QUANTIFYING SUSTAINABILITY FOR ENERGY DEVELOPMENT

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The University of Pennsylvania (commonly referred to as Penn) was founded by Benjamin Franklin in 1740. It is consistently ranked among the top research universities in the world, for both quality and quantity of research. As one of the most active and prolific research institutions, Penn is associated with several important innovations and discoveries in many fields of science and the humanities. Among them are the first general purpose electronic computer (ENIAC), the rubella and hepatitis B vaccines, Retin-A, cognitive therapy and others. Penn's academic and research programs are led by a large and highly productive faculty. Nine Penn faculty members or graduates have won a Nobel Prize in the last ten years.

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Abstract

This article critically reviews the existential need, history, role and status of applying quantitative scientific sustainable development in all human activities of globally-affecting magnitude. While it focuses on the critical topic of energy, the principles are the same for all other fields such as water and food. Sustainability metrics and their ongoing development are described, and their combination into a single aggregate indicator for functional use in analysis and optimization is formulated. In contrast with most studies that focus on using the metrics and indicators 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, (d) definition of time and space boundaries, and use of the very wide-ranged multiple scales, and (e) 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. The weaknesses of the political system to implement national and global sustainable development because of the need for long-term multi-generational and international scope, as well as the critical need for an ethical approach, are identified. There is clearly a need for effective multidisciplinary work, creating a common language and mutual respect: the advent of

sustainability science. References are liberally cited for those who wish to learn more.

1. Introduction: sustainability and its quantification

It is appropriate to introduce sustainability science by noting that the "Living Planet Index", a metric which measures trends in the Earth's biological diversity, has from 1970 to 2010 declined by 52%, and that the ratio between the "Ecological Footprint" (defined in[1] extended in[2]), 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, relative to the planet's biocapacity (the amount of biologically productive land and sea area that is available to regenerate these resources), increased by 50% in the same period[3]. In 2010 humanity required the capacity of 1.5 Earths to satisfy its consumption, meaning that we are already using and depleting nonrenewable reserves of the Earth.

> ***There is clearly a need for effective multidisciplinary work, creating a common language and mutual respect: the advent of sustainability science. References are liberally cited for those who wish to learn more.***

Among other existence-threatening phenomena resulting in important part due to unsustainable development are the rising effect of global warming, including the increasing melting of global ice and snow (e.g., on 25 February 2015 the Arctic ice reached its annual maximal extent that was the lowest in recorded history[4]), and increasing water contamination and scarcity: currently about 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical scarcity, and 500 million people are approaching this situation, and another 1.6 billion people, or almost one quarter of the world's population, face economic water shortage. The UN predicts that by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could live under water stress conditions[5,6].

All these trends are clearly unsustainable, increasingly alarming, and explicitly require immediate changes to implement sustainable development. For optimal consequences this must be done as scientifically as possible.

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 best known is that of the UN Brundtland commission 1987 report, recommending that "humanity makes development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"[7]. A similar but differently-worded remarkable statement was formulated about 200 years earlier by Thomas Jefferson, one of the, leaders of the USA revolution, authors of the U.S.A. constitution, and presidents: "Then I say the Earth belongs to each generation during its course, fully and in its right... Then no generation can contract debts greater than may be paid during the course of its existence"[8]. This statement is especially extraordinary and even prophetic because at that time (1789) the USA was sparsely populated and at least in principle not lacking in natural resources.

While providing an ethical and sensible direction, it is obvious that these statements/objectives are very difficult to quantify, since they do 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, the nature of the "debts" and their repayment, 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 comprehensively, the state of the art of quantitative sustainability analysis and point out some of the work needed to advance it to an applicable level. The current ambiguities in the definition of sustainability not only impede sensible development but also give rise to the fraudulent use of this existentially important concept and its terminology, thus diminishing its value by desensitizing society and sowing distrust[9].

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 overwhelmingly used 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 acceptable level*, makes a positive contribution to the satisfaction of human needs, and provides enduring economic value to the business enterprise[10]. Much of this definition is self-serving for industry, without adequate consideration of sustainability. For example, 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 inherent complexity, the sustainability metrics must satisfy some common sense criteria. The metrics must:

- Be inclusive of economical, environmental and social concerns (the three pillars of sustainability)
- Be relatively simple, and widely understandable,
- Be reproducible,
- Satisfy the laws of nature,
- Be normalized to allow easier comparisons

2. 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, medicine and health, and communications, involves energy/exergy use and conversion, use of materials, economic resources and human effort, and has byproducts that usually impair the environment. Performed in practically all cases at a rapidly increasing scale, the developments increasingly threaten local and often global sustainability.

* my underline

Some good examples for a transition to sustainability in the U.S. include 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)[11,12]. Green Chemistry, or Industrial Hygiene, programs and methodologies (cf.[13-17]) are other good world-wide example.

The distinct 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 mathematically complex systems that include ecosystems. The complexity of a system is in large part due to emergence** 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.

3. Development history of sustainability metrics

3.1 First: methodology descriptions

Due to the enormous complexity, the development of sustainability metrics started in 1983 with a largely non-quantitative description of the need for

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

sustainable development, and of general ways to go about it. The earliest comprehensive international effort is summarized in the above mentioned U.N. World Commission on Environment and Development report "Our Common Future", published in 1987[7]. 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 environmental, social, and economics 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[18], but which included 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"[19] 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, that 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.

The report emphasized the definition and use of indicators primarily for monitoring sustainability over time (as do the parallel UN groups), but scientists and engineers are typically more interested in their mathematical definitions for use in analysis and optimization.

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. In all cases, quantification promotes their more objective and scientific utility.

Since this paper focuses on sustainable energy development, the following sections emphasize energy metrics in particular. Some comments from our work on these and on sustainable energy development in the global context are available in[20-26].

3.2 Conventional (pre-sustainability) energy-related metrics

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
- Thermodynamic Second-Law efficiency: considered by itself, conducting a process closer to a reversible one under the same conditions makes it more sustainable[27].
- Energo-economics (e.g., Payback period, Return on Investment (ROI), Life-Cycle Analysis (cf.[28-33]) or exergo-economics (cf.[34-36])
- Embodied energy and exergy efficiency (cradle to cradle, or at least to grave)
- Energy-related environmental and social impact.

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

3.3 Towards sustainability: Extended metrics

Materials Throughput Analysis (MTA,[37-39]). It is a determination of the 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[40,41]. The specific extended exergy is defined as the sum of the physical, chemical and mechanical exergy plus the equivalent exergy of capital, labor, and environmental remediation 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, one work hour and to annihilate a certain amount of pollution, 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. It adopts the standard exergy accounting method of Szargut[42] 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[43,44], and an eco-exergy indicator was proposed[45].

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

Emergy[46,47], 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, and useful for some applications, emergy was found to have some definitional, conceptual and applicational deficiencies as a holistic sustainability metric[48], but is worth including as one the components, and refining.

3.4 Examples of 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[49]). 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[50]. Examples of sustainable development indicators in the U.S. are shown in Table 1.

The European Environmental Administration (EEA) has developed a core set of 37 indicators

European System of Environmental Pressure Indices (ESEPI)[51].

Starting with UN-developed guidelines for sustainability indicators[52], 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[53,54]. 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.

3.5 Composite indicators (metrics)*

It is desirable to define a minimal number of indicators (ideally one) that integrate all the metrics relevant for quantifying all the pillars of sustainability of the analyzed subject. A good example of a first step for an analysis which uses multiple metrics, including energy, exergy, emergy, economics, and emissions for several energy conversion processes (hydroelectric and thermoelectric ones and bioethanol production), but still without mathematical integration into a single indicator, is given in[55]. The specific 12 metrics used were:

* The terms "Indicator (or Index)" and "Metric" are used in the literature quite interchangeably and there is no universally accepted usage of the two terms. "Metrics" are, however, often defined as measures of parameters like weight of emissions, kWh electricity, km^2 land area use, etc., whereas "Indicators (or indices)" most often refer to a score that aggregates multiple metrics.

Table 1. An Illustrative Set of Indicators for Sustainable Development in the U.S.[50]

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 CDP • 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 nonattamment
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).

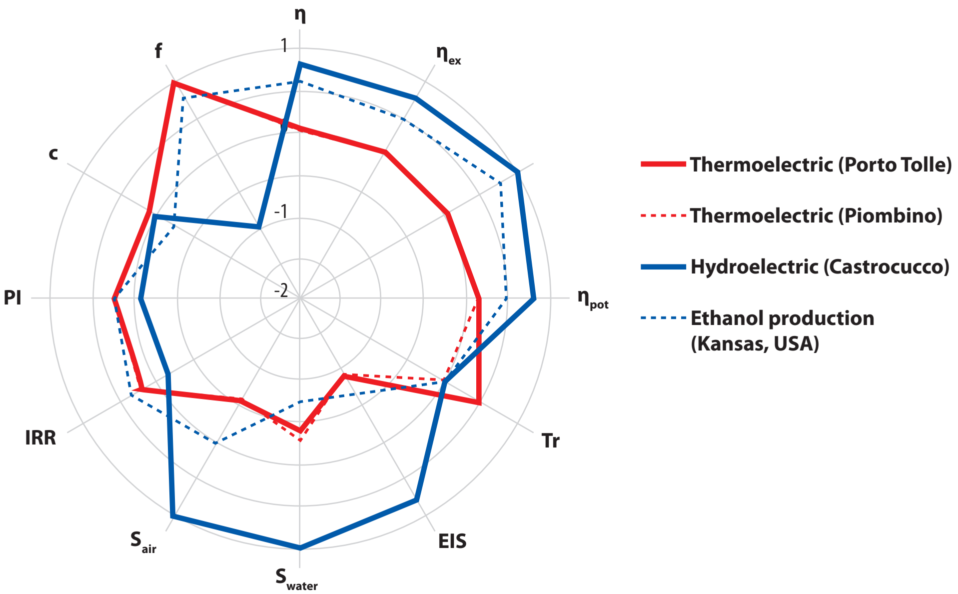

Fig. 1. A "spider" diagram representing 12 sustainability metrics for four different energy conversion processes[55].

- 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, s_{water}, 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 ac-

counting method[46]. 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[47].

The results, normalized in a way to be presented in a common "spider (or amoeba or radar) diagram" are shown in Fig. 1 for 4 processes, which allow their comparison in terms of these 12 metrics. Although the metrics are not aggregated to a single one, they allow an easy visual and quantitative comparative evaluation.

The next step in quantitative sustainability analysis would be to aggregate the values of the used metrics, Mi into a single composite sustainability indicator (CSI) using weights (wi) for each, which express their relative importance, as illustrated in Fig. 2.

The CSI are in their simplest way expressed as

$$CSI = \sum_i M_i\left(\vec{x}_{ij}\right) w_i\left(\vec{y}_{ik}\right)$$

$$\text{or} \quad CSI = \prod_i M_i\left(\vec{x}_{ij}\right) w_i\left(\vec{y}_{ik}\right) \quad (1)$$

or using some other mathematical aggregation method, where

$\vec{x}_{ij}$ the j system parameters that affect the metric M_i; Example: if a metric is environmental, the "system parameters" may be impact on biota, gaseous emissions, etc.

$\vec{y}_{ik}$ the k system parameters that affect the weight w_i; Example: if a weight is related to an environmental metric, the "system parameters" may be the relative importance of the impact on biota, gaseous emissions, etc.

i index of a metric-weight pair (M_i-w_i)
j index of a metric (M_i) – dependence parameter
k index of a weight (w_i) – dependence parameter

As shown in eq. (1), the metrics and their weights are usually functions of some system parameters, marked here as $\vec{x}_{ij}$ and $\vec{y}_{ik}$, respectively, and each one of these, in turn, can be expressed as a function of the system's component variables,

$$\vec{x}_{ij} = \vec{x}_{ij}\left(\vec{c}_{x,il}\right) \quad (2)$$

$$\vec{y}_{ik} = \vec{y}_{ik}\left(\vec{c}_{y,im}\right) \quad (3)$$

where

$\vec{c}_{x,il}$ the l component variables affecting the $\vec{x}_{ij}$; Example: if a "system parameter" is gaseous emissions, the "component variables" may be the type of power generation system, its fuel, etc.

$\vec{c}_{y,im}$ the m component variables affecting the $\vec{y}_{ik}$; Example: if a "system parameter" is gaseous emissions, the "component variables" may be the relative importance of the impact of the type of power generation system on the relative importance of gaseous emissions, etc.

l index of the component variables affecting the $\vec{x}_{ij}$

m index of the component variables affecting the $\vec{y}_{ik}$

Equations (1) – (3) create a composite sustainability index (CSI),

$$CSI = CSI\left\{M_i\left[\vec{x}_{ij}\left(\vec{c}_{x,il}\right)\right], w_i\left[\vec{y}_{ik}\left(\vec{c}_{y,im}\right)\right]\right\} \quad (4)$$

related by a system of equations expressing its dependence on all the chosen 'system parameters' and their 'component variables'. Thus established, CSI can serve as the objective function for mathematical sensitivity analysis and optimization, down to the level of 'component variables', or be part of it.

Obviously, rendition of eq. (4) to a mathematical form useful for further analysis requires knowledge of the functional dependences 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 are not easy to model mathematically. A simplified approach is outlined in[56] using decision theory and based on the General Indices Method, and further mathematical treatment is shown in[57] among others, and discussion of multi-criteria sustainability evaluation in[58].

Some models are in development for sustainability, for example The EU recently funded project INSURE

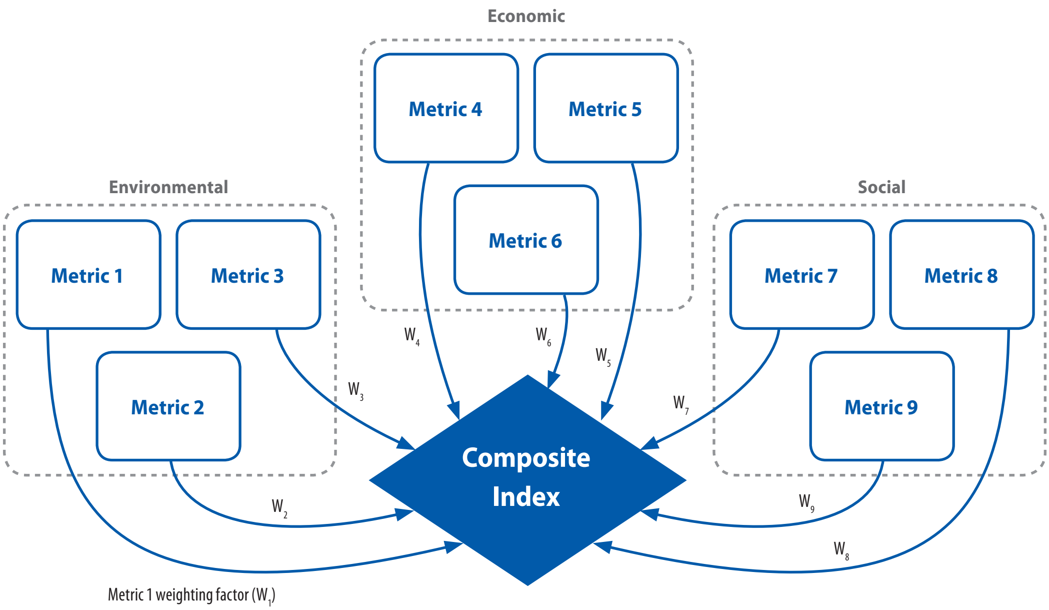

Fig. 2. A diagram for Composite Sustainability Index (CSI) construction (W_i is the weight associated with Metric i).

developed a flexible methodology for representation, analysis and evaluation of sustainability at the regional level. INSURE aimed to develop a practical and ready-to-apply method and toolkit for working with regional sustainable development indicators[59]. Validity of these evolving models is still unknown.

3.6 More on sustainability metrics and indices

Regardless of the specific definition, and their complexity, the sustainability metrics must satisfy some commonsense criteria, to be: Inclusive of economic, 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.

Perhaps the most daunting obstacle to sustainability analysis is not the just the definition and quantification of the appropriate metrics and weights, which is a very significant problem and burden for even "just" environmental impact statements (e.g.[59-61]) but the significant increase in their number, complexity and indeterministic nature (plurality). While many of the environmental metrics, such as concentrations of chemicals relative to desire values, is relatively simple ad deterministic, others such as those dealing with ecology are much more complex and unclear, and so are many of those associated with social impacts. Disciplinary and interdisciplinary work are, however, progressing rapidly to characterize sustainability as a science, and to that end quantitative scientific definitions of its metrics are evolving and gradually becoming a part of standards and regulations (e.g.,[62-68]). Since there are many definitions of sustainability indices and metrics, work is underway to establish easily-usable, appropriate and commonly accepted criteria but much remains to be done, which also constitutes an exciting challenge for all stake holders, from the global public, to users and scholars.

There is continuous progress towards development of social sustainability understanding and metrics (e.g.,[69], and[70] on quantifying the link between sustainability and human resources management, and[71] on managing corporate sustainability). It is noteworthy that the social pillar is not only for the society external to the entity but also for treatment of its own employees.

A useful review of eleven sustainable development (SD) indices for countries was published[72], 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). The paper concluded 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". Since the need for and importance of scientific development are unquestionable, we can regard this as a warning as well as an obvious encouragement for developing more appropriate indices and weighting methods, and methods of their use.

Achieving sustainability requires a new generation of scientists that are trained to adopt a holistic view of processes as embedded in larger systems. A commitment is urgently necessary to long-term sustainable planning and conduct, national, global and individual. Legislation is needed that long term sustainable planning well beyond the tenure of political leaders. Sustainable development requires a scientific approach, close and honest cooperation between all humans, across any borders they drew, humanitarian and brave vision of the future, and much respect for the environment that we so temporarily occupy.

An important step in the application of sustainable development is its use in the U.N. "Millenium Goals", established in a meeting of all world countries under UN auspices (The Millennium Summit) in 2000 and aimed to be met by 2015 (by now…). The quantitative indicators measure sustainability of countries and their development for meeting freedom from extreme poverty and hunger; quality education, productive and decent employment, good health and shelter; the right of women to give birth without risking their lives; and a world where environmental sustainability is a priority, and women and men live in equality.

In 2010 about 150 indicators were used (progress was made but the goals have largely not been met yet)[73].

A frequent problem beyond science and technology is the lack of transparency associated with metrics and indices used in many projects, since many environmental studies remain confidential for alleged commercial or security reasons, and that there is too little sharing of information (e.g.[74]). This defies principles of sustainable development and the essentially important public participation.

3.7 Sustainability weights

Weights (W_i in eq. (1)) are a quantitative expression of the importance of a metric (M_i) relative to the others. In some cases they are calculated using some quantitative analysis, but very often via polling, with some statistical significance, the opinions of experts and stakeholders, including decision makers that may include politicians. Weights can be established directly, or indirectly following a formal method, such as "pairwise comparison" or the "swing weight method" (e.g.,[61,66,67,75-78]). The determination of weights, whom to ask and by which method to calculate them, is likely to cause more controversy than other parts of sustainability analysis.

A procedurally complicating but vitally important component of the development of relevant and practical sustainability indicators is that broad-based sustainability metrics must carefully consider the needs and opinions of the stakeholders.

3.8 Solution methods for the sustainability composite indices

The CSI characterized by Eq. (4) is most often calculated by using multi-criteria analysis (MCA) techniques Case studies of EIA for pretreatment methods are calculated in[59] by using the MCA DEFINITE software tool[77], and further mathematical treatment is shown in[56,57], discussion of multi-criteria sustainability evaluation in[76-83], and fuzzy evaluation in[84].

3.9 The sustainability analysis process

The recommended quantitative process steps should be[62]:

1. Definition of the system and its spatial and temporal extent
2. Preliminary definition of the sustainability objective function and its units
3. Definition of all sustainability metrics and their system-variable dependence quantification (considering spatial effects and temporal evolution)

4. Reduction of their number to a necessary minimum
5. Normalization of the metrics and unification of their units
6. Final definition of the sustainability objective function and its units
7. Definition of the metrics' relative weights
8. Decision on the method of the aggregation of the metrics, considering space and time
9. Aggregation
10. Error analysis
11. Sensitivity analysis
12. Optimization
13. Testing under practical conditions
14. Iteration and development of learning experience for this and future projects.

A necessary and encouraging progress towards sustainable development would be standardization. The ISO 14000 environmental management standards[33] exist to help organizations minimize the negative effects of their operations on the environment (cause adverse changes to air, water, or land) and to help them comply with applicable laws and regulations). This was followed by ISO 2600:2010, Guidance on social responsibility[85]. The non-governmental organization Social Accountability International developed SA8000, one of the world's first auditable social certification standards for decent workplaces, across all industrial sectors. It is based on the UN Declaration of Human Rights, conventions of the ILO, UN and national law, and spans industry and corporate codes to create a common language to measure social performance[86]. Standards ISO 2600:2010 and SA 8000 are expected to be widely used for guiding and evaluating the quality of a company's social performance.

4. 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

In 2010 humanity required the capacity of 1.5 Earths to satisfy its consumption, meaning that we are already using and depleting nonrenewable reserves of the Earth.

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.
- Exacerbation by the difficulty in crossing disciplinary boundaries: lack of consilience* in the objectives of different disciplines that consider the economic, philosophical, cultural, and scientific and engineering aspects.
- Definition of time and space boundaries and use of the very wide-ranged multiple scales.
- The arrogance of specialization.
- 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.

5. The political/legislative aspects and obstacles

By definition, sustainable development of large scale must be planned and executed to maintain the well-being of future generations, meaning that it has to extend to the far future and be global in extent. Long-term strategic planning is, however, fraught with difficulties, which presently often make it impossible. In accord with a number of studies[87], it is recommended that currently the best planning option is the reflexive iterative process: monitoring the progress and circumstances periodically, adjusting for need changes in the plan, and carefully learning from the experience, while maintaining the overall objective, with appropriate participation of stakeholders.

Sustainable development also has responsibility across global (and beyond) geographic boundaries, both since the future generations we try to keep happy may live anywhere in the world and not just in the country of their ancestors' (our!) birth/residence, and because it is impossible in the long term to maintain sustainability of a country without ensuring the sustainability of most of the other countries on earth.

Preferred ways by which democratic governments could overcome them are also described in[87]. They range from more rigorous development and use of scientific methodology in sustainable development, through proper public education, longer terms of office of elected officials responsible for SD, and to enlightened legislation that employs reflexive sustainable development with participation of relevant stakeholders and establishes sustainable development leadership bodies that are given a legal/constitutional obligation and responsibility to ensure continuity of SD plans and implementation at the multi-generational time scale. All this must stand on a firm ethics foundation: it is widely recognized that corruption, on individual through corporate and to governmental levels, may be the strongest enemy of sustainable development. Much remains to be done, very creatively

6. Recommendations and conclusions

- Large projects (and a large number of small ones) must take sustainability into account, carefully
- Quantification of the project metrics (indicators) is very difficult (but possible) in these large very complex systems which have technical, ecological, economic and societal components
- The modeling and solution are 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
- 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.
- Achieving sustainability requires a new generation of scientists that are trained to adopt a holistic view of processes as embedded in larger systems.
- A commitment is urgently necessary to long-term sustainable planning and conduct, national, global and individual.
- Legislation is needed that forces + rewards long-term sustainable planning well beyond the tenure of political leaders.
- Morality: corruption, institutional to individual, is a major enemy of sustainable development.
- Innovation!
- The critical problems that sustainable energy development poses and the possible paths to the

* The unity of knowledge, a coming together of knowledge.

future create at the same time great opportunities for respected solutions by the engineering/scientific community:

- new and expanded creativity,
- higher employment,
- Higher job satisfaction
- special prospects for small enterprises and nations that are not hampered by the inertia inherent in larger organizations.

Sustainable development requires a scientific approach, close and honest cooperation between all humans, across any borders they drew, humanitarian and brave vision of the future, and much respect for the environment that we so temporarily occupy.

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Among other existence-threatening phenomena resulting in important part for unsustainable development are the rising effect of global warming, including the rising melting of global ice and snow (on 25 February 2015 the Arctic ice reached its annual maximal extent that was the lowest in recorded history), and increasing water contamination and scarcity.

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