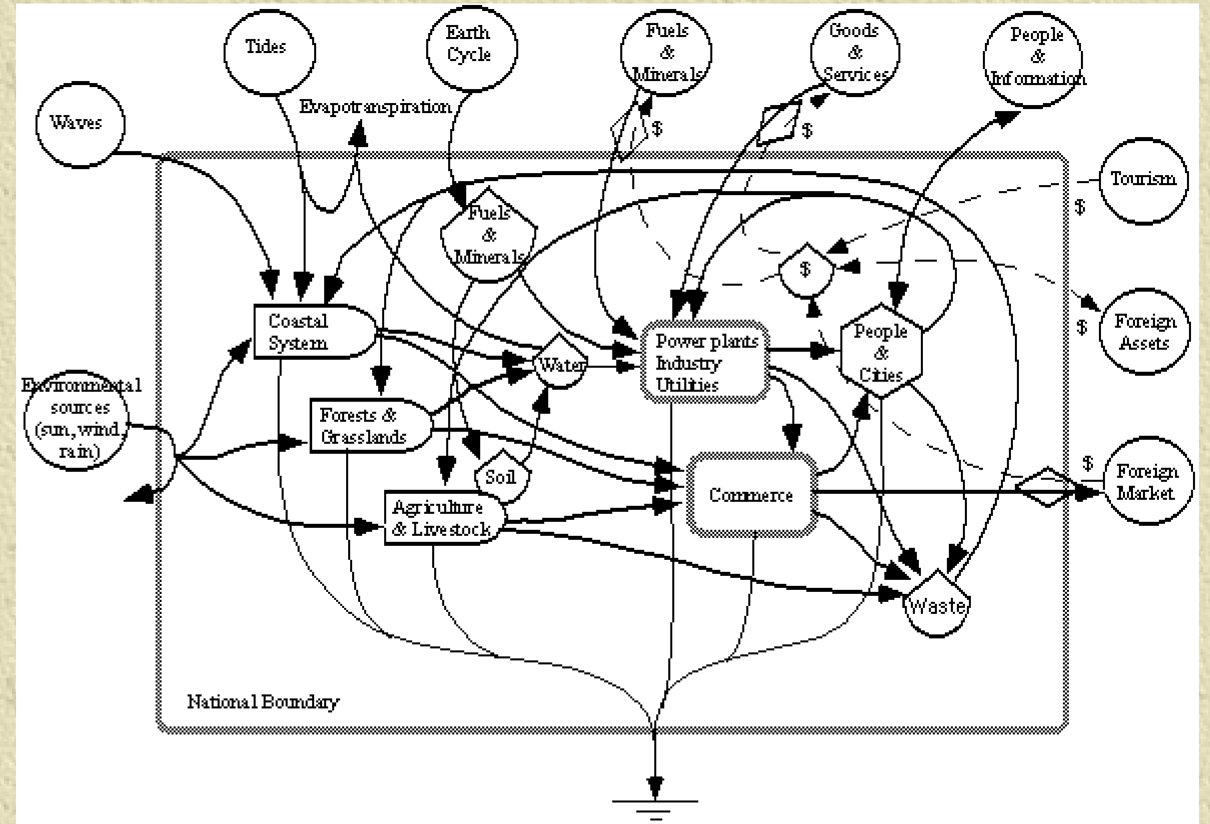
- Self-organization for maximum empower ensures that all available resources are utilized to the maximum possible extent and no unused resources are left.

Human Societies

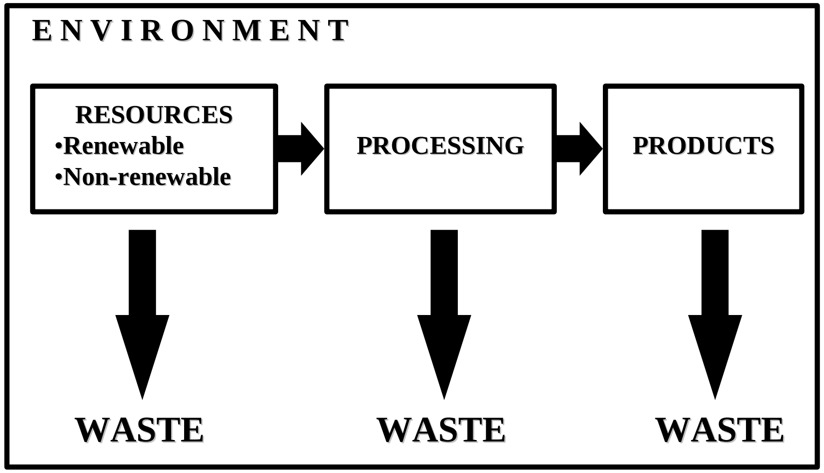
- Human societies use environmental energies directly and indirectly from both renewable energy fluxes and from storages of materials and energies from past biosphere production.

- Matter and energy flows to and from societies can be quantified in terms of LCA. Their environmental cost is quantified in emergy terms.

A typical national diagram.



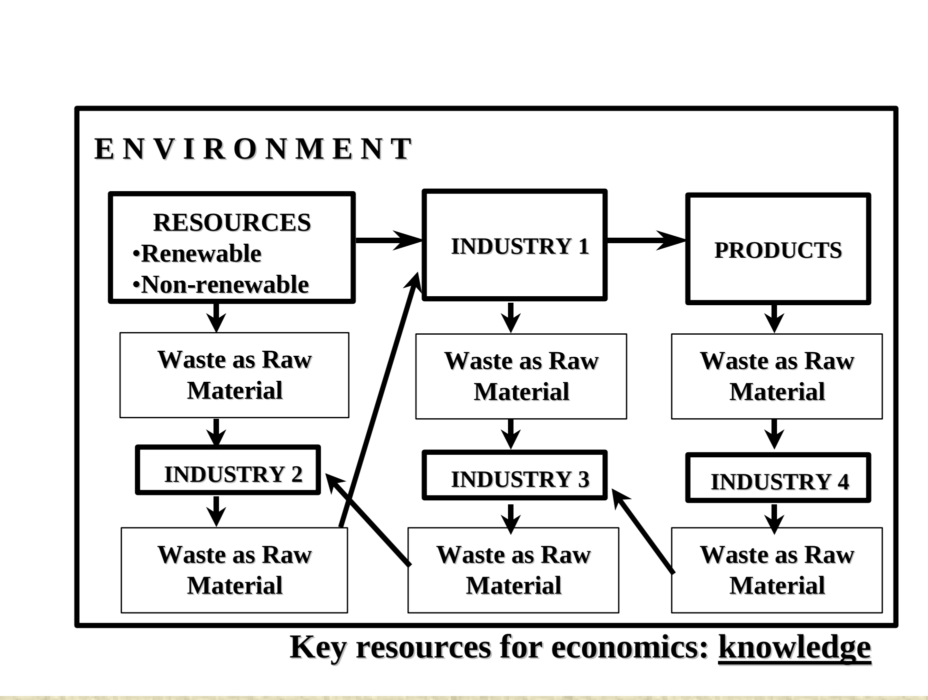
Societal metabolism:
The traditional "linear production" system



Key resources for economics: <u>land,</u> <u>labor</u> and <u>capital</u>

The actions of society, its use of resources and the load this resource use places on the biosphere are of great concern.

A “zero-emission” production system



Networks for maximum empower !

The strategy: Emulating the sustainable cycles of nature

- Similarly to natural ecosystems, societal re-organization for maximum empower requires complexity:

  - the largest possible number of components
  - the largest possible number of (onward and feedback) connections.
  - the largest possible number of patterns for resource use and exchange
  - information (knowledge, training, software,…)

  consistent with available resources.

  Therefore, economies must reorganize their cycles accordingly.

The Zero-Emission Framework

- The Zero-Emission concept "*represents a shift from the traditional industrial model in which wastes are considered the norm to integrated systems in which everything has its use…Society minimizes the load it imposes on the natural resource base and learns to do more with what the earth produces*" (Zero Emission Forum, 1999).

- Zero Emission strategies clearly indicate the way for Maximum Empower to be achieved in human dominated systems. Self-organization of technology and economies for optimum use of resources makes them more similar to natural systems without humans and increases success probability in a scarce resource world.

Advantages from Maximum Empower/Zero Emission strategies

- a) **Less resources are required** to drive the whole process than it would be needed if each sub-process were driven individually.

- b) **Less resources are released** unused and potentially able to drive undesired environmental transformations; as a consequence, less load on the environment is generated.

- c) **Synergic effects** (i.e., increase of benefits) become possible, due to exchange and collaboration links among components;

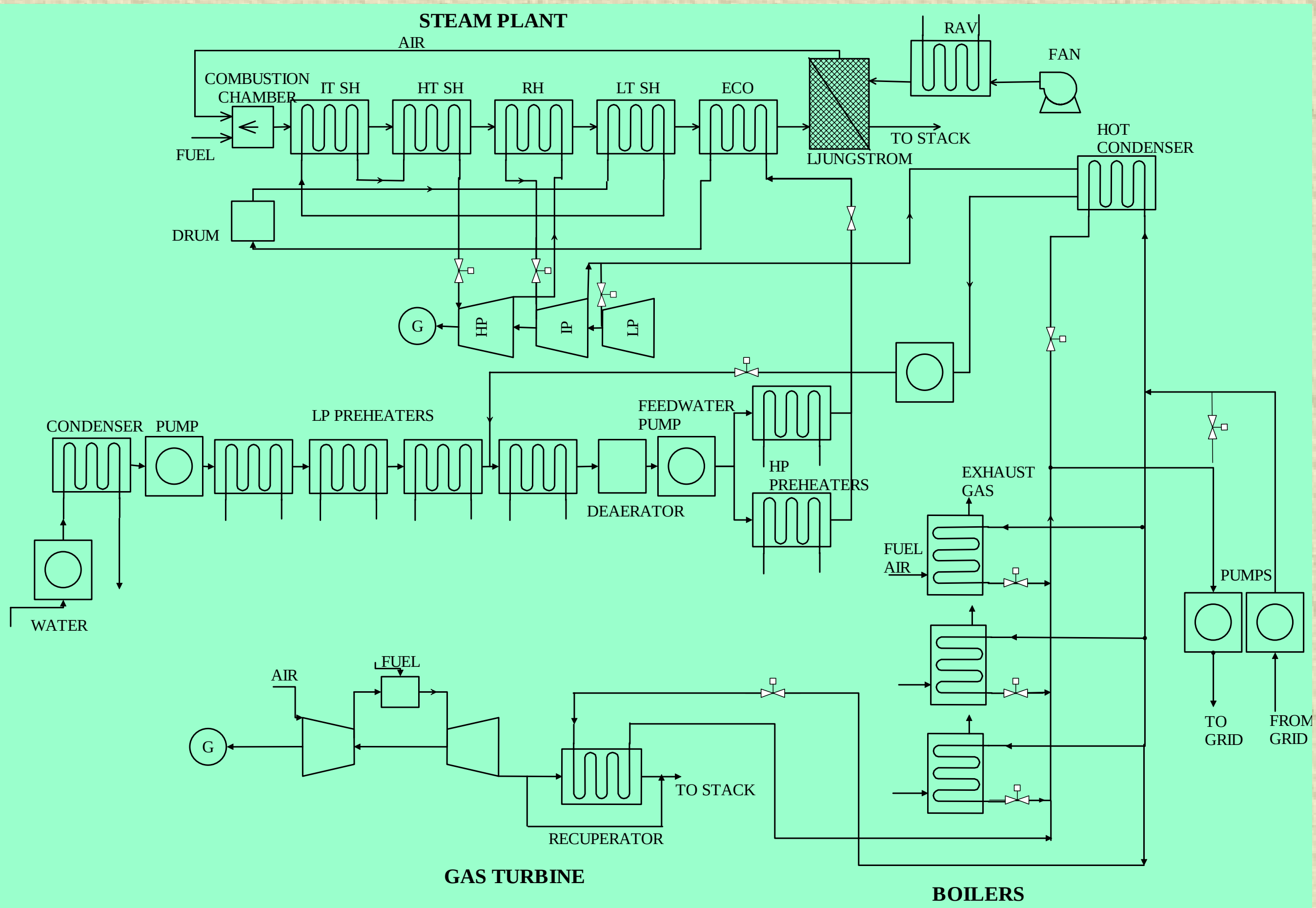
- d) The total **output is maximized**, since additional products are generated by usefully degrading still usable resources, instead of releasing them unused.

Case studies:
2 power plants in Italy

1) Torino, AEM plant, 171 Mwe, ST/GT, natural gas;

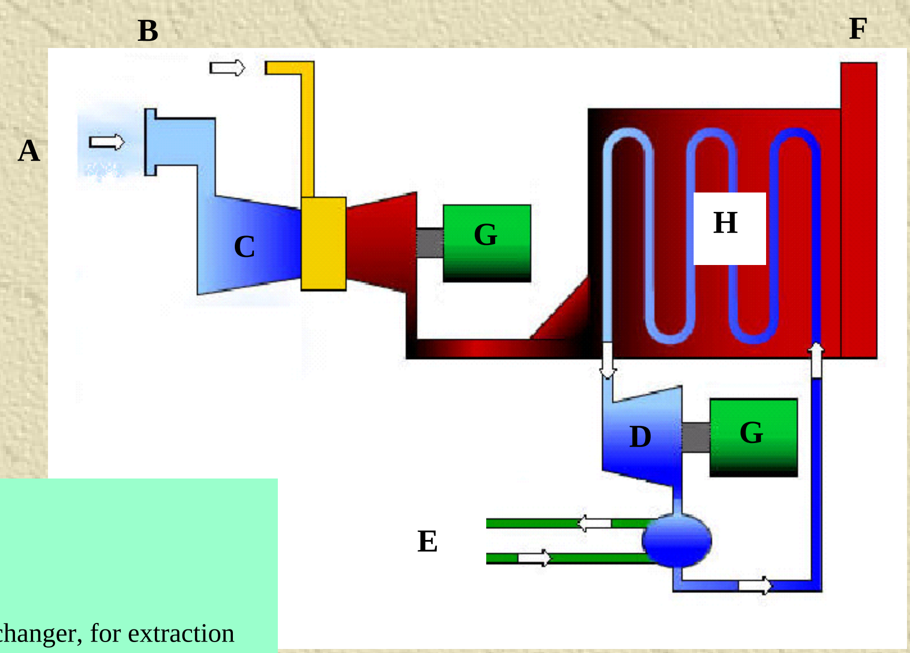
2) Porto Tolle, ENEL plant, 735 MWe, CCGT, natural gas.

Steam Turbine & Gas Turbine system
(Torino, Italy, AEM plant)



Combined Cycle Gas Turbine System

(Porto Tolle, Italy, ENEL plant)



A = input natural gas
B = input air for combustion
C = gas turbine
D = steam turbine
E = cooling water supplied to the heat exchanger, for extraction of waste heat and use for low enthalpy processes.
F = chimney
G = electric generators
H = steam generator

Calculating CCGT efficiency

- $\eta_{GT,F}$= (1500 K-800 K)/1500 K = **46.6 %** (gas turbine)
- η_{ST}= (800 K-500 K)/800 K = 37.5 % (steam turbine)
- η_{HE}= (500 K-293 K)/500 K = 29.4 % (final heat exchanger)

Since η_{ST} applies to the residual heat provided by the gas turbine, including irreversibility losses estimated as 15% of fuel energy, it can be recalculated relative to the input fuel, $\eta_{ST,F}$:

$$\eta_{ST,F} = (1- \eta_{GT} -0.15)*\eta_{ST} = \mathbf{14.4\ \%}$$

Similarly, the efficiency of the third step relative to the input fuel, $\eta_{HE,F}$, recalculated in a similar way, is:

$$\eta_{HE,F} = [(500\ K - 353\ K)/500\ K]*(1-0.466-0.15)*(1-0.375) = \mathbf{7.0\ \%}$$

The electric exergy efficiency is therefore **61.0%,** while the cumulative exergy efficiency of the system is **68.0%.**

Selected LCA results, STGT process

Main mass flows to the STGT process:	$g/(kWh_{el}*yr)$	$g/(kWh_{(el+q)}*yr)$
Concrete	0.464	0.449
Iron and steel	0.369	0.357
Copper	0.005	0.005
Diesel, cooling oil, lube oil	0.141	0.137
Natural gas	283.077	139.261

Main airborne emissions from the STGT process:	$g/(kWh_{el}*yr)$	$g/(kWh_{(el+q)}*yr)$
CO_2	739.336	363.719
CO	0.381	0.187
CH_4	0.014	0.007
VOC and HC	0.007	0.004
NO_x	1.036	0.510
N_2O	0.007	0.004
Particulate matter	0.017	0.009

Plant efficiency:	η_{el}	$\eta_{(el+q)}$
	24.65%	50.11%

Selected LCA results, CCGT process

Fuel supplied to the CCGT process:	$g/(kWh_{el}*yr)$	$g/(kWh_{(el+q)}*yr)$
Natural gas	114.395	102.535

Main airborne emissions from CCGT process:	$g/(kWh_{el}*yr)$	$g/(kWh_{(el+q)}*yr)$
CO_2	314.586	281.970
CO	0.089	0.079
CH_4	0.002	0.002
VOC and HC	0.005	0.005
NO_x	0.301	0.270
N_2O	0.002	0.002
Particulate m atter	0.034	0.031

Plant efficiency:	η_{el}	$\eta_{(el+q)}$
	61.1	68.1

Selected Emergy results

Transformities	seJ/J
STGT process:	
Electricity delivered	3.15E+05
Total exergy delivered (electricity + heat)	1.73E+05
CCGT process:	
Electricity delivered	1.76E+05
Total exergy delivered (electricity + heat)	1.58E+05

Improvements under study

- Use of residual heat from CCGT to support a new component device:

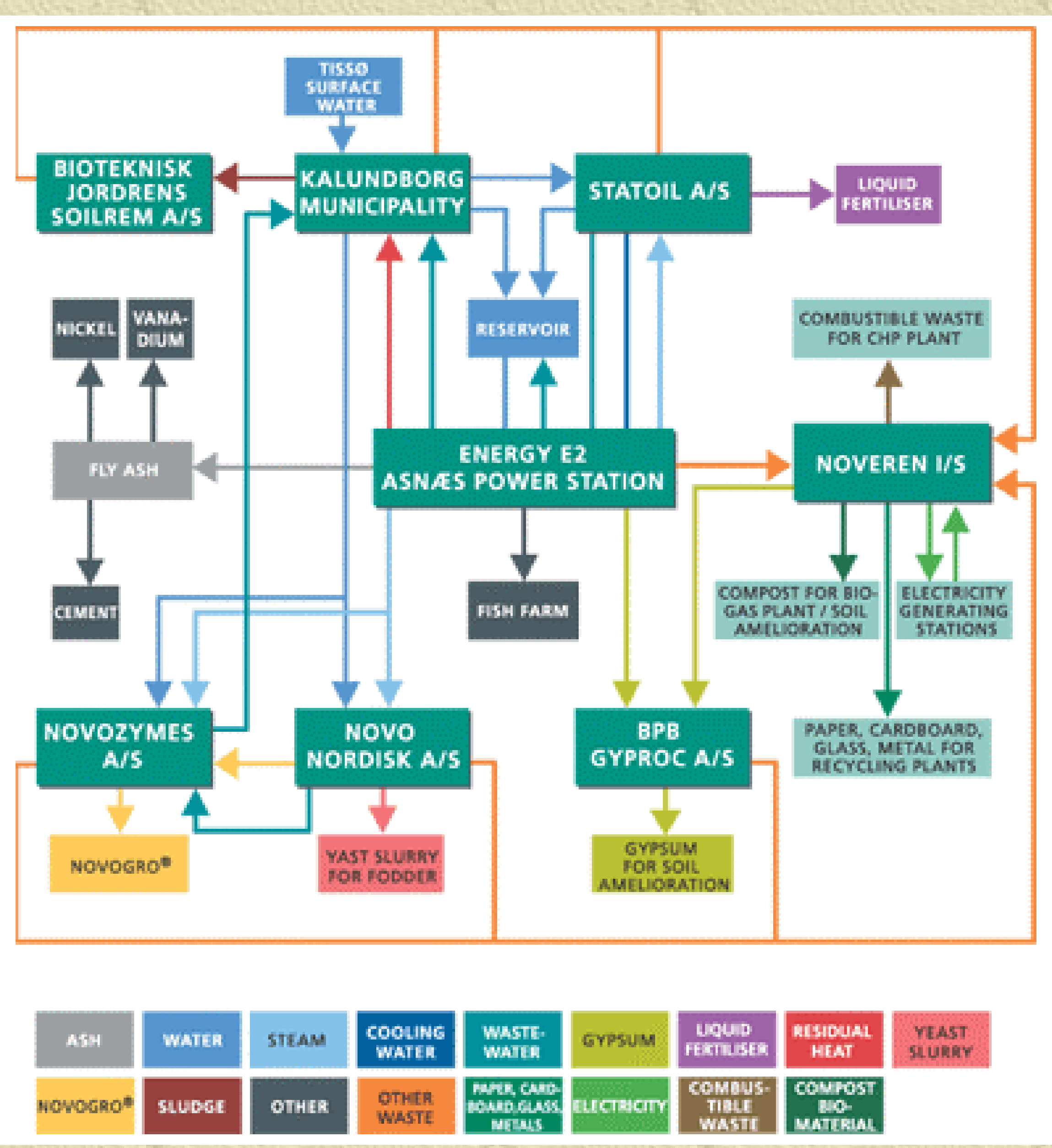
  a) coal gasification to syngas (H_2 and CO) followed by CO reforming to H_2 (product: H_2; advantage: burning coal impacts on the environment much more heavily than generating and burning H_2; problems: need for CO_2 storage).

  b) water thermolysis (products: hydrogen and oxygen; advantage: clean production of H_2 and no CO_2 emissions; problems: still immature technology).

The Kalundborg experience

(Danmark)

http://www.symbiosis.dk/



Main components and connections at Kalundborg

Material and energy flows between companies in Kalundborg

To	From		
	Statoil	Novo Nordisk	Asnaes
Statoil	–	–	Steam
Kemira	Sulphur	–	–
Novo Nordisk	–	–	Steam
Gyro	Gas	–	Gypsum
Sanest	Gas, cooling and waste water	–	–
Farms	–	Sludge	–
Fish Farm	–	–	Heat
District heating	–	–	Heat
Cement and road industry	–	–	Fly ash

Source: de Walle [12].

The total economic benefit of the exchanges pictured in the Table was estimated to be between 12 and 15 million 1996 US$ per year.

Implementing a strategy

- It is important to underline that the Kalundborg Eco-Industrial Park was not initially designed as such, but gradually evolved over a number of decades when the participants discovered that the establishment of energy and waste exchanges resulted in economic benefits for all parties involved.

- The environmental benefits achieved through the exchanges were not instrumental to their establishment but were merely seen as an accidental bonus.

Conclusions

- We do not want to be displaced too early by natural selection. Maximum Power/Zero Emission strategies are therefore urgently needed.
- The existing zero-emission systems evolved gradually without planning, but they appear a viable strategy for ecosystem-like, societal models.
- We therefore suggest the combined use of LCA and Emergy Synthesis as a suitable decision making tool for planning. Our present research is aimed at developing it as both a conceptual framework and a Software for the Italian ENEA – National Agency for New Technology, Energy and the Environment.

Thank you for your attention !

Comments are welcome...