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SUSTAINABILITY ATTRIBUTES AND THEIR IMPLEMENTATION IN ENERGY RESOURCES UTILIZATION

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ABSTRACT

Energy generation with fossil fuels produces emissions of greenhouse gases into the atmosphere and releases toxic chemicals into the environment. Greenhouse gases produce global warming which can cause climate change and costly human displacements. Toxic chemicals released into the environment produce health problems and damage the ecosystems. With fossil fuels providing today over 85% of energy needs and the Earth's population projected to increase by several billion people and energy needs projected to double by the middle of this century, considerable pressure exists to develop sustainable energy supply services. This poses an enormous challenge to engineers, economists, and policy makers.

The energy mix required to produce energy for humanity depends on the availability of energy resources, security of energy supply, climate change requirements, technological breakthroughs, financial conditions, and public acceptance. Population, standard of living, toxic and greenhouse gas emissions, thermodynamic limits imposed on biophysical processes, and economics and ethics of resource utilization produce some key sustainability indicators or attributes that need to be employed for guiding our path toward a sustainable energy future. Following a general discussion of indicators and frameworks of indicators, a small number of energy supply values or objectives are presented for the purpose of developing attributes that can measure the degree of accomplishment of these objectives. A systems approach is then employed to define indicators for generic energy supply services and a risk-based multi-criteria decision making procedure is presented for deciding which energy supply service option is most sustainable. The methodology can be applied locally, regionally, and globally, by both the energy services providers and energy policy makers.

1. INTRODUCTION

1.1 Sustainability Attributes

Agenda 21 Program of Action for Sustainable Development, adopted in Rio de Janeiro in 1992 during the United Nations Conference on Environment and Development, calls on all countries to develop indicators of sustainable development that can provide a solid basis for decision-making at all levels. However, the precise meaning of "sustainability" and "sustainable development" depends upon who is using these terms and in what context [1]. Can these terms be measured by suitable parameters, variables, or "sustainability indicators" and can these serve useful roles for implementing public policies that prevent the humanity to run out of food, energy, and other amenities which characterize the developed world and the aspirations of many underdeveloped societies?

Attempts to define sustainability usually emphasize the discipline to which the concept is applied, but a general consensus appears to be that it is a problem of the interaction between society and nature [2]. That what can be maintained under the existing conditions can be considered sustainable, but since both the natural systems and the society are self-organizing systems they are in general in non-equilibrium and thus dynamical entities that can change gradually and abruptly and coexist at best in a *local* equilibrium. According to the report *Our Common Future* of World Commission on Environment and Development of the United Nations [3], sustainable development points to a directional and progressive change of humanity. This report defines sustainable development as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs and aspirations". Sustainability in this form is an anthropocentric concept where the human-induced changes of the environment do not threaten the exchange processes between the humanity and the natural environment in which the society is expected to survive for an indefinite time. But how is sustainable development to be achieved and what exactly are the needs and aspirations that we should be aiming at and over what space and time frames remains unclear.

Sustainability of humanity is now being threatened by rapid population growth, technology and economic development that promote consumption, emissions of greenhouse gases (GHG) and hazardous air, water, and soil pollutants from industrial and commercial operations, rapid economic development of some developing countries which require an increasing supply of cheap (fossil fuels) energy, society that demands equitable distribution of resources, etc. The world population is projected to rise from 6.4 billion people today to 9 billion people by the middle of this century [4] and the energy requirement is expected to increase 30-40% by 2030 [5]. About 85% of the current energy needs are being supplied by fossil fuels (oil, gas, coal) which yearly emit some 40 $GtCO_2e$ of GHG into the atmosphere and are rapidly being depleted [6]. These gases remain in the atmosphere for several hundred years and cause warming of the Earth's climate system, sea level rise, melting of glaciers, and uprooting of hundreds of millions of people. We should therefore be able to recognize these and other threats and act accordingly, before our habitat is changed irreversibly and we have to deal with costly adaptations that are projected to cost 20% or more of the yearly word gross domestic product [7].

Many agree that we should switch from fossil fuels to alternative energy sources that cause much less pollution and health problems, decrease consumption in developed countries, and develop economically and socially the underdeveloped countries. But how exactly to accomplish this and other visions of the UN Millennium Development Goals [8] and what exactly to "develop" through the UN Sustainable Development Programme is open to debates and challenges of government policies that so far have not produced any large-scale results.

Several officials from the World Bank [9-10] suggested that our economic system should be managed by the dividends of our resources and that an increase in moral knowledge or ethical capital for mankind is required. Yet another former economist at this bank [11] argues for three approaches to sustainable development: (1) economic which maximizes income and maintains a constant or increasing stock of capital, (2) ecological which maintains resilience and robustness of biological and physical systems, and (3) socio-cultural which maintains stability of social and cultural systems. Because the first approach can be readily quantified and the others cannot, Rogers and co-workers [12] discuss several ways to achieve sustainability. One way is to leave everything in the pristine state, or return to its pristine state, but then this will never happen because this would involve too much pain and resources. To develop so as not to overwhelm the carrying capacity of the system is also difficult to quantify for we need to correlate the number of people with the standard of living that different cultures are willing to accept. The hypothesis of Kuznets [13] that as the per capita income rises people tend to take better care of the environment suggests that we should develop as quickly as possible, while Coase [14] suggests that the polluter and victim will arrive at an efficient solution by themselves. Another proposed economic solution is to let the markets take care of it through emissions trading and many people believe in this solution. Internalizing the externalities comes from the Asian Development Bank. Externalities represent part of the difference between private costs and benefits, and social costs and benefits, and can be accounted as part of the economic activity. Reinvest the rents from nonrenewable resources into the development of renewable resources and leave future generations the capacity to be as well off as we are now are yet some other proposed solutions to address the sustainability [15].

Sustainable economy is one that is able to generate and maintain income for individuals. Environment is sustainable if species within it continue to exist through the natural selection. But humans might consider the environment sustainable if it continues to provide the necessary services, such a clean water, food and air, resources for producing energy, pristine environments for recreation, etc. If our social system is not allowed to survive because our consumption patterns produce illness, loss of basic human services, and creates dissents among various cultures and individuals then the social system in not sustainable. However, a society does not have to be equitable to be sustainable, because the dictatorial systems have been sustained quite well for millennia [16]. To achieve sustainability we should sustain economy, protect the environment, achieve social goals, and maintain institutions that are able to safeguard such visions into the distant future. Sustainability is, therefore, influenced by value judgments and ethics, and Agenda 21 Program of Action and more recent elaboration of the principles in this document suggest the *sustainability principles* as summarized in Table 1. Principles 1, 2, and 4 require clear definition, focus on holism or self-contained systems, and the importance of time and spatial scales in the assessment of sustainability. Principles 5-10 emphasize the use of a limited number of indicators or attributes and how they should be developed and employed.

United Nations, International Atomic Energy Agency, and many other national and international agencies and organizations made noble attempts to compile extensive lists of sustainability indicators [18-21]. But some of the problems with these compilations are that they are general, voluminous, and left as guides to the nations, organizations, and businesses to develop their own strategies of sustainability.

A system is a physical or non-physical entity set aside for investigation, such as a region in space, a society composed of living things, a knowledge base, and so on, and from the system's point of view indicators are *variables or properties* that define its state or its viability [22]. The system variables are its operational attributes that define its conditions and are therefore determined on the basis of its constitution and nature of its interaction with the system's environment. We can speak of material systems that are amenable to descriptions with physical laws, economic systems that are governed by economic laws, natural systems that are governed by the coexistence of ecosystems, socio-cultural systems that have in common certain beliefs and values, etc. Indicators are supposed to condense the world's complexity to a manageable amount of meaningful information on the basis of which we can make decisions. Bossel [21], for example, groups human and natural systems into three groups: *Human system* consisting of individual development, social, and government subsystems; *support system* consisting of economic and infrastructure subsystems; and *natural system* consisting of environment and resource subsystems. He then develops a set of seven objectives or *orientors* (orientations) on the basis of which the indicators are developed for *each* system under consideration. Objectives are the highest levels of our believes, values, and interests and as such account for the viability (survival and development) of the system.

Table 1. Bellagio Principles gauging progress towards sustainable development [1,17].

1	What is meant by sustainable development should be clearly defined.
2	Sustainability should be viewed in a holistic sense, including economic, social and ecological components.
3	Notions of equity should be included in any perspective of sustainable development. This includes access to resources as well as human rights and other 'non-market' activities that contribute to human and social well being.
4	Time horizon should span 'both human and ecosystem time scales', and the spatial scale should include 'not only local but also long-distance impacts on people and ecosystems'.
5	Progress towards sustainable development should be based on the measurement of 'a limited number of indicators' based on 'standardized measurement'.
6	Methods and data employed for assessment of progress should be open and accessible to all.
7	Progress should be effectively communicated to all.
8	Broad participation is required.
9	Allowance should be made for repeated measurement in order to determine trends and incorporate the results of experience.
10	Institutional capacity in order to monitor progress towards sustainable development needs to be assured.

Indicators or attributes should therefore incorporate physical, economic, social, and institutional knowledge into decision making measure and calibrate progress toward sustainable development, provide an early warnings to prevent economic, social and environmental setbacks, and be useful tools to communicate ideas, thoughts and values [18]. To be useful indicators of sustainability, they are required to describe not only the present physical, biological, social, economic, and political conditions, but also how these conditions can be sustained into the future [16]. Our goal should be to discover a *minimal* number of such variables or effective indicators that can be used as a guide for making rational decisions about the progress towards sustainability. If a proper number of sustainability indicators can indeed be determined and their interrelationship backed by data they could be used to measure the progress for building more sustainable societies.

1.2 Frameworks of Attributes

Indicators should communicate, in easily understood terms, the current status of interacting systems, trends, warnings of threatening conditions, and useful understanding of causation [23]. Since both the natural and social systems are included in this interaction it is clear that this requires making choices at the interface of science and policy. Here the roles of scientists, public, and policy-makers are often unclear and in conflict, and a collaborative process should be established for the proper choice [24]. The literature on indicators is thus flooded with preferred choices of scientists, economists, ecologists, sociologists, and others, which according to Roe [25] simply reflects the complexity of describing sustainability and sustainable development that is acceptable to all and thus requires approaching it on a case-by-case basis. We are not yet in position to place precise measures on subjective issues such as human health, availability of open spaces, species diversity, preservation of ecosystems, quality of government policy, etc. But the indicators, and possibly their aggregation into indices, are essential for making policy decisions, and one way to develop this tool is to develop its building blocks on a case-by-case basis for either local, regional, national, or international communities. The indicators should have a direct relevance to target groups, simplicity in design, reliability, and incorporate proper spatial and temporal scales [26].

The *domain-based framework* determines indicators for different dimensions of sustainability (environment, economy, society, institutions) and needs to be modified to account for their linkages and broader sustainability objectives [27]. Thus, the International Atomic Energy Agency [19], with contributions from UNDESA, International Energy Agency (IEA), and other international and national organizations, grouped indicators into three groups: *Social* with 4 indicators, *economic* with 16 indicators, and *environmental* with 10 indicators, with a total of 30 indicators. Each indicator or attribute is carefully elaborated for policy relevance, methodological relevance, and data requirements. It is suggested that the approach for indicator use should consider: Selection of major energy priority areas, selection of indicators from the list that are relevant to these priority areas, compilation of data needed to cover the priority areas, compilation of time series for each indicator, and consideration of different policies based on different energy supply scenarios.

The *objective-based framework* provides general visions or directions towards sustainability and has been adopted by the United Nations Department of Economic and Social Affairs [18]. UNDESA lists 14 broad indicator themes (objectives) for sustainability: *Poverty* (income poverty, income inequality, sanitation, drinking water, access to energy, living conditions), *governance* (corruption, crime), *health* (mortality, health care delivery, nutritional status, health status and risk), *education* (educational level, literacy), *demographics* (population, tourism), *natural hazards* (vulnerability to natural hazards, disaster preparedness and response), *atmosphere* (climate change, ozone layer depletion, air quality), *land* (land use and status, desertification, agriculture, forests), *oceans, seas and coasts* (coastal zone, fisheries, marine environment), *freshwater* (water quantity, water quality), *biodiversity* (ecosystem, species), *economic development* (macroeconomic performance, sustainable public finance, employment, information and communication technologies, research and development, tourism), *global economic partnership* (trade, external financing), and *consumption and production patterns* (material consumption, energy use, waste generation and management, transportation). Many of these sub-themes are further split into finer subdivisions and on the basis of these subdivisions 96 indicators are defined. Each of these attributes is then associated with one or more sustainability themes and ranked as primary, secondary, or no importance to the theme in question. It is suggested that these indicators be used principally as guidelines to the countries to measure their progress toward sustainability. This framework reflects the relationship between indicators and sustainability goals and is suitable for dealing with local and global issues. The weak point of this framework is that it does not capture some complex interrelationships among the various dimensions of sustainability [28].

The *sectorial-based framework* produces indicators for various sectors, such as the agrarian sector [29], energy sector [30], or industry [31]. For the energy sector framework, the indicators are grouped into: *Resource indicators* (fuel, carbon steel, copper, aluminum), *environmental indicators* (carbon dioxide, nitrogen oxide, sulfur dioxide, waste), social indicators (new job, capital, diversity and vitality), and *economic indicators* (economic efficiency, capital investment, economic community). These indicators are then weighted based on a General Indices Method for several energy options (solar, wind, biomass, oil) and a “general sustainability indicator” is determined for the selected options. Similar groups are also chosen for the industry by specifying generic indicators for all industry and indicators that are sector-specific. The environmental group includes environmental impacts, environmental efficiency, and voluntary actions (pro-active response) indicators; the economic group includes financial and human-capital indicators; and the social group includes ethical and welfare indicators. If a specific sector needs to be analyzed for sustainability then additional sector-specific indicators need to be included into this list. Patlitzianas and colleagues [32] provide a review of different agencies producing energy policy indicators and propose three groups of sector-based indicators: *Security of energy supply*, *competitive energy market*, and *environmental protection*. The security of energy supply is expressed in terms of the dependence on fossil fuel imports and availability of primary energy sources. The competitive energy market indicators consist of the energy intensity, efficiencies of energy conversion systems, per capita energy consumption, and viability of energy transport sectors that can compete with international standards. The environmental group of indicators consist of the percentage of renewable energy sources in primary and electrical energy consumption, intensities of CO_2 emissions (per GDP, capita and gross domestic energy consumption), and application of Kyoto Protocol. The viability of energy transport sector is expressed in terms of independent energy regulation, private participation, dividing of public enterprise, energy law for the reforming and privatization of energy enterprises, and adjustment of energy pricelist, but no suggestion is provided how to quantify these attributes.

In the *causal framework* for developing indicators a cause and effect relationship is sought between sustainability parameters [1,32,33]. The simplest Pressure-State-Response (PSR) approach assumes that humans cause pressure on the environment, that this pressure causes a change of state of the environment, and that as a result the humans respond to this pressure. Pressures of human activities can be population growth, urban sprawl, human-induced deforestation, or rate of resource utilization. States of the environment can be concentrations of pollutants in the atmosphere, land, and water systems; populations of species in different ecosystems; amounts of resources for human consumption in water and land systems; equity values of socio-political systems; etc. Responses can describe effectiveness of actions and policies that move the system toward a more sustainable state. In the causal framework we are concerned with assessing the cause-and-effect relations, such as the effect on energy supply prices by an energy policy that promotes the utilization of renewable energy sources. Indicators measuring the rates of change are called the *control indicators* and they are prominent in the Driving Forces-Pressures-State-Impact-Response (DPSIR) framework that brings additional complexity, and problems, to the PSR framework [28]. The DPSIR framework has been adopted by the European Environmental Agency (EEA). The rates of change can be computed with respect to time, threats, management practices, natural hazards, etc., and thus the control indicators are important to ascertain the uncertainties associated with state and response indicators [24]. Both the response and rate-of-change indicators are supposed to measure the effectiveness of actions and policies and may thus suggest policy changes and avoidance of costly mitigation actions.

A proper management of energy supply (energy generation and distribution) is essential for achieving sustainability. The accessibility and availability of inexpensive energy is essential for economic and social developments, and because of this the developing nations are less concerned with the environmental and health consequences of using fossil fuels than the developed nations. But the manner in which the energy supply resources are used up is fundamental not only for the well-being of humanity but also for averting climate change that can affect both the developed and the developing nations, and the latter in particular. A list of future energy supply values or objectives for this sector are therefore presented and discussed in Section 2. These objectives are then employed to define the associated sustainability indicators on the basis of which decisions can be made for adopting more sustainable energy supply solutions. These decisions must, however, consider different weights of the indicators and these issues are discussed in Section 3. A risk-based multi-criteria decision making methodology for evaluation of different energy supply options is also discussed in this section. Section 4 provides conclusions.

2. ENERGY SUPPLY OBJECTIVES AND ATTRIBUTES

2.1 Energy Supply Objectives

Energy supply values or *objectives* express our values and beliefs in building a sustainable energy future and provide the *direction* or guide that leads to the design of more sustainable energy supply systems [34]. These objectives differ from goals that are either achievable or not and should be defined by an interdisciplinary group of professionals and stakeholders. The energy sector professionals must be included in this group because of their expertise in designing the necessary technology, and the environmentalists and ecologists should be included because the technology interacts with the environment that supplies the resources to make the technology possible and impacts the environment through the production of technology's waste products. The stakeholders are fundamental in this group because the energy supply technology provides them with the necessary services and capital. These services in turn increase the standard of living of both the local and global communities. The energy supply objectives, which can be viewed as fundamental, can be defined as follows:

1. Energy should be produced from sustainable natural resources.
2. Energy supply and distribution systems should limit the anthropogenic change of the environment.
3. Energy supply and distribution systems should not cause health problems.
4. Energy produced should be affordable.
5. The cost of energy should not decrease the standard of living.
6. Energy produced from sustainable fuels should be rewarded.

These six *fundamental* objectives state all that should be of interest in providing guidance for action and the foundation of a quantitative modeling or analysis dealing with future energy supply alternatives. These objectives are values abstracted from sustainability principles (Table 1) and can be further elaborated into more detailed sets of objectives that must apply not only to the energy system being considered, but also to *all* those systems that interact with the considered system. In carrying out this program one should insure that the additional objectives are not redundant and that they do not produce unnecessary complexity into the analysis. The above objectives are consistent with World Energy Council's four "A"s: *accessibility* (meeting energy demand for the increasing world population), *availability* (right energy mix for long-term stability of countries), *acceptability* (energy solutions for a living planet), and *accountability* (required policies, regulations and financing) [5]. They are also consistent with United Nations guidelines on sustainable development [18].

Objective 1 calls for the production of energy with sustainable natural resources. Energy emitted from the Sun and intercepted by the Earth is sustainable on the scale of human existence. This energy is naturally captured in biomass and when fossilized produces fossil fuels (oil, gas, coal) on the time span of hundreds of million years. The modern technological society has been built with these fuels and we are now approaching the limits of their extractions and must look for their substitutions. Sufficient reserves of coal and oil and gas shales exist worldwide for several hundred years [35], but their exploitation is limited by the society's acceptance of waste products, damage produced to ecosystems, and high economic cost. Forests can produce sustainable yield of wood, but the energy produced from burning wood can be very inefficient and cause significant pollution and health problems. The sustainability criteria for natural resources involve social, economic, and environmental issues, and depend on the ability of the society to deal with resource scarcity and resource substitution and acceptance of environmental consequences [36]. Objective 1 can be further refined as:

1.1 Energy produced from natural resources should not exceed the sustainable yield of these resources.
1.2 Energy produced from natural resources should be socially acceptable.

These two objectives call for an indefinite supply of energy for humanity that is socially acceptable. They call for a widespread capture of solar energy through a variety of technological processes (solar thermal, solar photovoltaic, ocean-thermal, tidal, wind). Geothermal energy and nuclear materials for fission reactors are limited by their accessibility and have therefore limited sustainability yields. If the energy released from fusion of light nuclei (deuterium and tritium) can be made practical through the ITER project [37], it could supply energy for humanity for millions of years [38]. Objective 1.2 limits the exploitation of natural resources according to the society's vision of sustainability and thus weighs differently for the developed and developing countries. This is because the developed countries are more concerned with their environment and the developing countries with building their economies.

When an energy supply or distribution service uses a natural resource such as land and produces emissions of GHG and discharges pollutants into the air, water and soil, this service can have a significant impact on the natural landscape, affect plant and animal life, produce unacceptable noise, cause global warming, deprive population from basic services (clean water and air and land to produce crops), and increase the health problems. Objective 2 requires the preservation of natural system and can be further elaborated as follows:

2.1 Energy supply and distribution systems should not be detrimental to the environment.
2.2 Releases of waste products and pollutants into the environment from energy supply and distribution systems should be limited.

Objective 3 places the emphasis on the health of life forms and is therefore different from objective 2.

It is generally recognized that the necessary ingredient of sustainable development is the availability of inexpensive energy, and electricity in particular, for billions of people. The fossil fuels provide today most of the energy needs precisely because they are economically viable. But this viability *excludes* the cost of externalities, such as the cost of the damage produced to the environment and the cost of health services to the society. Objective 4 can thus be refined more precisely as:

4.1 Energy produced should be affordable for promoting sustainable development.
4.2 Energy produced should be affordable after accounting for the cost of externalities.

Objective 5 requires that the energy services cause the society as a whole to be better-off in the future than it is today. Many agree that the transition from fossil fuels to alternative energy sources that are more sustainable should be accomplished within several decades, but this transition is very costly for both the developed and developing nations, since this entails the build-up of new and more efficient energy distribution systems and developing the necessary technology that can economically and socially compete with the relatively inexpensive form of energy from fossil fuels available today. The gross domestic product per capita of a country is normally regarded as the *de facto* indicator of the standard of living, but this standard is more than an economic well-being of an individual or a society and should also include the quality of social services (education, health, freedom of expression, equity, availability of recreational spaces, preservation of biodiversity) and maintenance of environmental services. Objective 5 can be therefore decomposed into several more specific objectives, but for our needs we will keep it restrictive by requiring:

5.1 The cost of energy should be competitive with other methods of production.
5.2 The cost of energy should include the cost of externalities.

Objective 6 specifies that the energy produced from sustainable fuels should be rewarded. Its purpose is to create incentives for industry to develop and implement renewable energy sources, since the human interest is one of the principal motivating factors that makes our modern society function and grow. Emissions of GHG are therefore tolerated by this objective, but the emissions above certain limits are inconsistent with other objectives. Use of nuclear fuels (fission and fusion materials) is also tolerated by this objective, but according to other objectives their use must satisfy social acceptability and other criteria.

By examining the revised set of objectives it can be seen that objective 5.1 is a member of objective 4.1 and objective 5.2 is a member of objective 4.2 and can be therefore eliminated from further consideration. Neither of the remaining objective appears to be redundant and we can now summarize our final energy supply objectives in Table 2.

Table 2. Energy supply objectives.

Objective	Description
I	Energy produced from natural resources should not exceed the sustainable yield of these resources.
II	Energy produced from natural resources should be socially acceptable.
III	Energy supply and distribution systems should not be detrimental to the environment.
IV	Releases of waste products and pollutants into the environment from energy supply and distribution systems should be limited.
V	Energy supply and distribution systems should not cause health problems.
VI	Energy produced should be affordable for promoting sustainable development.
VII	Energy produced should be affordable after accounting for the cost of externalities.
VIII	Energy produced from sustainable fuels should be rewarded.

These energy supply objectives meet the energy demand for the world's population (ACCESSIBILITY: objectives VI, VII, VIII), energy supply stability (AVAILABILITY: objectives I, II), energy solution for the world's population (ACCEPTABILITY: objectives II, VI), and regulatory policies required to make the energy production socially acceptable (ACCOUNTABILITY: objective III, IV, V). They should apply to those target groups that have to make decisions about the adoption of energy supply and conversion options, either on the local, regional, or national community levels (Figure 1).

Each of these communities can provide one or more energy supply services and consists of the *technical system*, humanity or *human system*, and the environment or the *environmental system* in which the technical and human systems are embedded. Together, these three systems make up the *local biophysical system* (LBS) in which nature, technology, and human culture coexist as an integrated and interacting entity. The local community or LBS interacts with one or more external communities and their environments which make up the *external biophysical system* (EBS). If an energy supply service pertains to a local town, for example, LBS is the town and everything outside the town, including the extraterrestrial environment, is EBS. If, however, LBS is a region, then everything outside this region is EBS. If, on the other hand, LBS is the world itself, then EBS is the extraterrestrial environment which provides radiant and gravitational energy from the Sun for making the life on Earth possible. A more detailed breakdown of the systems is clearly possible, but this complicates the analysis and may not necessarily produce better results.

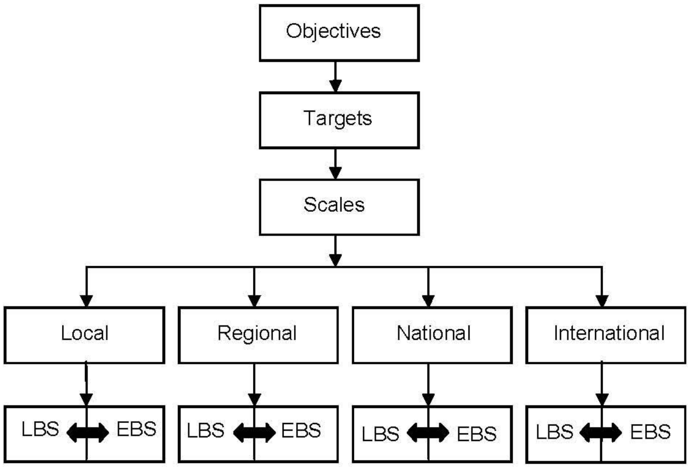

Figure 1. Energy supply objectives aim at target groups and apply to different spatial and temporal scales. Each of these scales is described by the local biophysical system (LBS) and the external biophysical system (EBS) indicators.

Figure 2 is a schematic illustration of LBS and EBS and their associated flows of materials and energy resources, energy services, and impacts from technology. An energy service, such as an electricity producing power plant, requires material resource (fossil fuels, biomass, household waste, nuclear fuel, plant construction materials) and energy for plant start-up and emergency operations, or Sun's radiant and gravitational energies if the plant captures these resources. The materials and energy flows could be used from LBS, EBS, or both. The plant can produce ash from the combustion of fossil fuels and other waste products, such as the spent fuel from a nuclear reactor. It can also produce emissions of GHG and toxic pollutants into the air, water and soil, and some of these waste products and pollutants can transcend the boundary of LBS and affect EBS. The electricity produced can be sold to local customers in LBS or exported to EBS via an electricity distribution grid. The society with its culture provides the necessary knowledge and labor to make the technical system operational and profitable.

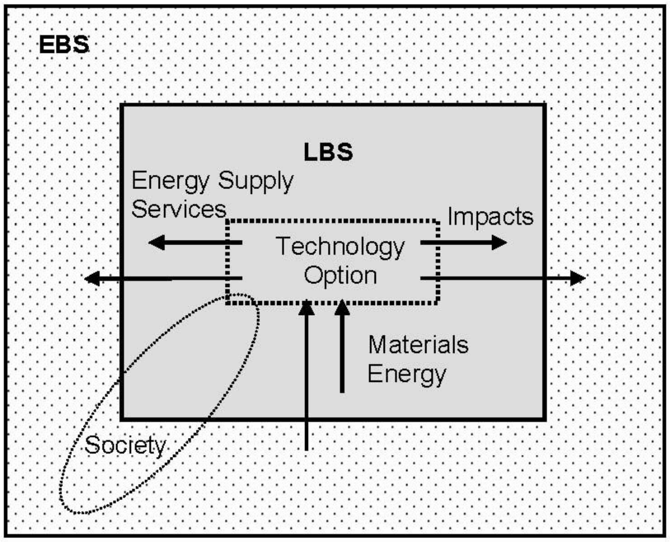

Figure 2. Local biophysical system (LBS) incorporates technology (energy supply services), local environment in which this technology is embedded, and a local society that interacts with this technology and environment. LBS interacts with the external biophysical system (EBS) with its own technologies, environment, and societal organizations. LBS technology requires materials and energy resources and produces energy services and impacts that may cross the LBS-EBS boundary.

Associated with LBS and EBS are the technical, economic, environmental, social, and institutional issues which are subjected to the limitations of energy supply objectives. Technical issues belong to the technical system and have to do with the engineering design of the energy supply option, such as the maximum power output, mechanical and thermal efficiencies of the equipment, extraction efficiencies of energy source materials, recycling and disposal efficiencies of waste products, capture efficiency of air pollutants, energy storage and distribution to local and external communities, etc. Unlike for a single piece of equipment where the technical performance indicators are straight-forward, this is not the case for an energy supply system where the energy distribution network, material preprocessing, waste material handling, etc. must also be accounted for.

Social issues do not lend themselves to quantification and include acceptance levels of waste generation and disposal, tolerance of GHG emissions and toxic dispersion of pollutants, taxes and/or carbon trading imposed to combat global warming, preservation of cultures and ecosystems, etc. Environmental issues are associated with the impact of technology on the environment, such as climate change, ozone depletion, acidification, toxic dispersion, material intensity and recyclability, environmental management, and so on. Economic issues deal with financial matters (investments, wealth creation, security of investment) and human capital (employment, investments in education, capital creation, health expenditures). Institutional issues deal with the capacity of institutions to promote participation, serve justice, regulate and enforce environmental laws, and so on.

Energy supply services produce impacts on one or more communities (local, regional, national, international), each of which possesses its economy and interacts with its environment through a societal structure. An energy supply service located in a local community affects both the LBS and EBS communities and it is up to decision makers to select the appropriate service that produces the most sustainable energy supply mix. This requires trade-offs to be made among the indicators that measure the degree of accomplishment of objectives, or the trade-offs between the objectives that determine their relative importance for sustainability.

2.2 Energy Supply Attributes

Indicators or attributes provide a means for evaluating goal accomplishments and should be defined by a panel of multidisciplinary experts for any particular problem area [39]. In our framework shown in Figure 3, LBS consists of technical, environmental, and human system indicators that provide the viability and performance of each individual subsystem. EBS indicators express the contributions of each of the three subsystems in LBS to the viability and performance of EBS and they must satisfy the same energy supply objectives as the LBS system. The indicators must measure the performance levels of these objectives and as such must be identified and quantified for different types of energy supply options. The indicators should be also standardized for performance tracking and comparison with different energy supply options [31].

It is common in Life Cycle Assessment (LCA) to express the environmental impacts per *functional unit* or a measure of the service provided [40], and several studies of sustainability indicators employ similar strategies [30,31, among others]. A suitable functional unit for an energy supply service is the kWh of electricity produced if the service produces only electricity. But such a service can also produce heat for district heating and the functional units are both electrical and heat energies. A household waste can be incinerated in a power plant that produces both electricity, heat, and materials for recycling, and the functional units include electric and heat energies and recyclable materials (copper, aluminum, iron, etc.). It thus appears that a better way to define the functional unit of an energy supply service is the average amount of energy consumed by a representative community (local, regional, national, international) in one year. But then, what exactly is such a *representative community* needs to be agreed upon. Afgan and others [30] employ such a functional unit of a community that utilizes 0.125 MkWh/y and needs to decide whether to use solar, wind, biomass, or oil energy sources. Azapagic and Perdan [31] do not employ the same functional unit for each of their sustainability indicators because they do not deal with any industry sector in particular. They normalize, instead, each indicator with its own functional unit.

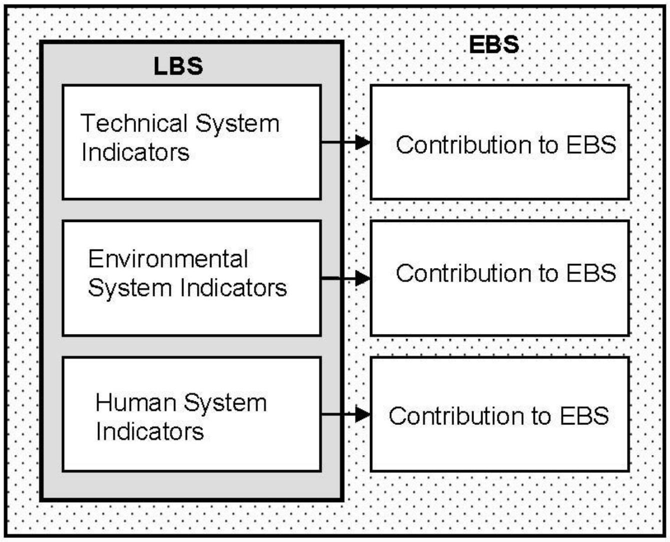

Figure 3. Energy supply sustainability indicators framework.

Before deciding on an appropriate number of energy supply indicators or attributes it is useful to list as many characteristics as possible of technical, human, and environmental systems of LBS, i.e.

A. Technical System

1. Energy supply system construction
1.1 Materials consumed
1.2 Energy consumed
2. Energy production system
2.1 Materials consumed
2.1.1 Nonrenewable
  - Primary (fuels: coals, crude oil, natural gas, oil shale, gas shale, fissionable materials; maintenance)
  - Secondary (petroleum products, manufactured solids and gases)
  - Freshwater consumed
2.1.2 Renewable
  - Primary (biofuels, geothermal heat, direct solar energy capture, fusion fuels)
  - Secondary (fuels derived from renewables)
2.2 Energy produced
  - Consumed for plant operations
  - Distribution to grid
  - Storage
  2.3 Quality of energy
    - Provided for energy production
    - Provided to distribution grid
    - Stored

2.4 Plant emissions
- Greenhouse gases
- Air pollution
- Acidification
- Water pollution
- Soil pollution
- Ozone depletion

2.5 Waste produced
- Recyclable
- Nonrecyclable
  - Stored in LBS
  - Removed from LBS

3. Auxiliary systems (electrical energy grid, heat energy grid, materials transport to and from the site, waste processing)

3.1 Materials consumed

3.1.1 Nonrenewable
- primary (fuels: coals, crude oil, natural gas, oil shale, gas shale, fissionable materials; maintenance)
- Secondary (petroleum products, manufactured solids and gases)
- Freshwater consumed

3.1.2 Renewable
- Primary (biofuels, geothermal heat, direct solar energy capture)
- Secondary (fuels derived from renewables)

3.2 Energy
- Consumed for systems operations
- Provided to stakeholders

3.3 Quality of energy
- Provided for plant operations
- Provided to stakeholders

3.4 Emissions
- Greenhouse gases
- Air pollution
- Acidification
- Water pollution
- Soil pollution
- Ozone depletion

3.5 Waste produced
- Recyclable
- Nonrecyclable
  - Stored in LBS
  - Removed from LBS

B. Environmental System

1. Consumption of natural resources for energy supply system construction

1.1 Materials
1.2 Energy

2. Consumption of natural resources for energy supply system operation

2.1 Nonrenewable
- Primary (coals, crude oil, natural gas, oil shale, gas shale, fissionable materials)
- Secondary (petroleum products, manufactured solids and gases)

2.2 Renewable
- Primary (biofuels, geothermal heat, direct solar energy capture, fusion fuels)
- Secondary (fuels derived from renewables)

3. Emissions from energy supply systems operations

3.1 Greenhouse gases
3.2 Air pollution
3.3 Water pollution
3.4 Soil pollution
3.5 Waste disposal

4. Ecosystems degradation

4.1 Land use
4.2 Loss of biodiversity
4.3 Materials quality reduction

C. Human System

1. Economics
- Capital investment cost and payback period
- Cost of energy supply
- Energy subsidies
- Carbon taxing and/or trading
- Job creation or employment
- Community cash flow
- Health care expenditures
- Environmental cleaning expenditures
- Education expenditures
- Security expenditures
- Standard of living

2. Social acceptance
- Noise and visibility
- Health care quality
- Nuclear safety
- Education quality
- Preservation of open spaces
- Combating poverty
- Community participation
- Human settlement development
- Capital creation

From this listing a *generic* set of energy supply services indicators can be developed that account for material and energy flows in various parts of LBS, economic viability of services, and consequences of services on the environment and society. The fuel materials used for producing energy services can be expressed in terms of their energy equivalents by employing the heating values of fuels [41], and many attributes can be rescaled by the population of the community under consideration, community's GDP, or some other measure. Scaling with respect to the amount of energy produced by the community in a certain time period (year, lifetime) can also be employed, but we will not follow this approach here because of the lack of a fixed standard that applies to such communities.

Normalization of indicators is, however, necessary when applying the multi-criteria decision making methodology to determine the highest ranking energy supply option (Section 3). Table 3 shows our preliminary choice of indicators which can be further manipulated and simplified as necessary for a particular group of energy supply services being considered.

Table 3. Indicators of technical, environmental, and human systems of LBS. Their correlation with energy supply objectives of Table 2 is shown within the square brackets. Those LBS indicators that contribute to EBS are underlined. Materials usage is expressed in tons (t) and the time interval is year (y).

Population	
P	population of the community (n)
PG	population growth in the community (n/y)
PD	human settlement development in community (n/km^2)
Technical System Indicators	
MC/P	materials consumption for construction and maintenance per capita (t/yn) [I]
PEC/P	primary energy consumption per capita (t/yn) [I]
RPEC/P	renewable primary energy consumption per capita (t/yn) [I]
SEC/P	secondary energy consumption per capita (t/yn) [I]
RSEC/P	renewable secondary materials consumption per capita (t/yn) [I]
H2O/P	water usage for energy production per capita (t/yn) [I]
EC/P	energy consumption per capita (kWh/yn) [I]
EP/P	energy production per capita (kWh/yn) [II, III, IV, V, VIII]
EPS/P	energy storage per capita (kWh/yn) [II, III, IV, V, VIII]
EM	energy mix produced (renewable/total) (%) [II, VIII]
EC/EP	energy cost per kWh produced ($/kWh) [VI]
ECS/EP	energy cost of subsidies per kWh produced ($/kWh) [VII]
WC/P	household waste consumption per capita (t/yn) [II, III, IV, V]
EXI/P	exergy input per capita (kWh/yn) [I; IV]
EXP/P	exergy produced per capita (kWh/yn) [II, III, IV]
EXS/P	exergy stored per capita (kWh/yn) [II, III, IV]
Environmental System Indicators	
GHG/P	greenhouse gas emission per capita (tCO$_2$e/yn) [III]
HAP/P	hazardous air pollutants emission per capita (t/yn) [IV, V, VIII]
HWSP/P	hazardous water and soil pollutants emission per capita (t/yn) [IV, V, VIII]
SO/P	acidification emission per capita (t/yn) [IV, V, VIII]
WG/P	waste generation per capita (t/yn) (commercial, industrial, nuclear) [IV, V, VIII]
WR	fraction of waste materials recycled (%) [II, VIII]
OZS/P	stratospheric ozone emission per capita (t/yn) [II, IV, V]
OZG/P	ground ozone emission per capita (t/n) [II, IV, V]
LD	land depletion (%)[I, II, VIII]
BL/P	biodiversity (number of species) loss per capita (%) [I, II, VIII]
Human Indicators	
GDP/P	gross domestic product per capita ($/yn) [II, VI]
IGDP	investment share of GDP (%) [II,VI]
JC/P	number of unemployed per capita (%) [II, VIII]
CC/P	capital created per capita ($/yn) [II, VI, VII]
HCE/P	health care expenditures per capita ($/yn) [II, V, VI]
ENE/P	environmental expenditures per capita ($/yn) [II, IV]
EDE/P	education expenditures per capita ($/yn) [VI]
SE/P	security expenditures per capita ($/yn) [II, V]
CP/P	public participation (%) [II]
NV	noise and visibility (%) [II]

Most of these indicators are self-explanatory and can be combined to produce different attributes. The carbon intensity (GHG/EP) can be multiplied by the energy produced per unit of GDP (EP/GDP) to produce the emission intensity per unit of GDP (GHG/GDP). The carbon intensity can be multiplied by the yearly energy produced per capita (EP/P) to produce the emission intensity per capita (GHG/P). And the carbon intensity (GHG/EP) and carbon productivity (GDP/GHG) can be produced from greenhouse gas emissions, energy produced, and gross domestic product. In the security expenditures one can include the cost of insuring the availability of resources for the period of the services and for the cost of maintaining the services secure from terrorism and other elements. Long-term security of investments is one of the main concerns of the energy supply industry [5].

Exergy analysis of energy systems provides a measure of irreversibilities associated with thermodynamic processes and is a good indicator of the *quality* of energy contained in the functional unit and energy lost in emissions and waste products [42,43]. For example, the difference between the exergies of input streams (fuel and raw materials) and output streams (emissions, wastes, and energy produced) has been proposed as a *thermodynamic indicator* [44] of energy quality. The energy (or first law of thermodynamics) efficiencies can be determined from the energy produced and energy contained in materials used for systems operations. The exergy (or second law of thermodynamics) efficiencies can be determined from the exergy contained in fuel materials and exergy contained in the energy and materials output streams. These and other thermodynamic efficiencies and indicators associated with energy storage and auxiliary systems operation can also be computed from the indicators in Table 3.

Public participation, noise, and visibility are expressed in the table on the percentage basis because of the subjectivity of these parameters. The fraction of people participating in a decision process is the simplest way of dealing with public participation, because a breakdown by age, sex, education, etc. complicates the analysis. Similarly, the noise can be measured in decibels, but different age groups are sensitive to different noise levels and by expressing noise as a fraction of the population that is affected by it is a simple way to deal with this parameter. Visibility can be very important to some and not very relevant to others, and most simply can be expressed as a fraction of population that is sensitive to this parameter.

Table 3 provides 3 population, 16 technical system, 10 environmental system, and 10 human system indicators, or a total of 39 indicators, but not all of them will be applicable simultaneously. For example, a service may employ only one or two types of fuels (oil and gas burning power plant) without providing heat to the customers and without incinerating household waste. Energy storage may have to be considered only in combination with intermittent energy sources (solar thermal and photovoltaic). And a waste to energy conversion system is designed to consume the household waste only. Waste materials are produced before and after burning coal and nuclear fuels, and may have to be handled within LBS, within EBS, or both. The pollutants emitted into air and water can also cross the LBS-EBS boundary and we must therefore consider those LBS indicators that impact EBS, the external biophysical system. These indicators are shown underlined in Tables 3 and satisfy the same energy supply objectives as the LBS indicators.

The external biophysical system can thus be affected by the materials needed for LBS, waste materials and emissions produced in LBS, energy supply services provided by LBS to EBS, and by the society of LBS that cares little about its environment. It is also possible for the energy supply and other services in EBS to affect the sustainability of LBS (through the emissions of greenhouse gases and air and water pollutants), but if each community can be made sustainable, then the combined system will be (strongly) sustainable. We must now consider how the energy supply indicators or attributes can be used in decision making for the purpose of choosing the optimum energy supply technology for the community.

3. ENERGY SUPPLY SERVICES DECISION MAKING

Once the objectives and corresponding indicators of energy supply services are available it is up to the decision makers to use this information for choosing the most sustainable service possible. But this decision is not simple, because the decision maker(s) should consider uncertainties, conflicting indicators, different forms of data (quantitative and qualitative) and information, multi-interests and perspectives, and accounting for complex biophysical and socio-economic conditions. The Multi-Criteria Decision Making (MCDM) methods are decision-making aids that have been used widely in economic, environmental, social, transportation, engineering, and many other sectors, and can provide solutions to many complex energy management systems once the indicators or attributes have been made available [45-46].

The MCDM problem for a sustainable energy supply service is formulated with p different energy supply options or alternatives

$$F_{ijkl} \quad : \quad l = 1,\dots,p$$

which must be evaluated on q criteria

$$A_m \quad : \quad m = 1,\dots,q.$$

The decision matrix is then expressed as follows:

$$\begin{array}{ccccc} \text{Criteria (attributes, indicators)} & A_1 & A_2 & \dots & A_q \\ \text{(criteria weights} & w_1 & w_2 & \dots & w_q\ ) \\ & & & & \\ \text{Energy supply option} & & & & \\ F_{ijk1} & x_{ijk11} & x_{ijk12} & \cdots & x_{ijk1q} \\ F_{ijk2} & x_{ijk21} & x_{ijk22} & \cdots & x_{ijk2q} \\ \dots & \cdots & \cdots & \cdots & \cdots \\ F_{ijkp} & x_{ijkp1} & x_{ijkp2} & \cdots & x_{ijkpq} \end{array}$$

where x_{ijklm} is the ranking or performance of alternative ijkl with respect to attribute m whose weight is w_m.

The DM process involves four stages: (1) formulation of options and selection of criteria, (2) weighting of criteria, (3) evaluation, and (4) aggregation. In Section 2 we formulated a set of criteria or indicators for measuring progress towards a sustainable energy future and for the DM analysis these indicators must be normalized. The criteria weights are then determined to show the relative importance of criteria. The acceptable alternatives are then ranked by MCDA methods with criteria weights and the alternatives' ranking is ordered. If different MCDA methods produce the same ranking, the DM process is ended; if not the ranking results are aggregated again and the best scheme is selected [46]. With many indicators to consider the MCDM procedure is highly dependent on the decision maker's preferences and works best if different groups of decision-makers agree on a compromise solution.

An alternative way of making decisions can be formulated as follows [34]. Here the decision maker considers several alternative designs a_i of producing electricity, for example (such as by employing solar thermal collectors, photovoltaic panels, utilizing different types of fossil fuels, etc.). Figure 4 shows the particular option called "solar thermal energy supply option". Each of these energy supply alternative a_i may be, however, subjected to several uncertainties such as plant citing. Each plant location may now require different design options (parabolic through concentrators, heliostats, paraboloidal dishes) and each design can be further subjected to additional uncertainties (such as sunshine availability). This produces energy supply options that are probabilistically distributed. Calling all such option events F_{ijkl} these alternatives must then be evaluated on q criteria, indicators, or attributes as in the

MCDM methods. In the following and final step it is necessary to work backward through the decision tree to determine which alternative has the maximum expected value. The advantage of this approach is separation of indicators into two groups: Those that are probabilistically distributed and local in nature and affecting principally LBS, and those that are specified by limits and affecting both LBS and EBS. Further elaboration of such a risk-based MCDM methodology (RMCDM) will be presented elsewhere.

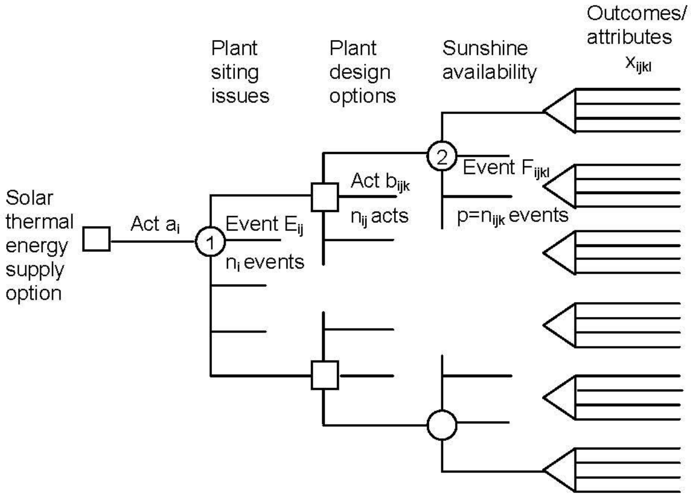

Figure 4. Decision tree for solar thermal energy supply option. Squares denote decision nodes from which fan out acts. From each act fan out events denoted by circles and with each event are associated more decisions. Any particular path through the tree defines a scenario and each scenario must be further evaluated on attributes, indicators, criteria, or outcomes [34].

4. CONCLUSIONS

Sustainability and sustainable development require that we keep improving our socio-economic conditions while insuring the viability of ecosystems and continual supply of necessary resources for our well-being. In a sustainable energy future the energy supply services can only tolerably degrade the environment without causing significant health problems and climate change effects. These services should also provide the necessary energy supply security and an acceptable energy cost for all of humanity.

But how to achieve this energy supply sustainability is at the present debatable, and in this work a small number of energy supply values and objectives are presented that should guide the design and choice of sustainable energy supply options. The level of achievement of these objectives is measured with different types of indicators or attributes. The indicators measure the viability and performance of the local biophysical system that includes the energy supply technology, environment that houses this technology, and the society which with its knowledge and labor interacts with other systems. The local biophysical system interacts with the external biophysical system and in the process can cause a change of this system's viability and productivity.

A risk-based multi-criteria decision making procedure is also presented for deciding which energy supply service option is most sustainable. This procedure calls both for the evaluation of the uncertainties associated with different options and for incorporating different weights of those energy sustainability attributes that require specification with limits. An application of this methodology to the selection of a solar thermal energy supply option is illustrated, but a quantification of this procedure will be presented elsewhere. The proposed methodology can be applied locally, regionally, nationally, or internationally.

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