About sustainability metrics

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IHTC-13 Panel Session

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Thermal Design and Optimization for Sustainability

Avram Bar-Cohen, Moderator

Design of large system which consume large quantities of resources or have large impacts will increasingly have to be sustainable

- Sustainable activities can be defined as those that meet the current needs without destroying the ability of future generations to meet theirs, with a balance among economic, social and environmental needs.
- Thermal design (e.g., power generation, propulsion, chemical processes, HVAC) is a good candidate for applying sustainability criteria since it is focused on energy/exergy use and conversion, often also uses large quantities of materials, and produces byproducts that may affect the environment; The GreenBuild initiative of the Sustainability Summit of Professionals (incl. AIA, ASHRAE…) is a good example
- The difficulty is in the fact that we now need to deal with Very Large Complex Systems (“VLCS”)

The first step: quantification of sustainability

- Ecological:
  - Quality of the environment as it impacts human life
  - Quantity, quality and accessibility of resources
- Economical
- Social

NOTE: ALL THE ABOVE ARE INTERRELATED AND TYPICALLY CONSIDERED ONLY AS IT AFFECTS HUMAN LIFE

One difficult component: Ecological Indicators (EI)

- **Must be well-defined**
- **It must be aggregate for the entire affecting "community" and the affected environment.**
- **That environment's boundaries must be practically defined in space and time (e.g., no effect of the Amazon butterfly wing flap on typhoons in China)**

Desirable properties of an Ecological Indicator

1. *An EI must be expressed by a -possibly simple- numeric expression that produces results that can be ordered in an unambiguous way (from "bad" to "good");*
2. *An EI must be calculated on the basis of intrinsic properties of the "community" and of the "environment";*
3. *The EI must be normalized in some sense (e.g., by expressing it as a ratio of the actual calculated value to an "average" value calculated for all similar communities that interact with that environment, or to an "ideal" measure of impact). This is important if we wish to compare not entirely similar communities;*
4. *The EI must be calculated on the basis of an unambiguous, reproducible method under a well-defined set of fundamental assumptions;*
5. *The EI must comply with the accepted laws of physics.*

The conventional* pre-"sustainability" metrics ("indicators")

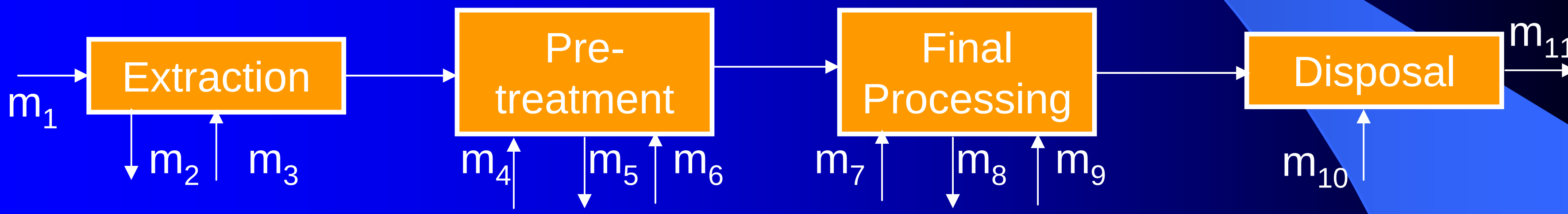
- Energy efficiency: considered by itself, using less energy makes the process more sustainable
- Exergy efficiency: considered by itself, destroying less exergy makes the process more sustainable
- Second-Law efficiency: considered by itself, conducting a process closer to a reversible one under the same conditions makes it more sustainable
- Energo-economics (e.g., Payback period, ROI, LCA): considered by itself, destroying less exergy makes the process more sustainable

Noam Lior and Na Zhang, "Energy, exergy, and Second Law performance criteria", Proc. ECOS 2005, Vol. 1, pp. 437-445, June 20-22, 2005, Trondheim, Norway; accepted for publication in Energy – The International Journal, 2006.

Definition attempts of partial value:

Material Throughput Analysis, MTA

Proposed in the '80s by some World Bank economists, "Material Inventory Analysis".



The EI proper is a normalized mass flow rate of resources per person (or per unit) per year:

$$MTA = \frac{\sum (m_1 + \ldots + m_{10})}{m_{11}}$$

a) Simple

b) S & Env

c) Normalised

d) Reproducible

e) Laws of Physics

MTA satisfies points a) through d) of the list of desirable properties given above.
It does not satisfy point e), (e.g. toxicity)

Metrics with expanded “technical” boundaries

Type of system	Energy Payback, years
Coal power plant	3.6
Nuclear power plant	2.6
Solar domestic hot water system	1.3-2.3
Solar photovoltaic system	2-6
Wind-electric generator	0.25-0.67

- *Embodied energy efficiency*: includes also the energy embodied in the production of the plant, in the materials produced by it, and in the materials and labor needed for its operation, for the distribution of its material products to the customer, and its final
- Present worth ***life cycle analysis*** (LCA), (cf. ISO (International Organization for Standardization) 14040 standard. ‘Environmental management—Life cycle assessment; 1997-2000. Switzerland; Some practical examples:

G. F. Jones and N. Lior, "Optimal Insulation for Solar Heating System Pipes and Tanks", Energy, The International Journal, 4, pp. 593-621, 1979.

G. Geoghegan and N. Lior, "A Comparative Economic Analysis of Straight through and Recirculation Solar Hot Water Systems", Energy, the International Journal, 9, 1, pp. 53-63, 1984.

Riccardo Battisti and Annalisa Corrado, Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology, Energy – The International Journal, 30, pp. 952-967, 2005.

A simple example of using energy, social, economic and global warming criteria (Herzog, 1998)

Table 1. Average Annual Percent Changes of Carbon Dioxide Emissions Variables for the US

Time Period	POP	GDP/POP	BTU/GDP	CO2/BTU	CO2
since 1973	+0.97	+1.67	-1.81	-0.17	+0.65
last 10 years	+1.02	+1.17	-0.70	-0.26	+1.21
since 1990	+1.01	+1.40	-0.66	-0.15	+1.60
last 5 years	+0.96	+1.80	-0.72	-0.14	+1.91

Table 2. Average Annual Percent Change Carbon Dioxide Emissions Variables for 1980-1993

REGION	POP	GDP/POP	BTU/GDP	CO2/BTU	CO2
OECD Europe	+0.5	+1.4	-1.0	-1.4	-0.5
Japan	+0.5	+3.0	-1.5	-0.7	+1.4
EE and FSU	+0.6	-1.5	+0.8	-0.9	-0.9
East Asia	+1.7	+4.9	+0.3	-0.5	+6.5
China	+1.4	+7.8	-4.4	0.0	+4.7
India	+2.0	+3.0	+1.1	+0.2	+6.3
Africa	+2.8	-1.7	+2.0	0.0	+3.2
OECD	+0.7	+1.8	-1.4	-0.7	+0.4
The World	+1.7	+0.8	-0.9	-0.4	+1.2

The EMERGY concept (Scienceman, Odum, 1970s), 1/4:

the total solar equivalent available energy that was used up directly and indirectly in the work of making a product or service (H.T. Odum 1996, H.T. & E.C. Odum 2000).

- Assuming that solar energy is our ultimate energy source, emergy expresses the cost of a process or a product in solar energy equivalents. all non-solar fows, of matter and energy, are brought back to “equivalent solar joules” (Solar Emjoules, Sej) by a proper set of coefficients, called *transformities*.

The EMERGY concept (cont. 2/4)

- Embodied in the emergy value are the services provided by the environment which are free and outside the monied economy.
  - Conventional accounting for quality and free environmental services, does not value resources monetarily, or society's willingness to pay; these free services that a system receives from the environment (e.g., the photosynthetic activity driven by the solar radiation, the dilution of pollutants by the wind, etc.) are just as much a requirement for the productive process as are fossil fuels for example.
  - energies necessary to support any particular economic activity in our societies, and thereby provide better framework for making policy decision.

The EMERGY concept (cont. 3/4)

- Non-emergy approaches to the evaluation of ecological, sociopolitical-economic, and industrial processes most often evaluate only nonrenewable resources, depending on what human technologies are able to extract from them
- Non-emergy approaches do not account for human labor, societal services and information.

The EMERGY concept (cont. 4/4)

- Emergy includes all of this, perhaps not perfectly, but in a way to help us understand that there is a huge network of supporting systems.
- While a step in the right direction, and having an enthusiastic (but relatively small) following, emergy was found to have some definitional, conceptual and applicational deficiencies, but is worth refining.

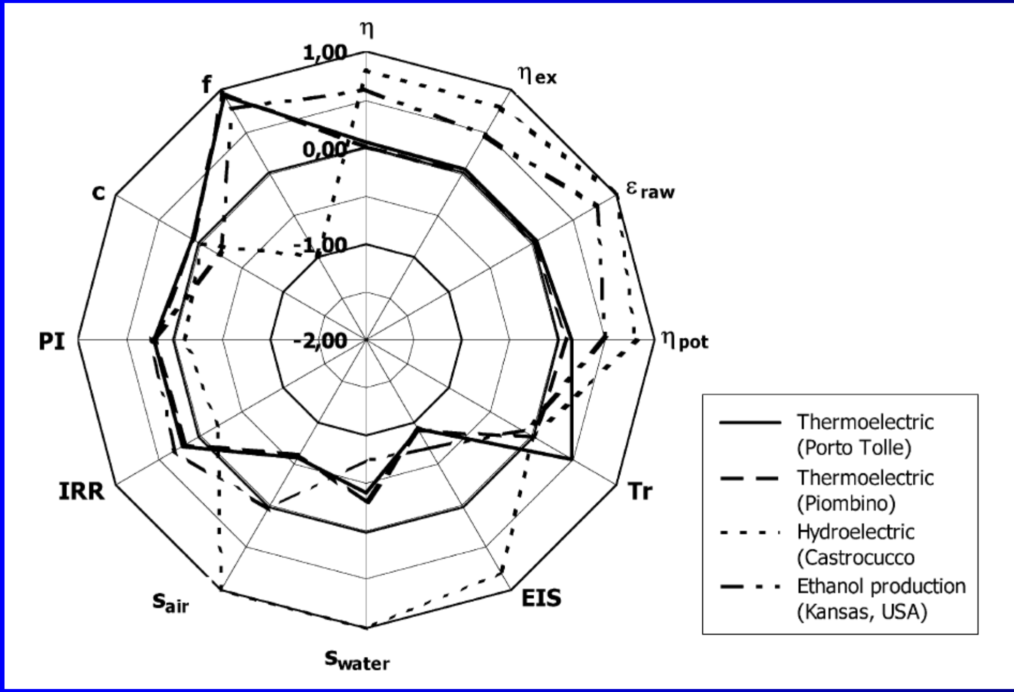
Some obvious deficiencies of emergy as a sustainability indicator

- The calculation of the transformities is difficult and is perforce based on very restrictive fundamental assumptions that may distort the results. For example, the transformity of oil in an underground field is ***estimated*** on the basis of an analysis of the geological processes that lead to its formation, and turns out to be 55400 Sej/J: it is clear that even a small error in this estimate is amplified as one proceeds downstream in the analysis, and may lead to a completely wrong value of the indicator Em for all products in which oil and its derivates are used.
- The calculation of the transformities does not include entropy considerations in any way
- It doesn’t contain the non-energy/exergy impacts, say toxicity, and certainly not socio-economic values.

An example of comparative sustainability analyss of a number of power generation plants

"An integrated assessment of energy conversion processes by means of thermodynamic, economic and environmental parameters", S. Tonon, M.T. Brown, F. Luchi, A. Mirandola, A. Stoppato, S. Ulgiati, ENERGY 2006.

- Evaluation by individual indicators:



Evaluates 12 energy, exergy, raw material use, environmental impact, economic, and emergy sustainability indicators

- The values can be combined into a single indicator using weights for each, and an optimum sought (e.g., Diwekar 2005).

Extended Exergy as an ecological indicator (1/2)
(Sciubba, papers 1998-2006)

The *specific extended exergy*, *ee*, is defined as the sum of the physical exergy plus the equivalent exergy of Capital (ee_K), Labour (ee_L) and Environmental Remediation (ee_O) activities. These ***equivalent exergies*** are expressed in kJ (their fluxes in kW), and ***represent the amount of primary resources required to generate one monetary unit (ee_K), one workhour (ee_L) and to annihilate a certain pollution (ee_O)***:

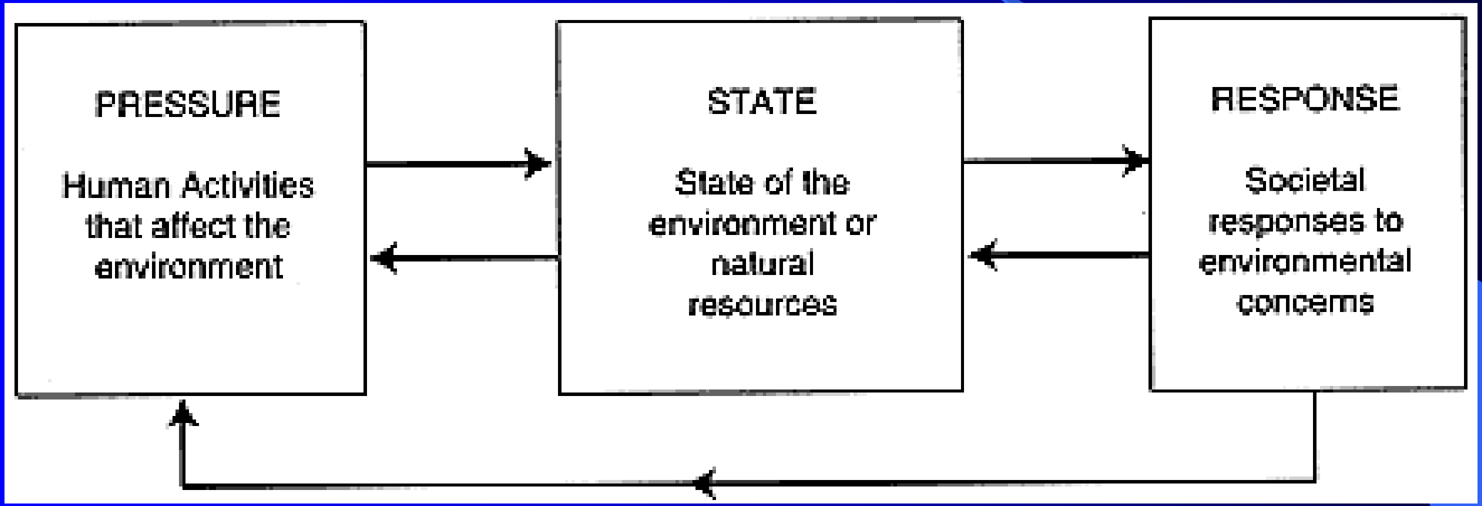
$$ee_{commodity} = e_{ph} + e_{ch} + e_k + e_p + ee_K + ee_L + ee_O$$

[J/kg, J/J or /unit]

Extended Exergy as an ecological indicator (2/2)

- The fundamental premise of Extended Exergy Accounting is that *economic systems are eco-systems that function only because of the energy and material fluxes that sustain human activities*. The correct measure for the cost of a commodity or a service is the extended exergetic content, and not capital or material flow or exergy or labour alone.
- EEA adopts the standard exergy accounting method of Szargut to embody into a product all of the exergetic expenditures incurred in during its production. Extraction, refining, transportation, pre-processing, final processing, distribution and disposal activities are computed in terms of exergy "consumption".
- The concept advances the state of the art but still suffers from some inconsistencies, inadequate accounting for human values, and "exergo-centric" belief.

Development of indicators for sustainability has aimed at combining assessments of three aspects of nature and society: economy, environmental quality, and human well-being



Pressure-State-Response framework for indicators of sustainable development.
Source: U.S. Interagency Working Group on Sustainable Development Indicators (1999).

National Academy of Science, Our common journey: A transition toward sustainability
National Academy Press, Washington DC, 2003

Multiple indicators (86 in UN study) are needed to chart progress toward the goals for meeting human needs and preserving life support systems, and to evaluate the efficacy of actions taken to attain these goals.

An Illustrative Set of Indicators for Sustainable Development in the U.S. (U.S. Interagency Working Group on Sustainable Development Indicators 1998).

Issue	Selected Indicators
Economic Prosperity	Capital assets Labor productivity Domestic product
Fiscal Responsibility	Inflation Federal debt-to-GDP ratio
Scientific and Technological Advancement	Investment in R&D as a percentage of GDP
Employment	Unemployment
Equity	Income distribution People in census tracts with 40% or greater poverty

Multiple indicators (2)

Housing	Homeownership rates Percentage of households in problem housing
Consumption	Energy consumption per capita and per dollar of GDP Materials consumption per capita and per dollar of GDP Consumption expenditures per capita
Status of Natural Resources	Conversion of cropland to other uses Soil erosion rates Ratio of renewable water supply to withdrawals Fisheries utilization Timber growth to removals balance
Air and Water Quality	Surface water quality Metropolitan air quality nonattainment

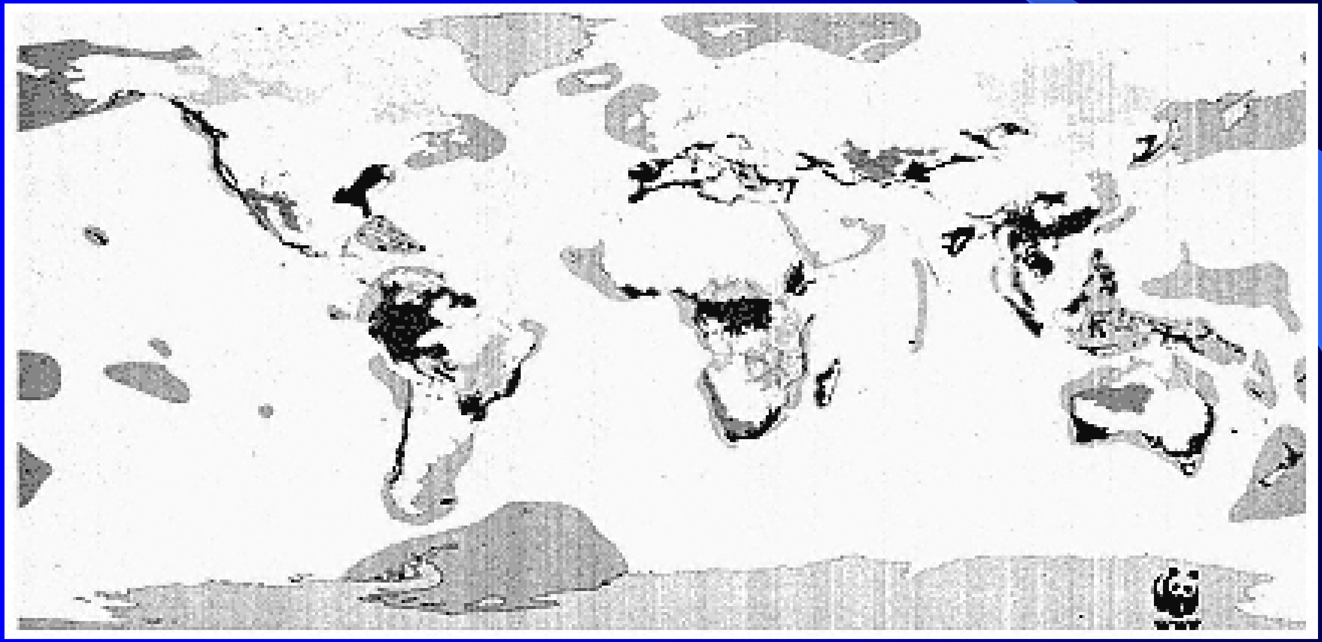
Multiple indicators (3)

Contamination and Hazardous Materials	Contaminants in biota Identification and management of Superfund sites Quantity of spent nuclear fuel
Ecosystem Integrity	Acres of major terrestrial ecosystems Invasive alien species
Global Climate Change	Greenhouse gas emissions Greenhouse climate response index
Stratospheric Ozone Depletion	Status of stratospheric ozone
Population	U.S. population
Family Structure	Children living in families with one parent present Births to single mothers

Multiple indicators (4)

Arts and Recreation	Outdoor recreation activities Participation in the arts and recreation
Community Involvement Education	Contributing time and money to charities Teacher training level and application of qualifications Educational attainment by level Educational achievement rates
Public Safety	Crime rate
Human Health	Life expectancy at birth

Application of indicators used to chart sustainability



Global 200 eco-regions proposed by the World Wildlife Fund.

Energy Indicators for Sustainable Development

The Need to Develop Indicators

- **To monitor Sustainable Development status and trends**
- **To assess effectiveness of policies in place**
- **To formulate integrated strategies and plans**
- **To become part of national statistical databases and programmes**
- **Responds to UN mandate, Earth Summit 1992 (Agenda 21- Chapter 40)**

Energy and Sustainable Development
The UN Effort

- **1992 – Rio Declaration**
- **1997- UN General Assembly**
- **2000 - World Energy Assessment and the Millennium Development Goals**
- **2001 - 9th Session of the CSD**
- **2002 - World Summit on Sustainable Development**
- **2005 – Interagency Report on Energy Indicators**

Project Objectives

- **To define a set of energy indicators and corresponding methodologies and guidelines**
- **To test and implement the indicators in a number of countries**
- **To assist countries in energy and statistics capacity building**
- **To complement the UN Commission on Sustainable Development Indicators effort**

Indicators for Sustainable Energy Development

An International Partnership

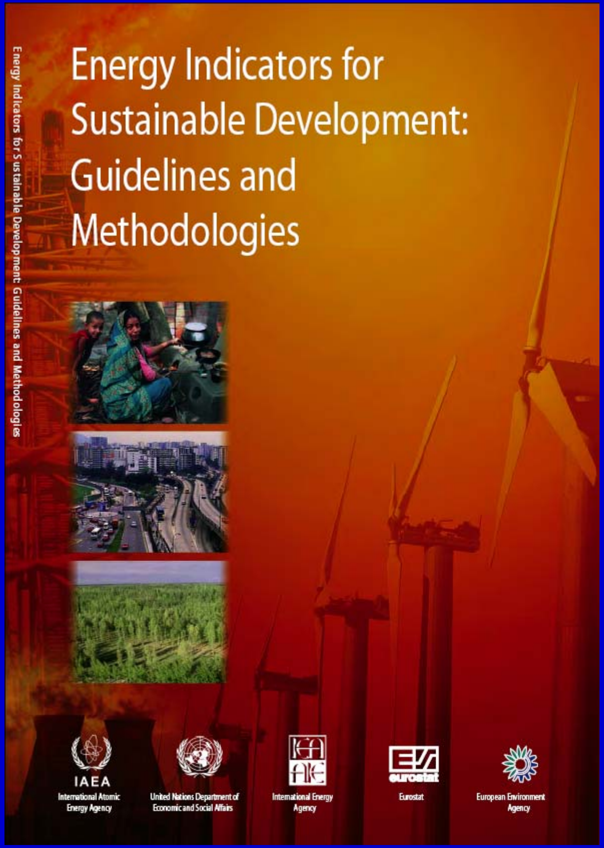
- Started in 1999
- Five International Organizations:
  - IAEA, UNDESA, IEA, EUROSTAT, and EEA
- Seven Participating countries:
  - Brazil, Cuba, Lithuania, Mexico, Russian Federation, Thailand & Slovak Republic

What Are Indicators of Sustainable Development?

- Not merely data but combinations of basic statistical data with extended significance
- Usually normalized or defined in terms of ratios, rates or proportions & disaggregated
- A bridge between primary data and interpreted information
- Useful to identify trends and relationships not evident from primary data
- Serve to monitor development and sustainability

Outcome I: A Five-agency Publication

Energy Indicators for Sustainable Development: Guidelines and Methodologies



Energy Indicators for Sustainable Development

SOCIAL

Affordability, Accessibility, Disparity and Safety

SOC**1.** Share of households (population) without electricity or commercial energy

SOC2. Share of household income spent on fuel and electricity

SOC**3.** Household energy use for each income group and corresponding fuel mix

SOC**4.** Accident fatalities per energy produced by fuel chain

ECONOMIC

Energy Use

ECO1. Energy use per capita

ECO2. Energy use per unit of GDP

Efficiency

ECO3. Efficiency of energy conversion and distribution

Resources

ECO4. Reserves to production ratio

ECO5. Resources to production ratio

Energy Indicators for Sustainable Development

ECONOMIC

Intensities

ECO6-10**.** Energy intensities by sector (agriculture, industrial, service, transportation and household)

Diversity

ECO11**.** Fuel shares in energy and electricity

ECO12. Non-carbon energy share in energy and electricity

ECO13. Renewable energy share in energy and electricity

Prices

ECO14. End use energy prices

Security

ECO15. Net energy import dependence

ECO16. Stocks of critical fuels per corresponding fuel consumption

Energy Indicators for Sustainable Development

ENVIRONMENTAL

Climate Change

ENV1. Greenhouse gases per unit of energy produced per capita, per GDP and by fuel

Air

ENV**2.** Ambient concentrations of pollutants in urban areas

ENV**3.** Air pollutant emissions from energy systems total & urban areas

Water

ENV**4.** Contaminant discharges in liquid effluents from energy systems

Land

ENV**5.** Soil area where acidification exceeds critical load

ENV**6**. Rate of deforestation attributed to energy use

Waste Generation and Management

Vera, Dubrovnik '05

ENV**7.** Ratio of solid waste to units of energy produced

ENV**8.** Ratio of solid waste properly disposed of to total generated solid waste

ENV**9.** Ratio of solid radioactive waste to units of energy produced

ENV10**.** Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste

Energy Indicators for Sustainable Development

Vera, Dubrovnik '05

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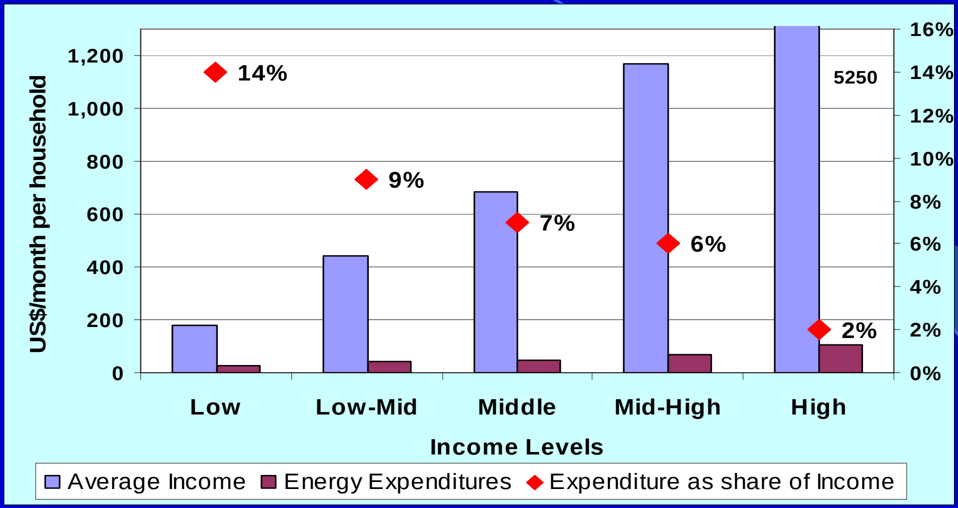
The Need to go beyond Energy Indicators

- ***Qualitative*** issues need to be considered (institutional, infrastructure, etc.)
- A *Quantitative Analysis* ***is not*** sufficient
- The approach has to be Systematic and Forward Looking
- A Comprehensive approach that incorporates all relevant issues is necessary
- In summary, ***Country Profiles on Sustainable Energy Development*** are needed

Energy Indicators for Sustainable Development

Social (Affordability SOC2)



Average Income and Monthly Household Energy Expenditures by Income Level, Brazil

- *The Poor have to use a larger share of income*
- *The Rich consume more energy and use a lower income share*
- *The fuels used by the poor are less efficient*
- *Many times the poor consume non-commercial fuel to avoid the cost of commercial energy, even if available*

Vera, Dubrovnik '05

conclusion

- Large projects must take sustainability into account, carefully
- Quantification of the project metrics (indicators) is very difficult in these large very complex systems which have technical, ecological, economic and societal components
- Useful work to that end is under way but much remains to be done

Some additional references

- Reuter MA et al, The metrics of material and metal ecology, Elsevier 2005.
- Urmila Diwekar, Green process design, industrial ecology, and sustainability: A systems analysis perspective, Resources, Conservation and Recycling 44 (2005) 215–235