About sustainability metrics for energy development

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ABSTRACT

This paper describes the role and status of sustainability metrics (indicators) and their ongoing development, points out obstacles, and makes recommendations for a more effective and timely progress in this endeavour which is critical to the transition to sustainability. The task is very difficult because we need to deal technical economical, ecological and social issue, composing a Very Large Complex Systems ("VLCS") in space and time that is not at all easy to define succinctly, or even at all. The conventional pre-"sustainability" metrics that include primarily monetary measures, energy, exergy, and Second Law efficiencies, energo- and exergo- economics, and use of materials and resources, and then metrics with expanded boundaries, which include embodied energy efficiency, present worth life cycle analysis (LCA), emergy, and "extended exergy" that also assigns exergy values to labor, ecological impact, environmental remediation, and money, are described. In the next step, their combination into a single aggregate indicator so that an optimum value can be sought is discussed. In contrast with most studies that focus on using the metrics mainly for monitoring progress to sustainability, this paper emphasizes the importance of integrating them into the design and development process, for a-priori creation of sustainable products and systems. Some of the main obstacles that scientists and engineers face in this endeavor are defined as (a) the reductionist practice of scientific research tends to focus on the details of a system, while paying little attention to the broader implications of the work, (b) the difficulty in crossing disciplinary boundaries due to lack of consilience (c) the arrogance of specialization, and (d) some weakness of tools for solving Very Large Complex Systems. While formidable, these obstacles can be overcome, especially through education beginning from the earliest ages. There is clearly a need for effective multidisciplinary work, creating a common language and mutual respect; the advent of sustainability science.

INTRODUCTION: SUSTAINABILITY AND ITS QUANTIFICATION

Sustainability is an increasingly common word in the broader society, often used in a somewhat loose fashion. It has many definitions which depend largely on the application and the user. Probably the most general and earliest one is *the way to meet the needs of the present without compromising the ability of future generations to meet their own needs* [1]. While providing an ethical and sensible direction, it is obvious that it is very difficult to quantify, since it does not define what the current needs are, what the composition of the future generations is, what their needs should be, which resources they would use, what the availability of these resources would be, and what the time frame is. Quantification of sustainability is a vital first step in human attempt to attain it, and in establishing the critically needed sustainability science, and the objective of this paper is to attempt to introduce, albeit not altogether comprehensively, the state of the art of sustainability metrics (or indicators) and point out some of the work needed to advance it to an applicable level.

The *needs* in the definition of sustainability are economic, social and environmental, and must be provided in a balanced manner. These three needs are considered to be the pillars of the sustainability concept, or the "*triple bottom line*" that must be met, replacing the single bottom line of monetary performance. They bring up a further serious complication, that of *values*: different individuals, families, communities, cities, and nations have different values, often widely so, and thus the definition of the needs is highly dependent on the individuals and groups, and also on time, and must thus be defined for all these different entities.

The difficulty in defining, and indeed satisfying activities that meet the above sustainability definition, at least in the short term, brought rise to less demanding "practical" definitions, such as that formulated by industry/commerce: *a sustainable product or process is one that constrains resource consumption and waste generation to an* <u>*acceptable level*</u> *(my underline), makes a positive contribution to the satisfaction of human needs, and provides enduring economic value to the business enterprise* [2]. In fact, many utilities take a minimalist sustainability indicator, that of meeting environmental regulations, which they would have had too meet anyway just for compliance with the local laws.

Regardless of the specific definition, and their complexity, the sustainability metrics must satisfy some common sense criteria. They must be:

- Inclusive of economical, environmental and social concerns (the three pillars of sustainability)
- Relatively simple, and widely understandable,
- Normalized to allow easier comparisons,
- Reproducible,
- Satisfy the laws of nature.

It is appropriate to introduce sustainability metrics by noting that the "Living Planet Index", a metric which measures trends in the Earth's biological diversity has declined since 1970 by about 30%, and that the "Ecological Footprint" (defined in [3] extended in [4]), which is the area of biologically productive land and water needed to provide ecological resources and services including land on which to build, and land to absorb carbon dioxide released by burning fossil fuels, increased by 70% in the same period [5]. These trends are clearly unsustainable and alarming.

THE IMPERATIVE: SUSTAINABLE DESIGN AND DEVELOPMENT

All development, macro to nano, such as power generation, propulsion, HVAC (heating, ventilation and airconditioning), chemical processes, manufacturing, materials making and processing, water, food, transportation, and communications, involves energy/exergy use and conversion, use of materials, economic resources and human effort, and produces byproducts that may affect the environment. Performed in practically all cases at a rapidly increasing scale, the developments increasingly threaten local and often global sustainability.

A good example for a transition to sustainability in the U.S. is the GreenBuild initiative of the Sustainability Summit of Professionals (American Society of Heating, Refrigerating and Airconditioning Engineers (ASHRAE), U.S. Green Buildings Council (USGBC), American Society of Interior Designers, American Institute of Architects (AIA), International Interior Design Association, CoreNet Global, Association for Corporate Real Estate Professionals, , Construction Specifications Institute, Urban Land Institute, International Facility Management Association, Building Owners & Managers Association, Association of Higher Education Facilities Officers, Institute of Real Estate Management, and Society for College & University Planning) [6,7]. Green Chemistry, or Industrial Hygiene, programs and methodologies (cf. [8-12]) is another good example world-wide.

The preference is to integrate sustainability onto the development and design, adding the environmental, economic and social impact equations to those we normally use in modeling systems and processes. The system spatial and time boundaries may typically be rather large, encompassing all of the steps from the extraction of raw materials to the final disposal of the system (preferably with a final recycling step) and remediation of the raw material source ("cradle-to-cradle" analysis), including all materials and energy flows, extending from the considered process, to the enterprise in which it takes place, further into the economy, and then into the environment. The difficulty is in the fact that we now need to deal with Very Large Complex Systems ("VLCS"), which are that way because they are large nonlinear dynamic and complex systems that include ecosystems. The complexity of a system is in large part due to emergence[1] and self-organization, hard to quantify phenomena. The mathematical modeling and solution of such systems is multiscale (in time and space), which must typically include uncertainty analysis and statistics because of uncertainties in data and prediction of future behavior.

DEVELOPMENT STAGES OF SUSTAINABILITY METRICS

First: methodology descriptions

Due to the enormous complexity, the development of sustainability metric started in 1983 with a largely non-quantitative description of the need for sustainable development, and of general ways to go about it. The earliest comprehensive international effort is summarized in the U.N. World Commission on Environment and Development report "Our Common Future", published in 1987, sometimes called the Brundtland Report [1]. The objectives of the Commission were to formulate a "A global agenda for change":

- "to propose long-term environmental strategies for achieving sustainable development by the year 2000 and beyond;
- to recommend ways concern for the environment may be translated into greater co-operation among countries of the global South and between countries at different stages of economical and social development and lead to the achievement of common and mutually supportive objectives that take account of the interrelationships between people, resources, environment, and development;
- to consider ways and means by which the international community can deal more effectively with environment concerns; and
- to help define shared perceptions of long-term environmental issues and the appropriate efforts needed to deal successfully with the problems of protecting and enhancing the environment, a long term agenda for action during the coming decades, and aspirational goals for the world community".

The Commission called for the UN General Assembly to transform this report into a UN Programme on Sustainable Development, which the UN did.

In November 1996, an international group of measurement practitioners and researchers from five continents came together under the auspices of the International Institute for Sustainable Development at the Rockefeller Foundation's Study and Conference Center in Bellagio, Italy, and formulated **The Bellagio Principles for Assessment of Sustainable Development** [13], which had no quantitative metrics.

The U.S. National Academy of Sciences National Research Council Policy Division Board on Sustainable Development published in 2003 a rather comprehensive study titled "Our Common Journey: a Transition Toward Sustainability" [14] that examines ways to attain sustainability. The study touches on sustainability indicators, concluding that **there is no consensus on the appropriateness of the current sets of indicators or the scientific basis for choosing among them.** Their effectiveness is limited by the lack of agreement on the meaning of sustainable development, on the appropriate level of specificity or aggregation for optimal indicators, and on the preferred use of existing as opposed to desired data sets.

To characterize the effectiveness of actions undertaken to reach the goals, they recommend at least four approaches: maintaining national capital accounts (natural, human, and produced capital resources); conducting policy assessments; monitoring essential trends and transitions; and surprise diagnosis (for the unexpected). It is interesting, but perhaps not surprising since the study was performed by a policy group, that they emphasize the definition and use of indicators primarily for monitoring sustainability over time (as do the parallel UN groups), while as scientists and engineers we are typically more interested in them as objective functions for establishing optimal design and development.

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[1] The arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems.

Metrics can be qualitative, defined by semantic ratings based on observation and judgment, or quantitative. They can be defined as absolute or relative. They can be time-independent, or dependent, such as those that compute the change in a particular quantitative metric over a given time-period.

Conventional (pre-sustainability) metrics (cf. [15])

These are usually single-purpose metrics, which are well known, and include:

- Monetary criteria, such as profit
- 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, Return on Investment (ROI), Life-Cycle Analysis (LCA- a rapidly evolving and adopted concept, cf. [16-21]) or exergo-economics (cf. [22,23])
- Embodied energy efficiency (cradle to cradle, or at least to grave)

While these metrics do not characterize the full aspect of sustainability with its triple bottom line, they can and often do serve as parts of a composite sustainability index.

Towards sustainability: Extended metrics

Materials Throughput Analysis (MTA.) Considered in 1980-s by some World Bank people, it is a normalized mass flow rate of all materials, from their extraction to disposal, per person (or per unit) per year. While valuable for some purposes, it is not descriptive of the triple bottom line.

Extended exergy [24]. The *specific extended exergy*, *ee*, is defined as the sum of the physical, chemical and mechanical exergy ($e_{ph} + e_{ch} + e_k + e_p$) 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 work hour *(ee_L)* and to annihilate a certain amount of pollution *(ee_O)*:

$$ee_{commodity} = e_{ph} + e_{ch} + e_k + e_p + ee_K + ee_L + ee_O \qquad (1)$$

with the units of J/kg, J/J or per unit of the parameter in question.

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 labor alone.

Extended Exergy Accounting adopts the standard exergy accounting method of Szargut [25] 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".

Extended exergy as sustainability indicators was used in several studies [26,27], and an eco-exergy indicator was proposed [28].

The extended-exergy concept advances the state of the art, but still suffers from some inconsistencies, inadequate accounting for human values, and "exergo-centric" belief.

Emergy [29,30]. It is a measure of the total solar equivalent available energy that was used up directly and indirectly in the work of making a product or service. Assuming that solar energy is our ultimate energy source, *emergy* expresses the cost of a process or a product in solar energy equivalents. Embodied in the emergy value are the services provided by the environment which are free and outside the monied economy.

While a step in the right direction, emergy was found to have some definitional, conceptual and applicational deficiencies [31], but is worth refining.

Some major indicators

A method for developing indicators that assess aspects of environmental and societal trends influencing sustainability is the Pressure-State-Response (PSR) that links between human actions and environmental consequences (see critique in [32]). Human activities exert *pressures*, that may alter the *state* of environmental variables, and those impaired states, in turn, elicit *responses*, such as regulations intended to reverse these alterations. The pressure, states and response can be measured, serving the basis for indicators (cf. [33]). Examples of sustainable development indicators in the U.S. are shown in Table 1.

Table 1 An Illustrative Set of Indicators for Sustainable Development in the U.S. [33]

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
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
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
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

Source: Based on U.S. Interagency Working Group on Sustainable Development Indicators (1998).

The European Environmental Administration (EEA) has developed a core set of 37 indicators European System of Environmental Pressure Indices (ESEPI) [34].

Starting with UN-developed guidelines for sustainability indicators [35], collaboration of five international agencies (IAEA, UNDESA, IEA, EUROSTAT, and EEA) began in 1999 a study of indicators for sustainable energy development for 7 countries: Brazil, Cuba, Lithuania, Mexico, the

Russian Federation, Thailand and the Slovak Republic, to help monitor their development and sustainability [35,36]. The chosen indicators of sustainable development for the study were combinations of basic primary statistical data with extended significance, usually normalized or defined in terms of ratios, rates or proportions, and were disaggregated. They were treated in a way to be useful to identify trends and relationships not evident from primary data. Thirty indicators were selected and used in the study.

It is obvious that broad-based sustainability metrics must carefully consider stakeholder needs, since there are many groups and individuals affected by them.

Composite metrics (indicators)

A good example for an analysis which uses multiple metrics, energy, exergy, emergy, economics, and emissions to several energy conversion processes (hydroelectric and thermoelectric ones and bioethanol production) is given in [37]. The specific 12 metrics used are:

- First Law efficiency η,
- Raw energy conversion coefficient, ε_{raw}, which quantifies the level of utilization of raw resources (non-renewable resources, fossil fuels). Its numerical value can range between η (no renewable energy used) and $+\infty$ (best use, no raw energy used at all). In comparison with η, ε_{raw} highlights how much raw energy can potentially be saved if renewables are substituted for fossil fuels to get the same products.
- Exergy efficiency, η_{ex}, which evaluates system performance in converting input exergy ('fuel' exergy) into exergy associated with the delivered products.
- Potential second law efficiency, η_{pot}, which assesses the potential additional exergy efficiency deriving from exploiting the outlet flows that exist as streams but are not considered as useful products and effectively used. These products are normally useful only under some conditions (e.g., the heat released with flue gases when low temperature heat is not needed nearby).
- Profit index (PI), which provides a direct measure of the investment performance by measuring the profit associated with the plant operation at the end of the economic life (NPW) referred to the initial investment.
- Internal rate of return (IRR), which assesses the ability to report profits. It expresses the value of the discount rate at which the investment involves no economic benefit. The greater this value, the more competitive the investment.
- Cost of products per unit exergy, c, which determines the efficiency in using the economic resources to get the products.
- Exergo-economic factor, f, which compares the plant capital cost against the cost of the irreversibilities linked with the process. In fact, the latter involves increased amounts of energy and material (and thus increased costs) in order to get the same products, if compared with ideal processes. In principle, the exergo-economic factor f may vary between 0 and 1.
- Environmental impact factor for air, s_{air}, and for water, swater, which provide a measure of the environmental performance of the process in releasing polluting substances to get the products. It compares the emission of selected substances or waste flow with an appropriate threshold value (directly referred to the legal limit for emission).
- Transformity (Tr), which provides a measure of both environmental quality of the product and efficiency of the generation process on the scale of the biosphere, according to the emergy accounting method [29]. It is defined as the ratio of the total emergy input to the total exergy of the outputs.
- Emergy index of sustainability (EIS), which measures the potential ability of the system in providing the highest benefit (emergy yield ratio (EYR)) to the economy versus the lowest environmental loading (environmental loading ratio (ELR)). It is therefore an aggregate measure of yield and environmental loading, i.e. a sustainability function for a given process (or economy), expressed in emergy terms [30].

The results, normalized in a way to be presented in a common "amoeba diagram" are shown in Fig. 1 for 4 processes, which allow their comparison in terms of these 12 metrics.

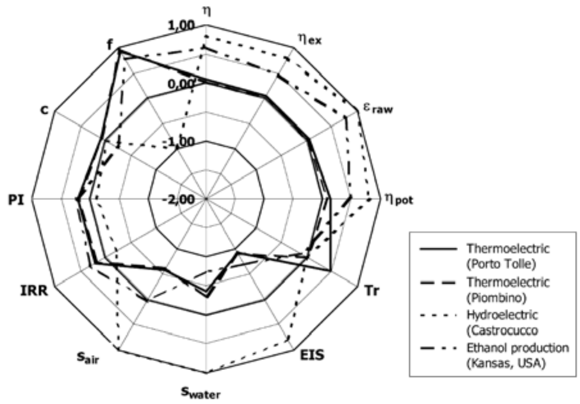

Fig. 1 An "amoeba" (or "radar") diagram representing 12 sustainability metrics for four different energy conversion processes [37].

The values of the metrics used, M_i can be aggregated into a single composite metric (*CM*) indicator using weights (w_i) for each, as

$$CM = \sum_i M_i w_i \tag{2}$$

if the individual metrics should be summed, or by any other operator, such as product, that produces the best mathematical composition of the individual metrics.

Obviously, we need the functional dependence of the metrics, and sometimes of the weighting factors, on the process parameters. The choice of weighting factors, consideration of uncertainties in data and assumptions, and the method of aggregation in dealing with these time-dependent very large complex systems is not easy to model mathematically. An interesting yet simplified approach is outlined in [38] using decision theory and based on the General Indices Method, and further mathematical treatment is shown in [39], and discussion of multi-criteria sustainability evaluation in [40].

Once the *CM*, with its dependence on the system parameters is thus established, it can serve as the optimization objective function, or be part of it, and the objective function can then be used to seek the optimal system solution.

A very useful review of eleven sustainable development (SD) indices for countries was recently published by Böhringer and Jochem [41], as to their consistency and meaningfulness: the Living Planet Index (LPI), Ecological Footprint (EF), City Development Index (CDI), Human Development Index (HDI), Environmental Sustainability Index (ESI), Environmental Performance Index (EPI), Environmental Vulnerability Index (EVI), Index of Sustainable Economic Welfare/Genuine Progress Index (ISEW/GPI), Well-Being Index (WI), Genuine Savings Index (GS), and Environmental Adjusted Domestic Product (EDP). They conclude that normalization and weighting of indicators are in general associated with subjective judgments and thus reveal a high degree of arbitrariness, scientific rules for establishing aggregation are often not taken into account, and, therefore, "SD indices currently employed in policy practice are doomed to be useless if not misleading with respect to concrete policy advice".

CORPORATE INTEREST IN SUSTAINABILITY, AND ITS INDICATORS, IS GROWING

It is highly encouraging that here is a rapidly growing interest of corporations to take a role in sustainable development, despite traditional conservatism and reluctance to make investments for uncertain far-future benefit. There are several solid reasons for this trend, including the improvement of their image in a world that is increasingly concerned about sustainability, impending government regulations (especially as related to the environment), a desire to take part in the sustainability market, and an increasing belief that even company-internal sustainable practices may increase the probability the company's sustainability (cf. [42]). A management strategy that incorporates eco-efficiency strives to create more value with less impact (cf. [43] for a good summary and examples). Especially in business, transparent reporting of sustainability must make sure that it is protective of proprietary information, thus the indices must be constructed in a way that- prevents back-calculation of confidential information.

One of the normalizing factors of indices is value-added ($), the revenue minus the cost of raw materials and utilities per pound of product. This denominator is particularly useful because it simultaneously captures reductions in costs and increases in net benefits, and it is not as susceptible to market vagaries as the revenue denominator.

The **ISO 14000** environmental management standards [21] exist to help organizations minimize how their operations negatively affect the environment (cause adverse changes to air, water, or land), comply with applicable laws and regulations). The Council on Economic Priorities (CEP) proposed SA 8000, a set of social accountability (SA) standards designed to follow in the path of other 'quality' standards. CEP hopes that, like the ISO 9000 and ISO 14000 series, SA 8000 will become the standard for evaluating the quality of a company's social performance [44]

A rather comprehensive proposal for a set of metrics to be used by industry was developed by Azapagic and Perdan [45], and further discussion about industry/business metrics is in [46,47].

Table 2 World Bank monitoring sustainability indicators [48].

FOCAL AREA	INDICATOR
Environment	■ Traditional fuel use as percentage of total energy use ■ Carbon dioxide per unit of gross domestic product (GDP) ■ Nationally protected areas as percentage of total land area ■ Adjusted net saving as percentage of gross national income ■ Environment components in country policy and institutional assessments
Water supply and sanitation	■ Percentage of population served by improved water supply ■ Percentage of population with access to improved sanitation
Education for All	■ Primary schooling completion rate
HIV/AIDS	■ HIV/AIDS prevalence among pregnant women age 15–24
Maternal and child health	■ Under-five child mortality rate ■ Share of births attended by a skilled professional
Investment climate and finance	■ Ease of foreign business registration (time and cost) ■ Number of clients reached by sustainable financial institutions ■ Capital adequacy ratios in line with or above the "Basel I" requirements of the Basel Committee on Banking Supervision
Trade	■ Change in exports and imports as share of GDP ■ Average unweighted tariffs

The Wold Bank

For example, the World Bank, taking a quantitative but very limited-scope bank-like attitude, has estimated the sustainability indicators as three capital accounts: (1) "produced" capital (national wealth: physical capital and financial claims), (2) natural capital (the resources and capitalized value of services provided by the natural world (the World Bank study took into account only the use values of natural resources, ignoring unpriced damage to ecosystems, as well as ecosystem services like the flood control capabilities of wetlands and aesthetic or moral dimensions of resource value), and (3) human resources (the economic value of labor, knowledge, and social institutions, estimated as the wealth residual, accounting for the generation of the actual flows observed in national income accounts [48]. Table 2 shows the World Bank monitoring sustainability indicators.

Dow Jones Sustainability Indexes [49]

Starting from 1999, Dow Jones, Inc. defines corporate sustainability as a "business approach that creates long-term shareholder value by embracing opportunities and managing risks deriving from economic, environmental and social developments." Based on specific metrics, which encompass both external and internal company practices, Dow Jones identifies sustainability leaders for the Dow Jones Sustainability Indexes. The evaluation is based on "Corporate Sustainability Assessment", which is a defined set of criteria and weightings used to assess the opportunities and risks deriving from economic, environmental and social developments for the eligible companies. Based on this sustainability assessment companies are ranked within their industry group and selected for the Dow Jones Sustainability Indexes, if they are among the sustainability leaders in their field. They are shown in Table 3.

Table 3 Criteria and weightings for the Dow Jones Corporate Sustainability Assessment [49]

Dimension	Criteria	Weighting (%)
Economic	Codes of Conduct / Compliance / Corruption&Bribery	5.5
	Corporate Governance	6.0
	Risk & Crisis Management	6.0
	Industry Specific Criteria	Depends on Industry
Environment	Environmental Performance (Eco-Efficiency)	7.0
	Environmental Reporting*	3.0
	Industry Specific Criteria	Depends on Industry
Social	Corporate Citizenship/ Philanthropy	3.5
	Labor Practice Indicators	5.0
	Human Capital Development	5.5
	Social Reporting*	3.0
	Talent Attraction & Retention	5.5
	Industry Specific Criteria	Depends on Industry

The World Business Council for Sustainable Development (WBCSD) [50]
Another example of the increasing corporate interest is the establishment and operation of the World Business Council for Sustainable Development (WBCSD) [43] which works with 190 companies in 35 countries to “provide business leadership as a catalyst for change toward sustainable development, and to support the business license to operate, innovate and grow in a world increasingly shaped by sustainable development issues.” Their focal areas are energy and climate, development, the business role, and ecosystems, and development and use of indicators is a part of all this.

The Global Reporting Initiative (GRI) [51]
GRI is a worldwide, multi-stakeholder organization that developed a widely used sustainability reporting framework and continues to work on its improvement and application worldwide. This framework sets out the principles and indicators that organizations can use to measure and report their economic, environmental, and social performance. The Reporting Framework is intended to facilitate transparency and accountability by organizations – companies, public agencies, non-profits - of all sizes and sectors, across the world.

OBSTACLES IN THE WAY OF SCIENTISTS AND ENGINEERS

The development of sustainability metrics is, as described above, a very formidable task, but it is a necessary requisite for an effective and timely transition to sustainable development. Some of the main obstacles that scientists and engineers face in this endeavor are:

- The reductionist practice of scientific research tends to focus on the details of a system, while paying little attention to the broader implications of the work.
- Exacerbated by the difficulty in crossing disciplinary boundaries: lack of consilience[2] in the objectives of different disciplines that consider the economic, philosophical, cultural, and scientific and engineering aspects.
- Definition of time and space boundaries, and multiple scales
- The arrogance of specialization.
- Weakness of tools for solving Very Large Complex Systems.

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[2] The unity of knowledge, a coming together of knowledge.

While formidable, these obstacles can be overcome, especially through education beginning from the earliest ages.

CONCLUSIONS AND RECOMMENDATIONS

- 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
- The modeling and solution are very difficult because the problems are dynamic, multi-scale and in many parts non-deterministic, and the data are difficult to collect: better knowledge and tools are needed
- Achieving sustainability requires a new generation of engineers and scientists who are trained to adopt a holistic view of processes as embedded in larger systems.
- Useful work to that end is under way but much remains to be done
- There is clearly a need for effective multidisciplinary work, creating a common language and mutual respect; the advent of sustainability science.

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