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EUSUSTEL – WP 8.2
A Conceptual Framework for Sustainable Electricity Supply

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1 Introduction

1.1 The Drive for Sustainable Development

At the beginning of the third millennium societies, especially in the industrialized world, face various severe challenges, among which the following ones rank on top:

- Elimination of hunger and poverty, i.e. creation of human living conditions for a growing population,
- Avoidance of intolerable changes of the earth's climate and degradation of the natural environment,
- Securing of economic development and sufficient employment in Europe.

These challenges are directly related to the energy system,

- since providing an increasing amount of energy services is a necessary precondition for eradicating hunger and poverty and even limiting the global population increase,
- since about three-quarters of anthropogenic emissions of CO_2 are released by the energy system,
- since today's energy system consumes the major share of finite fossil resources and is the single most important source of air pollution,
- since securing the economic productivity of developed countries will not be possible without a functioning energy infrastructure and competitive energy prices.

There is a fairly large consensus concerning the perception of the world's challenges, the same as for the pressing ethically and morally based action needs to care for the Third World and future generations, as well as for environment and climate concerns. As for the pathway to the future, however, controversial and partially even conflictive perceptions exist among various groups of society. This includes the development of an energy system that is judged sustainable for the future.

The concept of "sustainable development", which in 1987 first entered into political debates after the World Commission on Environment and Development (WCED) – also named the Brundtland Commission after its chairperson – had released a report on "Our Common Future" [1]. The Commission defined "Sustainable Development" as *"…development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

The Commission, with technology and the social organization as the main drivers for development, focused very much on the needs to manage economic growth in a way, so as to better protect the environmental resources.

"*The concept of sustainable development does imply limits, not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities. But technology and social organization can be both managed and improved to make way for a new era of economic growth. …Yet in the end, sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are made consistent with future as well as present needs."*

The key components in this interpretation are *needs* and *future generations*. It seems clear that the Brundtland Commission did not intend to recommend that peoples presently existing on a subsistence level should remain so in perpetuity, in the name of sustainability, a view with which this document concurs. The term *needs* therefore, must also be considered in the context of the aspirations and expectations communities may have of the development process and how these may be met sustainable. Sustainable development strategies therefore, seek to effect some improvement in the *quality of human life*, as measured by the provision of key indicators such as health, housing, income, employment and education (i.e. access to resources) without exceeding the carrying capacities of the supporting resource-base. This places resource management at the centre of sustainable development, in which resource usage is conducted in a manner which does not degrade the resource-base nor diminish the range of development options open to future generations. These issues of resource management, quality of life and inter-generational equity are therefore fundamental when considering sustainable development.

1.2 International Efforts for Sustainability

Aside of the above mentioned Brundtland Commission report a large variety of efforts have been launched both nationally and internationally aimed at defining sustainable systems. Some of the international efforts, having particular relevance for designing the framework for sustainability assessments intended with the Project, are highlighted here.

From the beginnings of industrialization in the 18th up to the middle of the 20th century development of societies was mainly determined by economical and social issues. Ecological aspects as avoidance and reduction of effluents into ambient air, water and soil, limits to exploitation of resources or protection of the flora and fauna, were not valued of high relevance. Evidences for the limited carrying capacity of nature, which had been shown by a few experts (Ricardo, Malthus), had no strong effect for practical life. Exceptions from this rule were apparent in two branches only, in forestry, where by the end of the 18th century the later net capital conservation named principle had been demanded by law in Germany and with the beginning of the 20th century in fishery.

The resource issue became a relevant theme for scientific research and politics towards the beginning of the 1970'ies again, triggered especially since 1972 by the Limits-to-Growth report of the Club of Rome. The report, although sometimes criticized for methodological deficits, initiated a new discussion about economic growth and the availability or finiteness of resources. In addition, the increasing environmental pollution associated with an industrial society's activities, e.g. due to unlimited pollutant release into air or water, was now critically perceived by an alerted publicity. Resource management and environment protection became topics on the national and international agenda. This could be seen from the UN Conference on Human Environment 1972 in Stockholm and the installation of the United Nations Environmental Programme (UNEP) on the international level, as well as the installation of ministers for environment on the national level. In the context of the Stockholm conference an interrelation between development and environment issues ("ecodevelopment") had been focused on the international policy level for the first time (cf. [2]).

The international debate on sustainable development, initiated with the Brundtland Commission report, continued in the 1992 UNCED Rio conference ("earth summit") and other subsequent international meetings. Albeit declarations of these conferences had no legally binding character their impact as guideline for policy has to be acknowledged. Examples are the Agenda 21 and the Kyoto convention, two action programs with defined goals, measures and instruments, which have been agreed and implemented by a large group of nations.

A particular result of the Rio conference regarding institutions and instruments was the installation of the UN Commission on Sustainable Development (CSD), intended to monitor, support and evaluate the initiation and implementation of nation's sustainable development processes. As for the Agenda 21, CSD has, together with national partners, established an indicator set for criteria of the social, ecological, economical and institutional development dimensions [3].

For the first time in history an instrument for national assessments, including a quantitative framework of sustainability, became available to countries, as a direct outcome of the UNCED conferences. Although application and implementation of this instrument is a national effort, which makes the process sometimes difficult to handle, as can be learnt from the implementation of the Kyoto convention on greenhouse gas emission reduction, the idea of a global sustainable development mechanism has been successfully launched.

Similar to the UN, an action programme for achieving sustainable development goals was established by the Organisation for Economic Co-operation and Development (OECD) for its presently 30 members, all industrialized countries with a few exceptions. The OECD's programme is focused on providing information on the conditions of the environment, especially with respect to critical developments, in order to stimulate actions by member states. The set of indicators includes approximately 50 individual variables. Of very high relevance for OECD were indicators related to activities of the energy sector, as the value added in the energy sector is quite significant for each national economy and energy is an important input factor for other sectors. Therefore changes in the energy intensity, energy mix and energy price were included in the reference indicators. Later, social factors, like health, employment and income impacts were added [16].

The European Union decided at the 1999 Helsinki summit of Heads of State and Government a strategy for sustainable development. To make the sustainability concept operational and a catalyst for a change, it felt necessary to focus on the biggest challenge to sustainability in the Union. Based on the criteria of severity, their long term nature, and their European dimension, these challenges pertain to climate change, resource use and social factors like public health, poverty and demographic changes [17]. The European Union has generally integrated these concerns into its relevant policy areas, e.g. among others into its Lisbon strategy for growth and competitiveness in Europe. It has continuously monitored the sustainability development in its member countries on various policy levels and adjusted its action programmes to the sustainability goals. Key objectives are: environment protection, social equity and cohesion, economic prosperity, meeting international responsibilities (see Sub-section 3.2.1 for details on the indicators of the EU sustainability strategy).

1.3 Project Objectives and Specific Task of WP 8.2

"Sustainable Development" is the general accepted guiding principle (concept) for further development in the European Union. The Gothenburg European Council of 2001 stated that "Sustainable Development offers the European Union **a positive long-term vision** of a society that is more prosperous and more just, and which promises a cleaner, safer, healthier environment – a society which delivers a better quality of life for us, for our children, and for our grandchildren. Achieving this in practice requires that economic growth supports social progress and respects the environment, that social policy underpins economic performance, and that environmental policy is cost-effective."

But, there are many different interpretations of what is meant by 'Sustainable Development' [32]. As for the future energy systems in the European Union and specifically the future electricity supply in its member countries a clear interpretation of "Sustainable Development" is necessary as basis for policy decisions and strategies. This is the reason why the EUSUSTEL Project has been initiated. EUSUSTEL stands for European Sustainable Electricity, a "Comprehensive Analysis of Future European Demand and Generation of European Electricity and its Security of Supply".

The EUSUSTEL project aims "…providing a fully consistent frame work for a secure electricity provision, that is the same time environmentally friendly and affordable" [18]. Furthermore, the strategic objectives of the EUSUSTEL project are "….to provide the Commission and the member states with coherent guidelines and recommendations to optimise the future nature of electricity provision and the electricity generation mix in Europe so as to guarantee an *affordable, clean and reliable*, i.e. '*sustainable*', electricity supply system."

This requires a common understanding of ‚Sustainable Development' amongst the project partners, which is also be used to assess the EUSUSTEL scenarios.

To address these objectives and to assure that a consensus is reached amongst the project partners about the term '*sustainable development*', a conceptual framework for sustainable electricity supply has been developed within WP8.2

The development of a conceptional framework as well as the discussion of criteria and indicators for sustainability, which is detailed further below in this Paper of WP 8.2, follows three specific aims:

- to assure a common understanding of 'sustainable development',
- to serve as guideline for the methodological approach and
- to indicate, which aspects are appropriate for sustainability assessments.

The Paper is outlined in the three subsequent Sections. Section 2 exposes the various concepts of sustainability that exist and determines the most suitable concept under a practical perspective. How sustainability of energy systems can generally be measured and which advantages and disadvantages are associated with the proposed methods, and the definition of impact criteria that should be included in the assessment as well as the deduction of quantitative indicators, measuring the scope of the impact are illustrated in Section 3.

2 The Notion and Concepts of Sustainable Development

The Section, dealing with the rationale underlying various sustainability concepts and illustrating essential attributes characterizing them, is based upon a comprehensive literature research.

2.1 What is Sustainable Development?

The concept of sustainable development is not a new one; generally accepted starting point of most of the present concepts followed by national activities or international efforts is the definition of the World Commission on Environment and Development (WCED), also known as the "Brundtland Commission", as given in Section 1. According to WCED (as well as the subsequent Rio conventions), sustainable development definitions are built on the two implicitly contradictory ambitions of sparing use of resources and further economical and social development [1].

"Growth has no set limits in terms of population or resource use beyond which lies ecological disaster. Different limits hold for the use of energy, material, water and land. Many of these will manifest themselves in the form of rising costs and diminishing returns, rather than in the form of any sudden loss of a resource base. The accumulation of knowledge and the development of technology can enhance the carrying capacity of the resource base. But ultimate limits there are, and sustainability requires that long before these are reached, the world must ensure equitable access to the constrained resource and reorient technological efforts to relieve the pressure."

"Economic growth and development obviously involve changes in the physical ecosystem. Every ecosystem everywhere cannot be preserved intact. A forest may be depleted in one part of a watershed and extended elsewhere, which is not a bad thing if the exploitation has been planned and the effects on soil erosion rates, water regimes and genetic losses have been taken into account. In general, renewable resources like forests and fish stocks need not be depleted provided the rate of use is within the limits of regeneration and natural growth. But most renewable resources are part of a complex and interlinked ecosystem, and maximum sustainable yield must be defined after taking into account system-wide effects of exploitation."

"As for non-renewable resources, like fossil fuels and minerals, their use reduces the stock available for future generations. But this does not mean that such resources should not be used. In general the rate of depletion should take into account the criticality of that resource,

the availability of technologies for minimizing depletion, and the likelihood of substitutes being available. Thus land should not be degraded beyond reasonable recovery. With minerals and fossil fuels, the rate of depletion and the emphasis on recycling and economy of use should be calibrated to ensure that the resource does nut run out before acceptable substitutes are available. Sustainable development requires that the rate of depletion of non-renewable resources should foreclose as few future options as possible."

Following these definitions and interpretations, it is the goal of sustainability to leave a heritage for future generations allowing them to design life to their aspirations and desires, while at the same time making use of the same potential as we do today. Or, expressed in different terms: sustainable development reconciles improving the economical and social living conditions of all (present and future) generations with securing the long-term natural resources.

This definition is very general in terms of its topics, and because of its generality, derived from equity for present and future generations (intra-generative and inter-generative equity), it is consensual for most people. It is however not explicitly determining in concrete terms, what has to be achieved for sustainable development, e.g. as for the future electricity supply systems. The broad and unspecific character of the Brundtland Commission's sustainability concept leaves scope for more concrete definitions and interpretations of the concept.

A more precise definition for sustainable development together with a mathematical problem formulation is given in [4]:

"Sustainable development is development that lasts…The context of sustainable development has always been that of intergenerational equity, as well as intragenerational equity, but the length of any particular time horizon is of course open for debate. It must be a few generations at least, but it will not be infinity. We might appeal to some 'coefficient of concern' to set pragmatic limit on how far into the future we look, say, 100 years. Of course, if individuals now already integrate future concerns into current actions and choices, 'sustainability' is of little concern, since it will be automatically taken care of."

The sustainability issue can be expressed by the following equation, whereby the wellbeing of an individual now (W_0) is determined by consumption now (C_0) and consumption by future generations over some time horizon, that is

$$W_0=f(C_0, C_1, C_2 \ldots C_T)$$

As is pointed out in [3], there is a dilemma with the weighting of the future by the present generation: *"The weighting required to generate this result is in fact the weighting that arises from generation's 0's time preference', that is, the discount rate. If we seek to maximize* W_0*, we are, by definition, maximizing the wellbeing of the current generation…."*

The link between sustainable development and the economist's traditional concept of economic growth is expressed in the following form

$$\text{Maximize} \int_{t=0}^{\infty} U(C_t).e^{-rt}dt,$$

where U is utility (wellbeing), C is real consumption per capita, and r is the utility discount rate, the rate at which future wellbeing is discounted. The economic problem is then to maximize the flow of consumption subject to the constraints imposed by the technology available to the economy.

The true problem of sustainability is then associated with 'correct' value of the discount rate.

"r is most often assumed to be greater than zero, even though there is no intrinsic reason for discounting future utility. There may, however, be good reasons to discount future consumption if we can feel assured that future consumption (and wellbeing) will be higher than it is currently…"

2.2 Sustainability Concepts

Sustainability concepts are among others characterized by the degree of sustainability. The following Sub-section illustrates scope and dimension of strong and weak sustainability models, two representations that mark extreme positions as for the preconditions for their validity and the deductions which can be made from their applications.

Another characterisation of sustainability concepts shown in this Sub-section is the categorization according to economical, ecological and social dimensions. Such model approaches are quite common as they measure impacts in the three dimensions, which are believed to be critical for a society's development and for which indicators can be defined and measured without difficulties. There are, however, specific shortcomings associated with the interpretation of such three- or other multi-dimensional approaches resulting from overlapping impacts. For instance, an economic impact (e.g. value added) quite often has a social dimension (income), and a social impact (e.g. health effect) quite often has an environmental dimension (damage of the ecological balance), and so on.

2.2.1 Strong and Weak Sustainability

Issues related to sustainability have been focused by several science disciplines in the past. Several concepts of inter- and intra-generative sustainability have been discussed in the economics research domains in particular. Different conceptual foundations and problem perceptions arose from these, as highlighted below.

A central approach of the neo-classical school of thoughts is the so-called "weak sustainability", which suggests a substitution paradigm according to which elements of the natural capital (renewable and exhaustible resources, assimilative and life preserving functions of nature) to a large extent can be replaced by man-made capital.

Sustainability concepts however, attributed to the school of ecological economics follow the perception of "strong sustainability", giving preference for ecologically based limitations as opposed to economic activities. Representatives of strong sustainability postulate a largely complementary pattern of natural and artificial capital, i.e. substitution between the two capital types is to a large extent not conceded. Arguments are the finite level of natural resources, the non-substitutable functions of nature and the insecure as well as non-reversible impacts for ecosystems. If man-made capital for production is substitutable within tight limits only, a consequence of this logic is that natural capital must be preserved (permanence of natural capital).

Both, the non-existent as well as the more or less unbounded substitution ability between natural and artificial capital, are not very reality oriented models. The two approaches apply the terms natural and man-made capital in a very abstract and undifferentiated form, so as to exclude them from any practical application. The term natural capital suggests a homogeneity, which is not accounting for different functions of nature, e.g. as a resource for industrial processes, in its abilities to assimilate and deposit substances, in their life preserving functions (fresh air etc.) and so on. The issue of substitutability of natural capital can logically be considered on basis of its relevant functions only.

Moreover, the strong sustainability concept is fundamentally not in line with the second law of thermodynamics, as every activity of man produces entropy by degrading workable energy and available material (see also Sub-section 2.4 for a detailed discussion). Life requires a permanent input of these constituencies, a fact which is in total contradiction with the postulate of non-substitutability of natural capital.

Approaches for practical implementation often are based upon a mixed conceptual form of strong and weak sustainability, denominated “critical weak sustainability” in the following. It embraces critical performance limits for some complementary functions of the natural capital, felt to be indispensable for life. Aside from those limits substitutability among the various components of natural capital is assumed. This perception of a “critical weak sustainability” seems to be the most appropriate approach for deriving practical guidelines from the sustainable development concept for the assessment of energy systems. The largest issue for practical implementation rests however in the determination of critical performance limits for the perceived non-substitutable natural functions.

2.2.2 Normative Models (Equity Postulate)

Sustainability, as defined in the Brundtland report and the Rio Declarations (see Section 1.), is linked with ecological, social, economical, cultural and institutional development aspects of the world’s societies. Viewing these different sections of sustainable development from a normative perspective for decision making the term “dimensions” or “pillars” has been widely established. Among the normative concepts made available so far, two generic categories can be differentiated: “Single-Pillar Models” and “Multi-Pillar Models” (cf. [2]).

Single-Pillar Models focus on the issue of man’s equitable management of the natural environment: Convinced that meeting the needs of present and future generations is possible up to that level only, where nature is preserved as basis for living and economic activities, *ecological postulates* must be given priority in case of conflicts. Economical and social aspects are no independent goal dimensions, but are considered as reasons or results of ecological disturbances. Preservation of ecological balance has to be managed in a socially and economically compatible way. An example for the application of such a Single-Pillar Model is [5].

Contrasting to such approaches are the Multi-Pillar Models, postulating equity among the various dimensions. Most of the known concepts follow the idea of a Three-Pillar Model, i.e. models accounting aspects of the ecological, economical and social dimensions under equitable ranking conditions. Some sources, however, plea for the additional installation of a “cultural” and/or “institutional” dimension (see e.g. [3]).

As for the justification of the equity postulates two argumentations are established, which are mostly used as alternatives, but in parts as complementary as well. The first argumentation, triggered by the question of the heritage for future generations, concludes that the heritage should not be limited to ecological goals. Instead, sustainability must include securing basic needs for human living conditions for present and future generations. The second argumentation states that the action area for sustainable development is limited by the carrying capacity of natural *and* social systems. Here, the equity postulate is backed by the expectation that civilizing developments are not only threatened by ecological, but equally by economical and social risks. Environment, society and economy are considered as independent, but interrelated, subsystems, the functionality and disturbance resistance of which have to be preserved for future generations. Goal of sustainable development is the long-term system preservation and the avoidance of damages in all three dimensions.

The institutional dimension, as far as considered at all, has a qualitatively different function. Whereas the other dimensions relate to the issue what sustainable development means by its content, is the institutional dimension linked with the question, *how* sustainable development could be implemented or which capabilities institutions should have, in order to carry out the job.

2.2.3 Critical Evaluation of Multi-Pillar Models

The concept of sustainability formed by the supporting elements of *economy, ecology*, and *society* has been suggested as a means to reduce the arbitrariness of the Brundtland Commission's concept by offering a means for quantitative analysis/assessment.

However, in practice the Three-Pillar Model turned out to be helpful for quantitative assessments within tight limits only. The reasoning behind the Three-Pillar Model's limited applicability is that independent sustainability goals were established for each of the dimensions, which is in full contradiction to the original integrative sustainability approach. Due to the partly competing or even totally conflictive goals, a discussion of the goals' significance is on the agenda during each attempt to apply the model in practice for sustainability assessments. The three dimensions approach is good for exhibiting the problem area. However, it will not be possible to derive concrete sustainability goals for the ecological dimension independent from economical and social issues.

A sustainability concept which leaves those limitations of the Three-Pillar Model totally aside is the "sandwich" approach", illustrated in Figure 1.

Here, sustainable development is defined by goals or objectives for societal or social development under the condition that natural resources and assets are exploited with a certain technology where the economy is the operator of a transformation process for the satisfaction of needs for goods and services. Since the social, economical and ecological dimensions are interrelated in manifold ways, the sandwich type structure of the sustainable development model is the adequate one for a balanced approach and assessment.

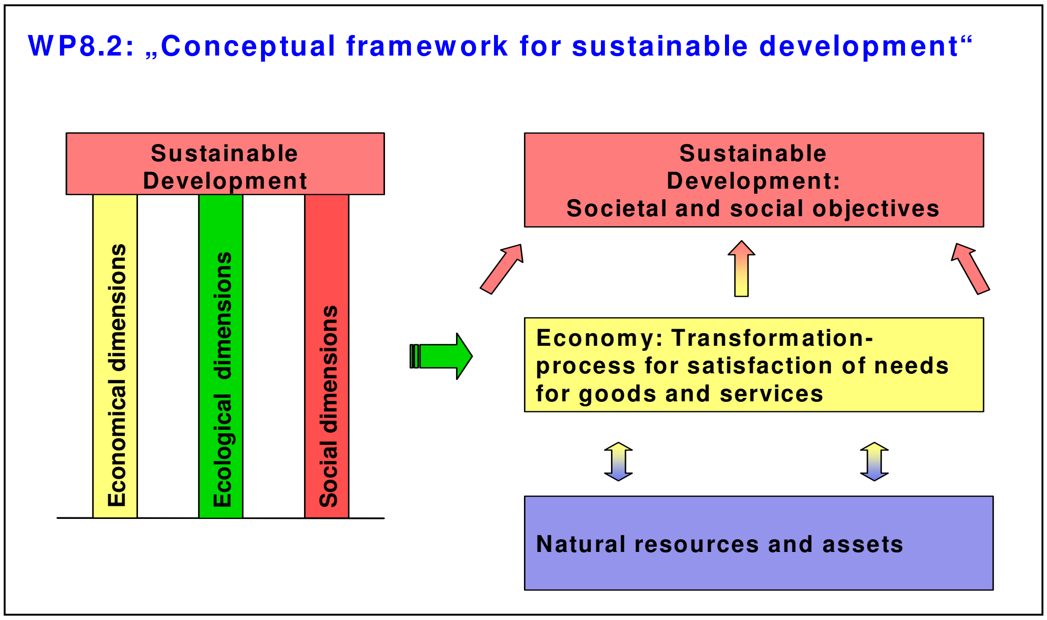

Figure 1: Three-Pillar Model versus an integrative concept of Sustainable Development

2.3 Ethical Sustainability Fundamentals

In order to make the sustainability concept concrete and to create preconditions for its implementation a consideration of the ethical basis is required. From an ethical viewpoint three principle motives are associated with the model (cf. [6], [7]):

- To exert equity towards all men within a generation (intra-generative equity),
- To exert equity towards all men in due course of the time (inter-generative equity),
- To preserve responsibility towards nature and its creation.

In ethical respect the sustainability concept is guided by the ambition to meet the needs of a growing population at present and in future, and to sustain human living conditions for all and permanently. Not to live on account of future generations and to create human living conditions for the entire mankind are postulates deducted from inter-generative, i.e. posterity related, as well as intra-generative, i.e. actuality related, equity considerations. Sustainable development, therefore, is a normative-ethical model related with the fundamental values of freedom, equity and solidarity in manifold ways.

2.4 Natural Science Fundamentals

Any attempt to define the concept of sustainability in concrete terms can only be sound if - as far as the material-energetic aspects are concerned - it takes the laws of nature into account.

In this context the second law of thermodynamics acquires particular significance. The Subsection details how this fundamental law is incorporated in man's efforts to create sustainable development conditions and illustrates what that means for the use of non-renewable resources and the impact from the energy sector on the environment.

2.4.1 Second Law of Thermodynamics

The fundamental content of the second law of thermodynamics is that life and the inherent need to satisfy requirements is vitally connected with the consumption of workable energy and available material.

Thermodynamically speaking, life inevitably produces entropy by degrading workable energy ("exergy") and available material and requires a permanent input of these constituencies. But available energy and material only constitute a necessary however not sufficient condition for life supporting states. In addition to this, information and knowledge is required to create states serving life. Knowledge and information, which may be defined as "creative capacity", constitute a special resource. Although it is always limited, it is never consumed and can even be increased. Knowledge grows. Increasing "creative capacity" that results in further technological development is of particular significance to sustainability because it allows for a more efficient use of natural resources and an expansion of the available resource base for generations to come. Within the context of defining the concept of sustainability, it is therefore essential to consider the evolutionary path to the future in a direct association with the advancement of science and technology [7], [8], [9], [10]. This enables future generations for instance

- to achieve living conditions with less workable energy and resources,
- to extend the available energy basis by deploying new energy types and resources,
- to extend the available resource basis by exploiting new resource sites and applying new materials,
- to reduce dissipation of available material by recycling processes and
- to minimize ecological burdens from dissipation of material and to decrease residue generation, while increasing the production of goods and services.

2.4.2 Use of Non-Renewable Resources

Within the context of defining the concept of sustainability in concrete terms, the need to limit ecological burdens and climate change can certainly be substantiated. It becomes more difficult when confronted with the question of whether the use of finite energy resources is compatible with the concept of "sustainable development", because oil and natural gas and even the nuclear fuels which we consume today are not available for use by future generations. This then permits the conclusion that the use of “renewable energy“, or “renewable resources“ only is compatible with the concept of sustainability.

But this is not sound for two reasons. First, the use of renewable energy, e.g. of solar energy, also always goes hand in hand with a need for non-renewable resources, e.g. of non-energetic resources and materials which are also in scarce supply. Second, it would mean that non-renewable resources may not be used at all - not even by future generations. Given that due to the second law of thermodynamics the use of non-renewable resources is inevitable, the important thing within the meaning of the concept of sustainable development is to leave to future generations a resource base which is technically and economically usable and which allows their needs to be satisfied at least at the same level with that today’s generation enjoys.

However, the energy and raw material base available is fundamentally determined by the technology available. Deposits of energy and raw materials which exist in the earth‘s crust but which cannot be found or extracted in the absence of the required exploration and extraction techniques or which cannot be produced economically will not contribute towards securing the quality of life. It is therefore the state of the technology, which turns valueless resources into available resources and plays a joint part in determining their quantity. As far as the use of limited stocks of energy is concerned this means that their use is compatible with the concept of sustainability as long as it is possible to provide future generations with an equally large energy base which is usable from a technical and economic viewpoint. It shall be recalled here that in the past proven reserves, i.e. energy quantities available technically and economically, have grown despite the increasing consumption of fossil fuels. Moreover, technical and scientific progress has made new energy bases technically and economically viable, for instance nuclear energy and part of the renewable energy sources.

2.4.3 Energy and Environmental Pollution

As far as the environmental dimension of sustainability is concerned, the debate should take greater note of the fact that environmental pollution, including those connected with today‘s energy supply, are primarily caused by anthropogenic flows of substances, by material dissipation, i.e. the release of substances into the environment. It is not, therefore, the use of workable energy which pollutes the environment but the release of substances connected with the respective energy system, for instance the sulphur dioxide or carbon dioxide released after the combustion of coal, oil and gas.

This becomes clear in the case of solar energy which, with the working potential - solar radiation - it makes available is, on the one hand, the principle source of all life on earth but is also, on the other hand, by far the greatest generator of entropy, because almost all of the sun‘s energy is radiated back into space after it has been devalued to heat at the ambient temperature. Since its energy, the radiation, is not tied to a material energy carrier, the generation of entropy does not produce any pollution in today‘s sense of the word. This does not, of course, exclude the release of substances and associated environmental pollution in connection with the manufacture of the solar energy plant and its equipment.

The facts addressed here are significant because they entail the possibility of uncoupling energy consumption and environmental pollution. The increasing use of workable energy and a reduction in the burdens on the climate and the environment are not, therefore, a contradiction in terms. It is the emission of substances that have to be limited, not the energy uses themselves, if the environment is to be protected.

2.5 Economics, Resource Use and Sustainability

Economy is the total product of a society’s activity for the production of goods and services meeting peoples demand. Markets with given clearing rules determine the behaviour of the actors in the economic process. This includes rules for the use of scarce resources, which in principle should be used efficiently.

Economical efficiency is always associated with efficient resource use, given that all scarce resources are accounted for in decisions of the actors. Under model conditions in a market economy scarce resources would be used efficiently and welfare maximized expressed in total cost – a system state which would be quite in line with the sustainable development concept. Reality, however, is different, as imperfections of markets might exist, like monopoly powers, asymmetrical dissemination of information or institutional barriers. Nevertheless it is important to notice that the general economic principle is in correspondence with the efficient use of resource principles derived from the concept of sustainability. This principle in connection with the provision of energy does not only refer to energy resources, but includes all other scarce resources, such as non-energetic raw materials, capital, work and environment necessary to provide energy services.

In the economy costs and prices serve as yardstick for measuring the use of scarce resources. Lower costs for the provision of the same service mean an economically more efficient solution which is less demanding on resources. The free use of environmental resources results in ecological damages, “external costs” for the environment, not charged from the causer but from third parties, e.g. the general public or future generations. In order to fully account for resource use in a market system and to apply efficient market clearing rules, it is absolutely necessary to internalize as much as possible external environmental cost [11].

There is, of course, a quantification problem associated with the internalization of external cost elements, as discussed in some detail in Section 3. Science has not progressed so far that all external effects can be taken into account, yet.

Sustainable development goals include an adequate economical growth to meet basic needs and aspirations for better life and a growing world population. In several EU countries, economic growth is required to achieve important social issues, such as financing of social security or increasing employment levels. Economy is, therefore, a means to meet society's goals, i.e. efficient economical activities are necessary, and a prerequisite for economic performance is preserving and extending competitive and market functions.

2.6 Putting the Concept of Sustainability in Concrete Terms and Making it Operational for the Energy Sector

The following Sub-section summarizes the preconditions that are necessary to translate sustainable development into concrete action terms. It then deducts operating or management rules and answers the question whether absolute or relative measurements of sustainability are appropriate in the context of the present Project.

2.6.1 Preconditions for Sustainable Energy Supply

Summarizing the above interpretations of sustainability concepts and its deductions the following preconditions as for *sustainable energy supply systems* are established.

An energy supply system is sustainable, if

- the potential for provision of energy services increases or does not decrease for the next generation,
- the substance release due to energy use does not exceed the natural assimilation capacity as a sink,
- energy services are provided with the least resource input possible, including the "environmental resource".

A consequence of the first aspect is that the known energy and resource base that is economically exploitable is not allowed to decrease. This includes successful further explorations, advanced extraction technology, increased energy productivity as well as making new energy sources available.

Resources used for the operation of the energy supply system comprise five essential factors: raw materials, energy, capital, labour and environment. Environment is understood here like a resource, because of its finite regenerative capacities. In order to measure the efficiency in terms of how much resources are used to provide one unit of energy services, a measuring method has to be defined which is able to attach differentiated values to competing energy systems. Such a method is introduced in subsection 2.6.3.

2.6.2 Operating or Management Rules

If sustainability shall not remain a theoretical construct, but become an instrument for practical application, its outline must be more specific. To make sustainability concrete several guiding or decision principles have been established. These principles, quite often named “management rules”, include very clear defined demands and interdictions.

As for sustainable future energy systems, the following management rules are derived, taking the above illustrated requirements for sustainable systems into account:

- the use of renewable resources shall in the long run not exceed their regeneration rate,
- non-renewable energy carriers and raw materials shall be used to that extent only, at which a physically and functionally equal economical substitution becomes available. The potential substitution might include additional exploitable resources, renewable resources or enhanced resource extraction productivity,
- substance released into the atmosphere shall in the long run not exceed the carrying capacity or assimilation ability of the environment,
- threats for human health associated with the provision of energy services shall be less than natural risks,
- the provision of energy services shall be achieved at the lowest total societal cost achievable.

The above listed management rules are also in accordance with the sustainability concept established in the early 1990’ies by OECD [12] supplemented with threats for human health, which the German Parliament considered essential when assessing future energy systems [13]. This catalogue of management rules is proposed to be adopted for the Project.

2.6.3 Absolute vs. Relative Sustainability

One of the essential reasons why sustainability concepts have been demanded by its early protagonists like the Brundtland Commission and others was the perception that the natural environment (air, water, soil) must be protected. The carrying limit of natural systems was considered and estimations were made as to when these limits would be reached.

These carrying capacities, e.g. the cumulative emission of *greenhouse* gases to limit climate change to a tolerable level, might then be used to assess the sustainability of developments of the system in question, e.g. the global energy system.

But when it comes to the comparison and assessment of energy technologies and energy supply chains, these absolute sustainability targets and limits are not applicable. The assessment has to be based on comparative measures of the various sustainability aspects on a functional unit basis, e.g. a kWh of electricity produced. In essence this means that we assess the relative sustainability of energy technologies e.g. with respect to the consumption of resources including the environmental resources. A useful measure for the overall resource consumption to provide an energy service are the total social cost per unit of energy service. These include the private as well as the external cost of an energy chain to provide an energy service.

3 Indicators for Measuring Sustainability

In order to transfer the concept of sustainability into an approach that is operational, i.e. to be able to effectively assess the sustainability of systems, quantitative determinations of the relevant systems performance are needed. Appropriate sustainability indicators are to be selected measuring system performance from any impact in the dimensions to be assessed within the defined scope of the concept. Sustainability indicators are expected to provide decision makers and the general public comprehensive information regarding essential system states, e.g. state and trend of the global ecosystem, the natural resources, the contamination with pollutants and significant socio-economic variables.

The following Section details, how indicators for sustainability assessment of energy systems are determined. At first basic requirements for energy system indicators are exhibited. Following are Sub-sections exploring examples of criteria and indicators found in literature. Finally relevant indicators are presented, able to measure the energy systems performance for the selected impact criteria.

3.1 Basic Requirements of Sustainability Indicators

It is essential to have clearly defined indicators when assessing sustainability. It is therefore important, before answering *how* to measure, to distinguish: what kind of information is needed, and in what forms, to support decision making for sustainable development, both for the short- and long-term.

Indicators may be defined as aggregates of more elementary data. Such composite information may have a higher significance for decision making than a variety of very independent single data, measured or collected for the same purpose. The relevance of each indicator for policy making must therefore given a high priority in the selection process.

A useful listing of desirable characteristics of physical indicators is contained in [4]:

1) Indicators must have *policy relevance,* which entails that they must

- be easy to interpret,
- show trends over time,
- be responsive to changes in driving forces,
- have threshold or reference values against which progress may be measured.

2) Indicators must be *analytically sound,* for example, based on a clear understanding of the goal of sustainable development.
3) Indicators must be *measurable,* that is, no matter how attractive the theoretical construct, if an indicator cannot be measured at reasonable cost, it is not useful.

3.2 Examples of Sustainability Indicators

Accepting the idea of measuring the relative sustainability of energy technologies or supply chains, there is nevertheless no unique or generally preferred criteria and indicator set for sustainability analyses. Which criteria and indicators to select, rather depends on the issues to be dealt with. General issues require a much different selection than sector- or sub-sector-specific problems.

Several international institutions have proposed or applied sustainability development indicators in the past on different aggregation levels. Some of those relevant for the further selection process are detailed below in the following categories:

- Indicators for the assessment of sustainable development in general,
- Indicators for the assessment of sustainable development of the energy sector and
- Indicators for the assessment of sustainability (relative) of energy technologies or supply chains.

Although the focus of this Paper is on the social dimension of sustainability the full set of indicators used by the various institutions is always shown in order to perceive the complete ambitions of the authors. Another reason for the presentation of the entire indicator set is the association with the sustainability dimensions, which is not always unequivocal. For instance health effects are sometimes associated with the social dimension, as they are caused by man's activities. In other examples health effects are included in the environmental dimension, because they are considered as impacts on nature. Income effects are likewise treated in different ways: sometimes as economic dimension effects, sometimes as social dimension effects. There are several more examples of non-equivocal indicator association. It is obvious that the association depends entirely on the issues to be addressed.

3.2.1 Indicators for Sustainable Development in General

CSD

As noted above the United Nations Commission on Sustainable Development (CSD) was established by the UN General Assembly in December 1992 to ensure effective follow-up of

United Nations Conference on Environment and Development (UNCED), also known as the Earth Summit (see Sub-section 1.2). The CSD established in 1995 the Work Programme on Indicators of Sustainable Development (WPISD) with the overall objective to provide decision-makers at the national level with indicators of sustainable development. The aim was to agree on a workable set of indicators by the year 2000 through a process of feed-back and revision.

Based on voluntary national testing and expert group consultations, a core set of 58 indicators and methodology sheets are available for all countries to use. This core set was derived from a working list of 134 indicators and related methodology sheets that were developed, improved and tested [19].

As a result of this iterative process, a final framework of 15 themes and 38 sub-themes has been developed to guide national indicator development beyond the year 2001. It covers issues generally common to all regions and countries of the world. It should be noted that the organization of themes and sub-themes within the four dimensions of sustainable development represents a ‘best- fit’ to guide the selection of indicators. This does not mean that issues should be considered exclusively within only one dimension. The social sub-theme of poverty, for example, has obvious and significant economic, environmental, and institutional linkages. The framework, together with the core set of sustainable development indicators, is summarized in Table 1 below.

Table 1: CSD Theme Indicator Set

SOCIAL		
Theme	**Sub-theme**	**Indicator**
Equity	Poverty (3)	Percent of Population Living below Poverty Line
		Gini Index of Income Inequality
		Unemployment Rate
	Gender Equality (24)	Ratio of Average Female Wage to Male Wage
Health (6)	Nutritional Status	Nutritional Status of Children
	Mortality	Mortality Rate Under 5 Years Old
		Life Expectancy at Birth
	Sanitation	Percent of Population with Adequate Sewage Disposal Facilities
	Drinking Water	Population with Access to Safe Drinking Water
	Healthcare Delivery	Percent of Population with Access to Primary Health Care Facilities
		Immunization Against Infectious Childhood Diseases
		Contraceptive Prevalence Rate
Education (36)	Education Level	Children Reaching Grade 5 of Primary Education
		Adult Secondary Education Achievement Level
	Literacy	Adult Literacy Rate
Housing (7)	Living Conditions	Floor Area per Person
Security	Crime (36, 24)	Number of Recorded Crimes per 100,000 Population
Population (5)	Population Change	Population Growth Rate
		Population of Urban Formal and Informal Settlements
ENVIRONMENTAL		
Theme	**Sub-theme**	**Indicator**
Atmosphere (9)	Climate Change	Emissions of Greenhouse Gases
	Ozone Layer Depletion	Consumption of Ozone Depleting Substances
	Air Quality	Ambient Concentration of Air Pollutants in Urban Areas
Land (10)	Agriculture (14)	Arable and Permanent Crop Land Area
		Use of Fertilizers
		Use of Agricultural Pesticides
	Forests (11)	Forest Area as a Percent of Land Area
		Wood Harvesting Intensity
	Desertification (12)	Land Affected by Desertification
	Urbanization (7)	Area of Urban Formal and Informal Settlements
Oceans, Seas and Coasts (17)	Coastal Zone	Algae Concentration in Coastal Waters
		Percent of Total Population Living in Coastal Areas
	Fisheries	Annual Catch by Major Species
Fresh Water (18)	Water Quantity	Annual Withdrawal of Ground and Surface Water as a Percent of Total Available Water
	Water Quality	BOD in Water Bodies
		Concentration of Faecal Coliform in Freshwater
Biodiversity (15)	Ecosystem	Area of Selected Key Ecosystems
		Protected Area as a % of Total Area
	Species	Abundance of Selected Key Species

Continuation of Table 1

ECONOMIC		
Theme	**Sub-theme**	**Indicator**
Economic Structure (2)	Economic Performance	GDP per Capita
		Investment Share in GDP
	Trade	Balance of Trade in Goods and Services
	Financial Status (33)	Debt to GNP Ratio
		Total ODA Given or Received as a Percent of GNP
Consumption and Production Patterns (4)	Material Consumption	Intensity of Material Use
	Energy Use	Annual Energy Consumption per Capita
		Share of Consumption of Renewable Energy Resources
		Intensity of Energy Use
	Waste Generation and Management (19-22)	Generation of Industrial and Municipal Solid Waste
		Generation of Hazardous Waste
		Generation of Radioactive Waste
		Waste Recycling and Reuse
	Transportation	Distance Traveled per Capita by Mode of Transport
INSTITUTIONAL		
Theme	**Sub-theme**	**Indicator**
Institutional Framework (38, 39)	Strategic Implementation of SD (8)	National Sustainable Development Strategy
	International Cooperation	Implementation of Ratified Global Agreements
Institutional Capacity (37)	Information Access (40)	Number of Internet Subscribers per 1000 Inhabitants
	Communication Infrastructure (40)	Main Telephone Lines per 1000 Inhabitants
	Science and Technology (35)	Expenditure on Research and Development as a Percent of GDP
	Disaster Preparedness and Response	Economic and Human Loss Due to Natural Disasters

OECD

The OECD three-year horizontal project on sustainable development was launched by OECD Ministers in April 1998. They called for the elaboration of the Organization‘s strategy “in the areas of climate change, technological development, sustainability indicators and the environmental impact of subsidies“. The project aimed at making the sustainable development concept operational for public policies and at substantive outputs for the meeting of OECD Ministers in 2001, including a series of Background Reports, based on the work of various OECD Directorates and affiliates. The sustainable development framework referred to integration of economic, social and environmental factors in a way that will meet society‘s concerns at the lowest cost, and will highlight the linkages and trade-offs between these areas. Table 2 includes the core list of environmental performance indicators [20].

Table 2: Core List of OECD Environmental Performance Indicators

Issue	Area	Indicator
Pollution Issues	Climate Change	CO2 emission intensities
	Ozone Layer Depletion	Ozone depleting substances
	Air Quality	Air emission intensities
	Waste	Waste generation intensities
	Water Quality	Waste water treatment connection rate
Resource Issues	Water Resources	Intensity of use ofwater resources
	Forest Resources	Intensity of use of forest resources
	Land Resources	Changes in land use and in key ecosystems
	Energy Resources	Intensity ofuse ofenergy resources
	Mineral Resources	Intensity ofuse ofmineral resources
	Biodiversity	Protected areas

The OECD has contributed to the debate on environmental performance and economic growth by reviewing the extent to which its 30 member countries are meeting their sustainable development objectives. Lessons learnt from the 30 country reviews that have been published since 2002 as part of the regular OECD Economic Surveys indicate that environmental performance has improved in several respects since 1990, but that costs have at the same time risen dramatically [21].

EU Commission

As pointed out in the introductory part of the Paper the EU Heads of States and Government decided at its 1999 Helsinki summit to make sustainable development a guiding principle for its policy decisions and to review progress made continuously. Since this decision sustainability has become an integrated part of EU policy (see Sub-section 1.2). The guiding principles for sustainable development declared at the recent 2005 Council of the European Union include the key objectives exhibited in Table 3 [22]:

Table 3: European Union Key Objectives of Sustainable Development

Objective	Action
Environment protection	Safeguard the earth's capacity to support life in all its diversity, respect the limits of the planet's natural resources and ensure a high level of protection and improvement of the quality of the environment. Prevent and reduce environmental pollution and promote sustainable production and consumption to break the link between economic growth and environmental degradation.
Social equity and cohesion	Promote a democratic, socially inclusive, cohesive, healthy, safe and just society with respect for fundamental rights and cultural diversity that creates equal opportunities and combats discrimination in all its forms.
Economic prosperity	Promote a prosperous, innovative, knowledge-rich, competitive and eco-efficient economy which provides high living standards and full and high-quality employment throughout the European Union.
Meeting our international responsibilities	Encourage the establishment and defend the stability of democratic institutions across the world, based on peace, security and freedom. Actively promote sustainable development worldwide and ensure that the European Union's internal and external policies are consistent with global sustainable development and its international commitments.

The most recent sustainability review issued by the EU Commission lists seven unsustainable trends, including climate change and clean energy, public health, poverty and social exclusion, an ageing society, management of natural resources, land use and transport and external aspects of sustainable development [23]. Among the most ambitious agenda for economic and social reforms in the EU is the Lisbon strategy for growth and competitiveness in Europe. This strategy, which has been renewed recently, became "…an essential component of the overarching objective of sustainable development…" [24].

The EU Commission proposed no official set of indicators measuring the sustainable development progress, but points for instance to the set of variables listed in Table 4 published by Eurostat, to illustrate the trends [25].

Table 4: Indicators for Sustainable Development published by Eurostat

Dimension	Indicator
Environment	Greenhouse gas emissions
	Emissions of CO_2 by transport activities
	Population of wild farmland birds
	Fish stocks in European marine waters
	Municipal waste collected
	Energy intensity of the economy
	Share of renewable energy
Social	Employment rate (total, female, male, older persons)
	Early school leavers
	At-risk-of-poverty rate
	Inequality of income distribution
	Old age dependency ratio
	Total fertility rate
	Net inwards migration
Economy	Public pension expenditure
	Total R&D expenditures
	Total private and public investment
	Official development aid

Helmholtz-Gemeinschaft deutscher Forschungszentren (HGF)

The Helmholtz-Gemeinschaft deutscher Forschungszentren (HGF) engaged itself since 1998 in a composite project aimed at making the sustainability concept operational. The group collected a very comprehensive indicator set, including key and additional indicators for various target areas. Table 5 exhibits a selected sub-set of HGF's long list of key indicators [2].

Table 5: Sub-set of Key Indicators Proposed by HGF

General Target: Securing man's existence		
Rule	**Theme**	**Key indicators**
Basic needs	Securing man's existence	Rate of poor poulation
		HPI index of UNDP
	Health	Life expectancy
		Childrens' and mothers' mortality rate
		Health state
	Food	Overweight persons
		Fruit and vegetable consumption
		Communities without food stores
	Living	Expenditures for living
		Ratio of homeless persons
		Public financial support for living expenditures
Protection of health		Critical load of contaminants in air
		Noise level
		Heavy metal concentration
		Dangerous persistent organic compounds
Autonomous existence		Number of social welfare recipients
		Unemployment rate
		Long-term unemployment
Eqitable rights for use of nature		CO2 emissions per capita
		Agreed international conventions
Balance of income differences		GINI coefficient
		Theil coefficient

Continuation of Table 5

General Target: Preservation of society's productive capital		
Rule	**Theme**	**Key indicators**
Sustainable use of renewables	Biodiversity, Ecosystems	Endangered species
		Loss of species
		Area used for living and transportation
		Rate of protected land/marine area
	Forest resources	Wood felling/wood breeding
		Increase of monocultures
		Ratio of FSC areas
	Fish resources	Ratio of endangered fish species
	Water resources	Water collected/water supplied
	Soil resources	Ratio of ecologically used agriculural area
		Agrarable area exceeding tolerable yield
Sustain. use of non-renewables	Energy resources	Consumption of non-renewable resources
		Ratio of renewables on TPE
		Range of non-renewable resources
	Non-energetic resources	Consumption of non-renewable resources
Sustainable use of nature as sink	Stratospheric ozone depetion	Days with ozone reduced layer thickness
		Release of ozone destroying substances
	Climate change	CO_2 emissions
	Photosmog	NOX emissions
		NMVOC emissions
	Acidification	SO_2 emissions
		NH_3 emissions
	Water pollution	Aea with animal-related N-release into soil
	Soil toxicity	Anthropogenic increase of heavy metals
		Pesticide consumption
		Hazardous waste
Avoidance of technical risks		Number of plants with licensing duty
		Number of severe accidents
		Accidents in transport of dangerous goods
SD of assets	Invested assets	Maintenance/Expansion investments
		Gross capital assets
	Human and knowledge asset	Population differentiated according to educatic
		R&D related jobs of engineers/scientists
		R&D expenditures/GNP
		Ratio of demand/offer for apprenticeships
	Productivity, competitivenes	Export-import ratio of products
		Relative patent frequency

Continuation of Table 5

General Target: Preservation of development options		
Rule	**Theme**	**Key indicators**
Society's decision processes		Poll participation Potential appeal of court for associations Institutional civil participation in decisions Number of subscribers for civil right groups Works council union of workers degree of organisation
Equal chances		Income/school education Gender empowerment Kindergarten offers Ratio of immigrants with higher education Internet access
Preservation of cultural heritage		Number of UNESCO cultural heritage sites Buildings under monument protection International meeting sites
Preservation of cultural function of nature		Total number of protected area Diversity loss in agriculture
Preservation of social functions		Persons engaged in unions Time for cost-free engagements Number of sites for social meetings Crimes per thousand Racistic crimes Unions per thousand

Other Institutions

Various research institutions have focused on economic and social indicators and investigated how useful those are in practice as a framework for sustainability assessment. An example is the Centre for the Study of Living Standards (CSLS) which, among others, reviewed existing indicators of economic and social well-being, 11 in total [26]. Some of them which could be of interest for the Project are exhibited in Table 6.

A total of 22 variables that contribute to economic and social well-being are included in the fives indexes surveyed for the case study Canada. The use of these variables for each index is given in Table 6. The index that encompasses the most variables is the IEBW, with 16, followed by the GPI and MEW with 9 and10, respectively, 8 for the ILS, and 6 for the ISH. A number of observations from Table 3 are given below.

- The ISH stands out from the other indexes with its emphasis on social variables.
- The ILS is the least developed on the economic indexes. Its inclusion of variables for household facilities and financial wealth is unique.

• The IEBW attempts the most comprehensive definition of economic well-being, but it does omit leisure, which is included in the MEW and GPI.
• Similar variables are included in the MEW and GPI, which is not surprising as the starting point for the GPI was the MEW.

Table 6: Variables Included in Indexes of Economic and Social Well-being (CSLS)

	GPI Genuine Progress Indicator	**MEW Measure of Economic Welfare**	**IEBW Index of Economic Well-Being**	**ISH Index of Social Health**	**ILS Index of Living Standards**
Income/wages				X	X
Personal consumption	X	X	X		X
Non-market activities	X	X	X		
Leisure	X	X			
Government spending			X		
Household facilities					X
Regrettables	X	X	X		
Capital stock	X	X	X		
Financial wealth					X
R&D			X		
Natural resources	X	X	X		
Educational attainment		X	X		X
Pollution	X	X	X		
Foreign debt	X	X	X		
Income distribution	X		X	X	
Poverty			X	X	
Unemployment			X	X	X
Social program coverage			X	X	
Health spending		X	X		
Crime				X	
Life expectancy			X		X
Social indicators					X

3.2.2 Indicators for Sustainable Development of the Energy Sector

IAEA, UNDESA, IEA, Eurostat and EEA Co-operative Effort

The International Atomic Energy Agency (IAEA) in co-operation with the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), Eurostat and the European Environment Agency (EEA) defined a detailed set of social, economic and environmental indicators for sustainable development, as exhibited in Table 7. While each agency has an active indicator programme, one goal of this joint endeavour has been to provide users with a consensus by leading experts on definitions, guidelines and methodologies for the development and worldwide use of a single set of energy indicators [28].

Table 7: SD Indicators of IAEA, UNDESA, IEA, Eurostat and EEA

Social				
Theme	**Sub-theme**	**Energy Indicator**		**Components**
Equity	Accessibility	SOC1	Share of households (or population) without electricity or commercial energy, or heavily dependent on non-commercial energy	– Households (or population) without electricity or commercial energy, or heavily dependent on non-commercial energy – Total number of households or population
	Affordability	SOC2	Share of household income spent on fuel and electricity	– Household income spent on fuel and electricity – Household income (total and poorest 20% of population)
	Disparities	SOC3	Household energy use for each income group and corre-sponding fuel mix	– Energy use per household for each income group (quintiles) – Household income for each income group (quintiles) – Corresponding fuel mix for each income group (quintiles)
Health	Safety	SOC4	Accident fatalities per energy produced by fuel chain	– Annual fatalities by fuel chain – Annual energy produced

Continuation of Table 7

Economic				
Theme	**Sub-theme**	**Energy Indicator**		**Components**
	Diversification (Fuel Mix)	ECO11	Fuel shares in energy and electricity	– Primary energy supply and final consumption, electricity generation and generating capacity by fuel type – Total primary energy supply, total final consumption, total electricity generation and total generating capacity
		ECO12	Non-carbon energy share in energy and electricity	– Primary supply, electricity generation and generating capacity by non-carbon energy – Total primary energy supply, total electricity generation and total generating capacity
		ECO13	Renewable energy share in energy and electricity	– Primary energy supply, final consumption and electricity generation and generating capacity by renewable energy – Total primary energy supply, total final consumption, total electricity generation and total generating capacity
	Prices	ECO14	End-use energy prices by fuel and by sector	– Energy prices (with and without tax/subsidy)
Security	Imports	ECO15	Net energy import dependency	– Energy imports – Total primary energy supply
	Strategic Fuel Stocks	ECO16	Stocks of critical fuels per corresponding fuel consumption	– Stocks of critical fuel (e.g. oil, gas, etc.) – Critical fuel consumption

Continuation of Table 7

Environmental				
Theme	**Sub-theme**	**Energy Indicator**		**Components**
Atmosphere	Climate Change	ENV1	GHG emissions from energy production and use per capita and per unit of GDP	– GHG emissions from energy production and use – Population and GDP
	Air Quality	ENV2	Ambient concentrations of air pollutants in urban areas	– Concentrations of pollutants in air
		ENV3	Air pollutant emissions from energy systems	– Air pollutant emissions
Water	Water Quality	ENV4	Contaminant discharges in liquid effluents from energy systems including oil discharges	– Contaminant discharges in liquid effluents
Land	Soil Quality	ENV5	Soil area where acidification exceeds critical load	– Affected soil area – Critical load
	Forest	ENV6	Rate of deforestation attributed to energy use	– Forest area at two different times – Biomass utilization
	Solid Waste Generation and Management	ENV7	Ratio of solid waste generation to units of energy produced	– Amount of solid waste – Energy produced
		ENV8	Ratio of solid waste properly disposed of to total generated solid waste	– Amount of solid waste properly disposed of – Total amount of solid waste
		ENV9	Ratio of solid radioactive waste to units of energy produced	– Amount of radioactive waste (cumulative for a selected period of time) – Energy produced

Continuation of Table 7

Environmental				
Theme	**Sub-theme**	**Energy Indicator**		**Components**
		ENV10	Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste	– Amount of radioactive waste awaiting disposal – Total volume of radioactive waste

Enquete Commission of German Parliament

The German parliament (Bundestag) established the "Enquete Commission" on "Sustainable Energy Supply under the Conditions of Globalization and Liberalization" with the aim to contribute to the implementation of sustainability goals developed in the frame of the UN strategies for energy and development. The Commission compiled a very comprehensive indicator set, an excerpt of which is exhibited in Table 8 [7].

Table 8: Indicator Sub-set of Enquete Commission of the German Parliament

Ecological indicators			
Area	**Indicator type**		**Indicators**
	Pressure	**State**	
Anthropogenic climate change	X		Direct greenhouse gas (CO_2, CH_4, N_2O, HFC, PFC, SF_6) Indirect greenhouse gas (NO_X, CO, NMVOC)
Environmental and health threats	X		Air pollution (SO_2, NH_3, particles)
Acidification		X	Exceeding critical loads
Area required for living/transport	X		Living/transport area needs Area needs for energy sytem Level of undivided transport-poor area
Toxic waste from energy system	X		Non-toxic non-radioactive waste Toxic non-radioactive waste from energy generation Toxic non-radioactive waste from investments/disposal
Radioactive waste from energy system	X		Accumulated HL rad. waste Nuclear fuel inventory Accumulated LL rad. waste
Energy sector related system change		X	Area of specific ecosystems Protected area Index of essential species
Energy sector related soil impacts	X		Erosion due to biomass use for energy Erosion due to hydropower generation Devastation due to mining and dams
Energy sector impact on water quality		X	Impacts from cooling and mining Impacts from hydropower generation
Health risks	X		Health risks of the energy system and energy chain Probability of typical accidents Extent of typical accidents

Continuation of Table 8

Social indicators			
Area	Indicator type		Indicators
	Pressure	State	
Employment effects from energy sector		X	Employment effect from energy system change Direct employed in energy sector
Cost impacts of energy consumption		X	Household expenditure for energy

Economical indicators			
Area	Indicator type		Indicators
	Pressure	State	
Energy resources		X	Annual primary energy consumption
Share of TPE		X	Renewables, fossil, nuclear
Health risks	X		Annual material input (biotic, mineral, metal, other abiotic) Material input for specific energy chains
Consumption and production		X	Primary energy consumption/GNP Final energy consumption for commercial consumers Final energy consumption for transportation Final energy consumption for residential consumers Specific fossil/renewable energy for electricity generation Specific energy fper production unit
Depletion of energy resources		X	Static range of coal, oil, natural gas, nuclear fuels Biomass use ratio
Meeting the transport demand		X	Passenger transport volume (car, bus, rail, ship, plane) Goods transport volume (car, rail, ship, plane)
Consumption pattern		X	Living area endowment
Cost of energy system		X	Absolute cost of energy system Specific cost of energy system
Total cost of energy sytem		X	External cost (absolute, specific) Social cost (absolute, specific)
Cost impacts		X	Expenditures of economy for energy
External supply security		X	Net imports of energy
Technical supply security		X	Interruption period

3.2.3 Indicators for Sustainability (Relative) of Energy Technologies or Supply Chains

Nuclear Energy Agency (NEA)

The Nuclear Energy Agency (NEA) proposed a set of sustainable development indicators for the nuclear energy sector [12]. Table 9 provides a summary of the eighteen proposed indicators. Data for most of them are readily available in published national or international statistical series, although some consistency checking and harmonization in units and reporting procedures might be necessary in order to ensure comparabi1ity across countries.

NEA's indicator set is designed for a technology specific assessment of the nuclear energy system and its fuel cycle. When assessing sustainable development, however, it is meaningful to compare competing technical systems, such as renewable, fossil and nuclear power plants and its associated fuel chains. A reduction to different nuclear plants and fuel cycles would spare most of the significant results for decision making from the analysis and does not seem useful.

Table 9: Proposed List of Indicators (OECD/NEA, 2002)

INDICATOR	UNIT
ECONOMIC	
Share of nuclear energy in total primary energy consumption	%
Total nuclear energy generation	TWh
Nuclear generation per capita	TWh/cap.
Average availability factor of nuclear units	%
Marginal production cost	USmill/kWh
ENVIRONMENTAL	
Natural uranium consumption	tU/year
Land requirements	km^2
Radioactivity released to the atmosphere by nuclear energy facilities	Bq/year
Radioactivity released to water by nuclear energy facilities	Bq/year
Volume of solid waste	m^3/year
Share of solid waste in interim storage	%
SOCIAL	
Employment in the sector	Person x year
Manpower cost in the sector	US$/year
Number of days of work lost by accidents on nuclear sites or professional illnesses	day/year
Work related fatalities in the nuclear energy sector	Number/year
Dose to workers	Sv/year
Fatalities in the public due to nuclear energy activities	Number/year
Number of accidents in nuclear facilities (INES)	Number/year

International Committee on Nuclear Energy (ILK)

ILK adopted the set of criteria and indicators exhibited in Table 10. This list has originally been established by the Paul Scherrer Institute within its GaBE Project for the assessment of sustainability of electricity supply technologies including nuclear power generation in a case study for Germany [13].

Table 10: Criteria and Indicators Employed in the ILK Study

Dimension	Impact Area	Indicator	Unit
Economy	Financial Requirements	Production cost	c/kWh
		Fuel price increase sensitivity	Factor*
	Resources	Availability (load factor)	%
		Geo-political factors	Relative scale
		Long-term sustainability: Energetic	Years
		Long-term sustainability: Non-energetic	kg/GWh
		Peak load response	Relative scale
Environment	Global Warming	CO_2-equivalents	tons/GWh
	Regional Environmental lmpact	Change in Unprotected Ecosystem Area	km^2/GWh
	Non-Pollutant Effects	Land use	m^2/GWh
	Severe Accidents	Fatalities	Fatalities/GWh
	Total Waste	Total weight	tons/GWh
Social	Employment	Technobogy-specific job opportunities	Person-years/ GWh
	Proliferation	Potential	Relative scale
	Human Health lmpacts (normal operation)	Mortality (reduced life-expectancy)	Years of Life Lost/GWh
	Local Disturbance	Noise, visual amenity	Relative scale
	Critical Waste Confinement	“Necessary“ confinement time	Thousand years
	Risk Aversion	Maximum credible number of fatalities per accident	max fatalities/ accident

*Increase of production costs due to doubling of fuel costs

Paul Scherrer Institute (PSI)

The goal of this study was to examine a limiting range of nuclear fuel cycles in the context of sustainability with respect to cost, proliferation, and long-term radiation doses associated with radionuclide releases from a range of repository environments. An important component of the study was the investigation of the influence of increased fuel burn-up in the “front-end” technologies on the range of performance metrics (cost, proliferation, waste). The perspective of this multi-criteria study, the indicator set of which is exhibited in Table 11, was that of a nuclear utility, and both the tools and results are thereby aimed to supplement utility responses to policies formulated to deal with these sustainability issues [29].

Table 11: SD Indicator Set of PSI Study on Nuclear Fuel Cycle

Attribute		
Economy	Economic Competativeness	Fuel resource (U or Th)
		Separative work, SW
		Conversion, CV
		Capital, CAP
		Fuel Fabrication, FF
		Storage, ST
		Processing, PR
		Transportation, TR
		o Spent Fuel, TRSF
		o High-Level Waste, TRHLW
		o Fissile Material, TRFM
		Encapsulation, EN
		o Spent Fuel, ENSF
		o High-Level Waste, ENHLW
		Repository disposal, RP
		o Spent Fuel, RPSF
		o High-Level Waste, RPHLW
		Other Operating and Maintenance (O&M) Costs
		o Fixed O&M
		o Variable O&M
		Decontamination and Decommissioning (D&D) Costs
		Levelized NFC cost
		Levelized Cost of Electricity
	Financial	Total Cost
		Construction Time (IDC)
		Accident/Liabiliity Insurance
	Technol. Avail.	Governmental R&D
		o Basic Research
		o Process Development
		o Safety
		- Operational
		- Core-Desruptive Events (CDE)
		Non-Governmental R&D
		o Similar to above
		o Commercialization Issues

Continuation of Table 11

Sustainability Attribute	Criteria	Indicator
Environmental and Public Health	Use of Non-Renewable Resources	Energy recovery per kg fuel
		Overall energy gain or Q-value
		Energy Intensity at Resource Level
	Transportation	Fresh fuel
		Waste
		o Spent Nuclear Fuel (SNF)
		o High Level Waste (HLW)
		o Transuranic (TRU = Pu + MA) Materials
	Land Use and Occupation	Mining and Milling (MM)
		Generation Plant Requirments
		FF + PR Requirements
		Waste
		o IMRF
		o Repository
	GHG Emissions	Life Cycle Needs/Assessment (LCA)
	Waste	Operational Amounts
		o Volumes
		o Activity
		D&D Amounts
		o Volumes
		o Activity
		Classification
		o HLW
		o LLW
		o TRU
		o Mixed (Radiological + Chemical)
		Radiological Impacts
		o Radiotoxicity
		o Dose
		- Individual
		- Collective
		Confinement Times
		o HLW
		o LLW
		o TRU
		o Mixed (Radiological + Chemical)
		Human Health Effects
		o Operational
		o Severe Accident
	Safety	Operational Amounts
		o Reactor
		o Frontend/Backend Facilities
		Severe Accdidents (LFE)
		o Reactor
		o Frontend/Backend Facilities

Continuation of Table 11

Sustainability Attribute	Criteria	Indicator
Society	Human Resource / Worker Opport.	Work / Professional Opportunities
		Skill Advancements
	Economic Impacts	Increses per-capita GDP
		Autonomy of Resource, Energy Self-sufficiency
		Decreased/Increased Unemployment
	Proliferation Risk	Short-Term Concerns
		Long-Term Concerns
		Alternative Routes (non-NFC) to Mass Destruction
		o non-commercial routes for SNM acquisition
		o non-nuclear WMDs
	Public Acceptance	Risk Aversion
		o Severe Accidents
		o Proliferation Risks
		o Energy Costs
		o Sustainability Ethic
		Technogical Understanding / Education
		Cultural Orientations (ala Culture Theory)

Institut für Energiewirtschaft und Rationelle Energieanwendung (IER)

The Institut für Energiewirtschaft und Rationelle Energieanwendung (IER) of Stuttgart University assessed the sustainable development of energy technologies and supply chains for the state of Baden-Württemberg in Germany. The indicator set derived for this study is exhibited in Table 12 [8].

Table 12: Indicator Set Applied by IER in Baden-Württemberg SD Study

<table>
<tr><th>Dimension</th><th>Impact Area</th><th colspan="2">Indicator</th><th>Unit/kWh</th></tr>
<tr><td rowspan="14">Ecological</td><td rowspan="4">Resource requirements</td><td colspan="2">Exhaustible energy carrier</td><td>kWh</td></tr>
<tr><td colspan="2">Copper ore</td><td>kg</td></tr>
<tr><td colspan="2">Bauxite</td><td>kg</td></tr>
<tr><td colspan="2">Iron ore</td><td>kg</td></tr>
<tr><td>Climate effects</td><td colspan="2">Greenhouse potential</td><td>kg CO_2 equivalent</td></tr>
<tr><td rowspan="2">Acification/Eutrophication</td><td colspan="2">Acidification</td><td>kg SO_2 equivalent</td></tr>
<tr><td colspan="2">Eutrophication</td><td>kg PO_4^{3-} equivalent</td></tr>
<tr><td rowspan="5">Waste</td><td rowspan="3">non-radioactive</td><td>Residential and production</td><td>kg</td></tr>
<tr><td>Construction</td><td>kg</td></tr>
<tr><td>Hazardous</td><td>kg</td></tr>
<tr><td rowspan="2">radioactive</td><td>Heat releasing</td><td>m^3</td></tr>
<tr><td>Non-heat releasing</td><td>m^3</td></tr>
<tr><td rowspan="4">Social</td><td>Work opportunity</td><td colspan="2">Direct employment</td><td>Workers</td></tr>
<tr><td>Income generation</td><td colspan="2">Added value</td><td>€</td></tr>
<tr><td rowspan="2">Health effects</td><td colspan="2">Public effects</td><td>YOLL</td></tr>
<tr><td colspan="2">Occupational effects</td><td>YOLL</td></tr>
<tr><td rowspan="3">Economical</td><td rowspan="3">Cost</td><td colspan="2">Private cost</td><td>€</td></tr>
<tr><td colspan="2">Public cost</td><td>€</td></tr>
<tr><td colspan="2">Total societal cost</td><td>€</td></tr>
</table>

International Energy Agency (IEA)

The International Energy Agency (IEA) established a set of "issues" to be considered in the context of "…an integrated approach to economic, environmental and social components of bioenergy systems" [27] (see Table 13). Most of the issues on the macro (-economic) level as well as those on the energy supply and demand side can be translated into quantifiable indicators for an assessment of sustainability of various energy technologies. The issues of the social and institutional dimension however focus on fairly general problem descriptions that need clear definitions and further differentiation into sub-systems in order to determine indicators for quantitative measurements.

Table 13: Issues Related with Local Bioenergy Production (IEA)

Dimension	Relevant Issues (Areas for which indicators shall be defined)
Social	Increased Standard of Living Environment Health Education Social Cohesion and Stability Migration effects (mitigating rural population) Regional development Rural diversification
Macro Level	Security of Supply/ Risk Diversification Regional Growth Reduced Regional Trade Balance Export Potential
Supply Side	Increased Productivity Enhanced Competitiveness Labour and Population Mobility (induced effects) Improved infrastructure
Demand Side	Employment Income and Wealth Creation Induced Investment Support of Related Industries
Institutional Aspects	Democratic decision processes Participatory problem solving Local problem solving.

4 Summary and Conclusions

The concept of sustainable development is not a new one; generally accepted starting point of most of the present concepts is the definition of the World Commission on Environment and Development (WCED), also known as the “Brundtland Commission. According to WCED, sustainable development reconciles improving the economical and social living conditions of all (present and future) generations with securing the long-term natural resources. However, there are several approaches proposed on how to define sustainability in precise terms, which include conflicting principles.

Sustainability concepts are among others characterized by the degree of substitutability. A central approach of the neo-classical school of thoughts is the so-called “weak sustainability”, which suggests a substitution paradigm according to which elements of the natural capital (renewable and exhaustible resources, assimilative and life preserving functions of nature) to a large extent can be replaced by man-made capital. Sustainability concepts however, attributed to the school of ecological economics follow the perception of “strong sustainability”, giving preference for ecologically based limitations as opposed to economic activities. Substitution between man-made and natural capital are strictly excluded in this concept. Both, the non-existent as well as the more or less unbounded substitution ability between natural and artificial capital, are not very reality oriented models.

Approaches for practical implementation often are based upon a mixed conceptual form of strong and weak sustainability, denominated “critical weak sustainability”. It embraces critical performance limits for some complementary functions of the natural capital, felt to be indispensable for life. Aside from those limits substitutability among the various components of natural capital is assumed. This perception of a “critical weak sustainability” seems to be the most appropriate approach for deriving practical guidelines from the sustainable development concept for the assessment of energy systems.

Most of the known sustainability concepts follow the idea of a Three-Pillar Model, i.e. pillars representing the ecological, economical and social dimensions under equitable ranking conditions. Sometimes additional installation of a “cultural” and/or “institutional” dimension are suggested. However, in practice the Three-Pillar Model turned out to be of limited value. The main reason for its’ limited applicability is that its’ three dimensions are strongly interlinked and connected an independent from each other.

A conceptually sounder understanding of sustainability is the integrated ecological, economical and social dimension concept. It is based on the understanding that natural resources and assets (including the environment) are exploited and used to be transformed via technologies to satisfy societal needs for goods and services, where the economy is the operator of this transformation process.

Any attempt to define the concept of sustainability in concrete terms can only be sound if it takes the laws of nature into account. In this context the second law of thermodynamics acquires particular significance. Thermodynamically speaking, life inevitably produces entropy by degrading workable energy ("exergy") and available material and requires a permanent input of these constituencies. But available energy and material only constitute a necessary however not sufficient condition for life supporting states. In addition to this, information and knowledge is required to create states serving life. Knowledge and information, which may be defined as "creative capacity“, constitute a special resource. Although it is always limited, it is not consumed and can even be increased. Knowledge grows. Increasing knowledge or "creative capacity" resulting in further technological development is partially significant for sustainability, because it allows for a more efficient use of natural resources and an expanding of the economically available resource base for the generations to come.

Within the context of defining the concept of sustainability in concrete terms, the need to limit ecological burdens and climate change can certainly be substantiated. The energy and raw material base economically available is fundamentally determined by the technology available. As far as the use of limited stocks of energy is concerned this means that their use is compatible with the concept of sustainability as long as it is possible to provide future generations with an equally large energy base which is usable from a technical and economic viewpoint.

As far as the environmental dimension of sustainability is concerned, pollution connected with today‘s energy supply, is primarily caused by anthropogenic flows of substances, by material dissipation, i.e. the release of substances into the environment. It is not the use of workable energy which pollutes the environment but the release of substances connected with the respective energy system, for instance the sulphur dioxide or carbon dioxide released after the combustion of coal, oil and gas. The increasing use of workable energy and a reduction in the burdens on the climate and the environment are not, therefore, a contradiction in terms. It is the emission of substances that have to be limited, not necessarily the energy uses themselves, if we want to protect the environment.

The economic dimension deserves a special attention within the sustainability definition, as it is quite often misunderstood or misinterpreted. Economical efficiency is always associated with efficient use of scarce resource in an economy, given that all scarce resources are accounted for in decisions of the actors.

This is to say that the general economic principle is in correspondence with the principle of efficient resource use of the concept of sustainability. This principle in connection with the provision of energy does not only refer to energy resources, but includes all other scarce resources, such as non-energetic raw materials, capital, work and environment necessary to provide energy services. In order to fully account for resource use, it is necessary to internalize the external cost. Total social costs are a suitable yardstick for measuring the utilization of scarce resources.

Summarizing the interpretations of sustainability concepts and its deductions the following preconditions as for *sustainable energy supply systems* can be established. An energy supply system is sustainable, if

- the potential for an economic provision of energy services increases or does not decrease for the next generation,
- the substance release due to energy use does not exceed the natural assimilation capacity as a sink,
- energy services are provided with the least resource input possible, including the "environmental resource".

These general rules for a sustainable energy supply system are not directly applicable when it comes to the comparison and assessment of energy technologies and energy supply chains. Here the assessment has to be based on comparative measures of the various sustainability aspects on a functional unit basis, e.g. a kWh of electricity produced or a unit of energy service provided. The relative sustainability of energy technologies is basically determined by the overall consumption of resources including environmental resources on a functional unit basis. One useful measure for the overall resource consumption, that is the relative sustainability are the total social cost per unit of energy service. These include the private as well as the external cost of an energy chain to provide an energy service.

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