Sustainable Energy Technologies

Options and Prospects

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Chapter 2
Sustainability Concept for Energy, Water and Environment Systems

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Abstract. Sustainability has become an unavoidable issue in all major planning and undertakings that involve future use of energy, water and any other natural resources. In order to ensure sustainable growth of our society, we must satisfy the sustainability criteria and meet the constraints imposed by the finiteness of all natural resources and the dynamics of their natural renewal. But how do we quantify and measure sustainability and how do we ensure that the sustainability requirements are fulfilled? We consider the sustainability concept for energy, water and environmental systems and its interaction with current major global trends: globalisation, democratisation and decentralisation. In the assessment of global energy and water resources we consider the current resource consumption and possible scenarios for meeting future demands. We then move to the definition of the sustainability concept. In order to introduce a measure of sustainability, we focus on possible definitions of respective criteria with specific application to energy system design. It is argued that multi-criteria sustainability measurements of options for an energy system must be based on four sets of indicators: technological efficiency, economic, environmental and social indicators.

Key words: Sustainability, energy, water and environment system, resources, limits, sustainability measures.

2.1 Introduction

Our civilisation has developed under economic, social and ecological limitations. The industrial revolution brought with it the recognition that in order to improve the quality of life there must be coordination of development among different commodities. This has resulted in economic and social benefits based on the natural capital available for technological development.

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Throughout the history of human society, the cyclic development of human structures has affected changes in the pattern of social structures. Critical states at specific periods of time created new complexities in human society. The industrial revolution added a new complexity by introducing new commodities. As we near the end of the industrial revolution, it has become evident that complexity indicators such as population, economics, material resources, social structure and religious devotion have reached another critical state.

A number of scholars have highlighted the unique state of our current civilisation. Attention has been focused on indicators related to material resources and the environment. In our lifetime there have been many attempts to emphasise different aspects of the use of material resources. Some of those are based on ethical and religious principles regarding our responsibilities to humanity and to the divine. Warning signs have been given that we are nearing certain limits after which the changes will be irreparable. The first and second energy crises have shown our vulnerability. Recent claims have been made that the concentration of CO_2 in the Earth atmosphere is reaching a limit that may trigger irreversible changes in the environment with catastrophic consequences for life on our planet. Sustainable development encompasses economic, social, and ecological aspects of conservation and change. The essence of sustainability is the need to preserve the natural cycles of renewal, i.e., the balance between consumption and natural resource recovery. Or, as postulated by the World Commission on Environment and Development (WCED), "to satisfy our needs without compromising the ability of future generations to meet their own needs". This definition is based on the ethical imperative of equity within and between generations. Moreover, apart from meeting the basic needs of all, sustainable development implies sustaining the natural life-support systems on Earth, and extending to all the opportunity to satisfy the aspirations for a better life. Hence, sustainable development is more precisely defined as "a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations".

The first issue is concerned with the objectives of sustainable development; that is, "what should be sustained" and "what kind of development is preferred". These are normative questions that involve value judgements about society's objectives with respect to social, economic, and ecological system goals. These value judgements are conveniently expressed in terms of a social welfare function, which allows an evaluation of trade-offs among the different system goals.

The second issue deals with the positive aspect of sustainable development; that is, the feasibility problem of "what can be sustained" and "what kind of system we can devise". It requires one to understand how the different systems interact and evolve, and how they could be managed. Formally, this can be represented in a dynamic model by a set of differential equations and additional constraints. The entire set of feasible combinations of social, economic and ecological states describes the temporal transformation space of the economy in the broadest sense.

Complexity is the property that describes the state of a complex system [1, 2]. It is a multi-criteria indicator that comprises all the individual characteristics of the system. A complex system is an entity that characterises a structure with a large number of interacting elements. Elements have different structures. Elements in biology are structured to perform specific functions. A typical example is the DNA molecule, comprising a large number of elements interacting among themselves. In information theory the structure of elements is described as an internet network with a large number of nodes for information exchange. In the energy system we can describe a complex system as a system that produces, transports and utilises different energy sources. The complexity of these systems is the internal property of the system expressed as the wholeness property. This implies that the complexity describes the essential characteristic of the system.

If the complexity is described in thermodynamic terms, it represents the internal parameter of the system expressed by agglomerated indicators describing the specific property of the system. If we take into consideration only the material system, we can take the entropy of the system as the macroscopic property of the system. These can be applied to chemically bounded molecules. Prigogine [3, 4] has determined the characteristic property of these systems as entropy generation. This means that every interaction between elements accompanied by mass, momentum and energy exchange is ultimately connected and contributes to the entropy generation in the system. It should be taken into consideration that the entropy generation is defined per unit mass of the system and represents a specific property of the system. So the entropy generation represents the complexity property of the system.

If we take into consideration a non-material system where complex properties include entities which are not defined per unit mass of the system, we have to introduce a notion which represents the wholeness of the system. A good example of this type of complex system is the Internet system. Large numbers of nodes are connected in a large net which transfers information among the nodes. If we assume that transfer of information contributes to the increase of the informativity of the system, it follows that the increase of informativity is equivalent to the increase of the complexity of the system. In this respect the informativity is equivalent to complexity.

In order to comprehend the full complexity of sustainability and to develop a rational sustainability concept, we need to draw on up-to-date scientific knowledge from different fields. For that purpose, it is imperative that we not only inform, but that we alarm, the scientific community at large, that we focus their attention on sustainability and urge their contribution of relevant knowledge to synthesising a comprehensive notion of sustainable science that will aim at better understanding of the future of our planet [5].

2.2 Sustainability and Global Processes

In the complexity definition of the sustainability concept there are three clusters of indicators which are used to describe the state of the global system: the resource, environmental and social clusters. There are also three processes that are immanent to the development of our planet: globalisation, democratisation and decentralisation [6]. Even though there are many cases in which these processes are in conflict, the full scale effects of these processes are of fundamental importance for the understanding of issues such as the behaviour of complex systems. In order to relate these processes to sustainability and to account for their effects in the estimate of the sustainability of a system, it is necessary to introduce criteria for their quantification and measure.

Globalisation. Recently it has become evident that economic forces drive the transfer of capital, material, resources and manpower throughought the world without obstacles imposed by local, state and regional boundaries. The contemporary revival of interest in the field of international political economy has coincided with an unprecedented restructuring of the world economy, referred to as globalisation. The forces of change associated with globalisation have been felt through states and societies to such an extent that it has become the focus of much research across the social sciences. Yet, despite recognising that globalisation represents a critical issue in the development of political economy, the interdisciplinary approach combined with economic theories pursued so far has not provided a foundation that is adequate for consolidation of the field. Interdisciplinary insight into the global economy needs knowledge of the structure of the system as well as the parameters that describe the state of the system. The intensity of globalisation is assessed by the quantities that are used as indicators reflecting the state of the system under consideration. This implies that the process of economic reform will be measured by changes in respective indicators over time. The globalisation process is taking place within the system, so that the system parameters are supposed to be the measuring parameters of the intensity of processes in the system. In this respect the intensive parameters of the system are to be used in the determination of the state of the system. In the terminology of Thermodynamics, the intensive parameters are specific quantities of the respective extensive parameters. In this case, it could be understood as specific capital, specific material, specific resources and specific manpower. In engineering practice, in order to become operational, indicators have to be measured as the state parameters of the system. Since we are interested in measuring the change of the state of the system, it is necessary to introduce as indicators of the globalisation process the respective change of the intensive parameters of the system. So, as indicators for the globalisation process, the following parameters can be adopted: rate of change of specific capital, rate of change of specific material, rate of change of specific resources and rate of change of specific manpower.

Democratisation. Democracy is the principle of equity of rights, opportunity and treatment [7]. The process leading to the establishment of social organisation based on the principles of democracy is democratisation. So, the democratisation process can be defined within different boundaries including the local, regional and global environment. The intensity of the democratisation process is dependent on the number of attributes reflecting the ethnic, religious, cultural and educational

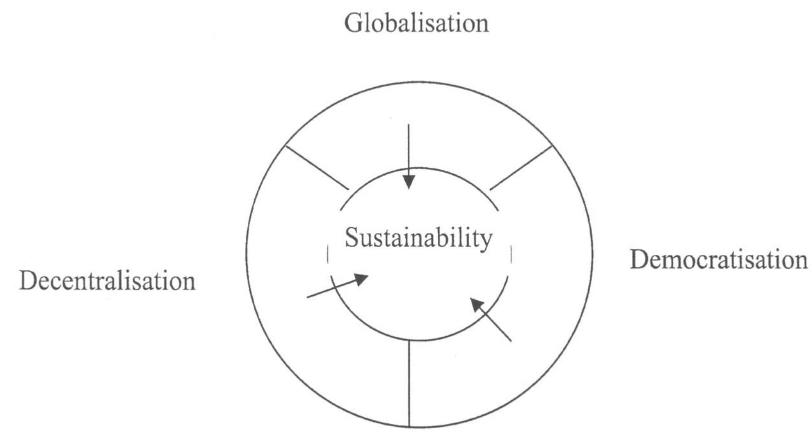

Fig. 2.1 Schematic presentation of interaction: Sustainability – Globalisation – Democratisation – Decentralisation.

environment. For every structured social system the respective indicators reflecting different aspects of the democratisation process can define the intensity of that process. Individual parameters defining specific characteristics of democratisation can be used to measure the intensity of that process. Among those are: equity of rights, job opportunity and treatment. Each of the parameters can be defined as the specific value of the internal parameter of the system under consideration. As the internal parameters, the indicators of the democratisation process can be defined as: the specific number of citizens participating in the voting system, the specific number of job opportunities in the system etc. Since the respective indicators cluster also defines the democratisation process, it is of interest to make the assessment with reference to the effect of the social parameters defined by the democratisation of the observed system. Again, we have to form a respective aggregation function which will describe the state of the system. In this respect the sustainability assessment can be used as the decision-making paradigm for the system assessment.

Decentralisation. It has long been considered that large energy and water systems are economically better justified than small systems. The economic indicators and constraints prevailing at the time were indisputably in favour of large systems, acting as the driving force in the decision-making process. With a new wave of miniaturisation, it has become evident that in a complex system assessment priority may be given to smaller systems [8]. This trend applies to all segments of life and human activities, ranging from technology to societal organisation. For example, the new trend in governance systems is to encourage regional autonomies in state organisation and to transfer more and more decision rights to local and regional governments. The same can be said of the development of energy, water and environmental systems. Smaller cogeneration units have become an attractive solution in many areas, leading to better economic, environmental and social values in the use of available resources. The modern micro gas turbine in conjunction with cogeneration has proved to be justified by the complex assessment method. Of course, this should be proved by applying a network system to investigate options and pathways for an accelerated transition towards sustainable energy technologies and systems. However, in a number of cases it has been shown that the appropriate selection of the criteria and respective indicators with corresponding decision-making procedures will give priority to decentralised systems.

The aggregation function for the decentralisation assessment should include all parameters that are of importance to the assessment of the system. Adoption of this procedure, which will lead to the formation of clusters of indicators represented by the respective sustainability indicator, will enable us to define an appropriate sustainability index which represents the quality of the system.

In addition to the three global processes discussed above, there are other factors and processes that also play an important role in quantifying sustainability. Recall that there are three essential life support systems, namely, energy, water and environment. Each of these systems comprises a large number of subsystems defined with different indicators reflecting economic, environmental and social criteria. In everyday life there is a need for decision-making actions governed by a number of criteria. Fundamental advances in our ability to address such issues as the behaviour of complex systems will be required. Besides those criteria leading to the decision for large systems, there will be more and more criteria which will make it possible to apply knowledge about different aspects of the system, including its interaction with other systems, interaction with the environment, and its *reflection* to the social environment. In this respect, there will be a need to have an education system which will accommodate basic knowledge with operational sustainability assessment.

2.3 Limits

Energy, water and environment are essential commodities, necessary for human life on our planet. These three commodities have been fundamental resources in the economic, social and cultural development of our civilisation. In the early days of human history it was believed that there were abundant reserves of these commodities. With the industrial revolution the use of resources drove economic and social development. With the increase of population and a respective increase of the standard of living, natural resources have become a scarcity in some regions. With the further increase in demand it has become evident that the scarcity of natural resources may become a global problem and affect human life on our planet. The Club of Rome was among the first to draw world attention to the potential limits of our planet's natural capital. The energy crises in 1972 and 1978 focused the attention of our community at large on the limits of energy resources [9] and various institutions launched programmes to investigate the scarcity of natural resources on a global

Table 2.1 Assessed energy resources (WEC Members Commission 2003).

	Total 10^9 toe	CPE %	North America %	Latin America %	West Europe %	Africa %	Asia-Pacific %	Middle East %
Coal	606	5.5	27.9	2.1	28.4	27.0	0.4	8.7
Oil	148	8.9	4.9	12.8	5.5	7.6	13.1	2.0
Gas	147	7.6	4.7	3.6	9.9	31.5	41.6	0.8

scale. It has become clear that modern society has to adopt a new philosophy, based on limited natural resources.

2.3.1 *Energy*

In 1886 Boltzmann [10], one of the Fathers of modern physical chemistry, wrote that the struggle for life is not a struggle for basic elements or energy, but a struggle for the availability of energy transferred from the hot Sun to the cold Earth. In fact, life on Earth requires a continuous flux of solar energy to support the energy capturing by photosynthesis [11]. The Sun is an enormous machine that produces energy by nuclear fusion and offers planet Earth the possibility of receiving large quantities of available energy (exergy). Every year the Sun sends 5.6×10^{24} joules of energy to the Earth and produces 2×10^{11} tonnes of organic material through photosynthesis. This is equivalent to 3×10^{21} joules/year. In the billions of years since the creation of planet Earth this process has led to the accumulation of enormous energy in the form of different hydrocarbons. Mankind's energy resources rely heavily on the chemical energy stored in fossil fuel. Table 2.1 shows assessed energy resources [12, 13].

Energy and matter constitute the Earth's natural capital, which is essential for human activities such as industry, amenities and services. Our natural capital, as the inhabitants of the planet Earth, may be classified as:

- Solar capital (providing 99% of the energy used on the Earth).
- Earth capital (life support resources and processes including human resources).

Many suggest that this natural capital is being rapidly depleted. Many also suggest that contemporary economic theory does not appreciate the significance of natural capital in techno-economic production.

All natural resources are theoretically renewable, but over widely different time scales. If the time period for renewal is small, they are said to be renewable. If the renewal period is longer but takes place within the time frame of our lives, they are said to be potentially renewable. The renewal of some natural resources is only possible through geological processes which take place on such a long time scale that for all practical purposes they are regarded as non-renewable. Our use of natural material resources involves no loss of matter as such. All Earth matter remains with the Earth, but in a form which cannot be easily used. When the quality or useful

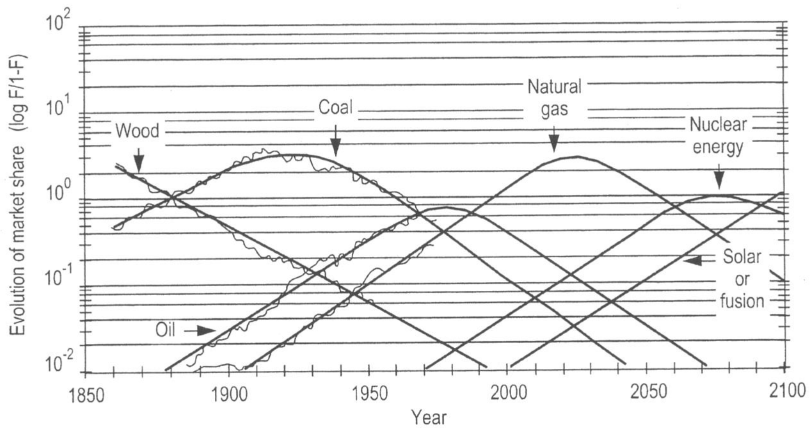

Fig. 2.2 Market penetration of primary energy sources.

part of a given amount of energy is degraded due to use we say that its entropy is increased.

Because of the abundant energy resources in the early days of the industrial revolution, the development strategy of our civilisation was based on the assumption of unlimited energy resources, as well as the assumption that no other limitations existed which could affect the development of human welfare. It has been recognised that the pattern of energy resource use has been highly dependent on the development of technology. It is therefore instructive to observe the change in the consumption of different resources through the history of energy consumption. Worldwide use of primary energy sources since 1850 is shown in Figure 2.2 [14, 15].

In Figure 2.2 "F" denotes the market fraction of each primary energy source at a given time. Two factors affect the energy consumption pattern. The first is related to technological development, and the second to the availability of the respective energy resources. Obviously, these patterns of the use of energy source are developed under constraints pertaining to the total level of energy consumption and reflect the existing social structure both in numbers and diversity [16–18]. World energy consumption is shown in Figure 2.3.

Looking at the present consumption pattern of energy sources, we see that oil supplies about 40% of total energy, coal around 30%, natural gas 20% and nuclear energy 6.5%. This means that fossil fuels currently supply 90% of our total energy. In the past several decades our civilisation has witnessed changes which have brought our long-term prospects into question. Non-recyclable fossil fuel is an exhaustible natural resource that will one day no longer be available. As they are our main source of energy it is of common interest to learn how long these fossil fuel resources will be available. This question has attracted the attention of a number of distinguished authorities attempting to forecast the energy future of our planet.

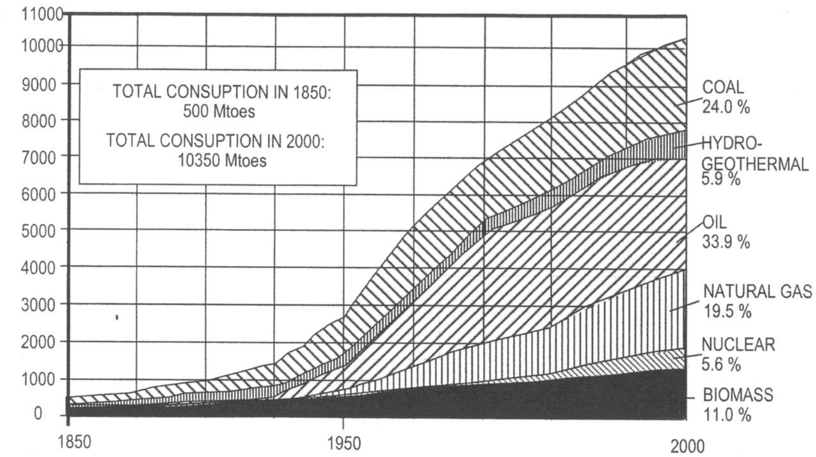

Fig. 2.3 World energy consumption.

The Report of the Club of Rome "Limits to Growth", published in 1972, was among the first which pointed to the finite nature of fossil fuels. After the first and second energy crises the community at large became aware of the possibility of the physical exhaustion of fossil fuels. It is known that the estimates of the exploitable reserves depend on the involved exploitation cost. For oil, based on the exploitation costs of under $20 per barrel, it was estimated that the proven reserves have over the past twenty years levelled off at 2.2 trillion (10^{12}) barrels, Over the last 150 years we have already consumed one-third of that amount, or about 700 billion barrels, which leaves only the remaining 1.5 trillion barrels. Compared with the present consumption, that means that oil is available for the next 40 years only.

Figure 2.4 shows the estimated residual life forecast for the three main fossil fuels over the last half of the century. According to the present forecast, coal is available for the next 250 years and gas for the next 50 years. It is also evident that while fuel consumption is increasing, new technologies for the discovery of new resources are becoming available and the continuous increase in price is shifting the limit of what is considered as exploitable, leading to an extension of the time period for exhaustion of the available energy sources.

It is known that energy consumption is dependent on two main parameters; namely, the amount of energy consumed per capita and the growth of population. It has been proved that there is a strong correlation between the Gross Domestic Product and energy consumption per capita. Figure 2.5 shows the economic growth and energy consumption for a number of countries in 1991.

Whatever the accuracy of our prediction methods and models, it is clear that uncertainty in our calculation may affect the time scale but not the essential under-

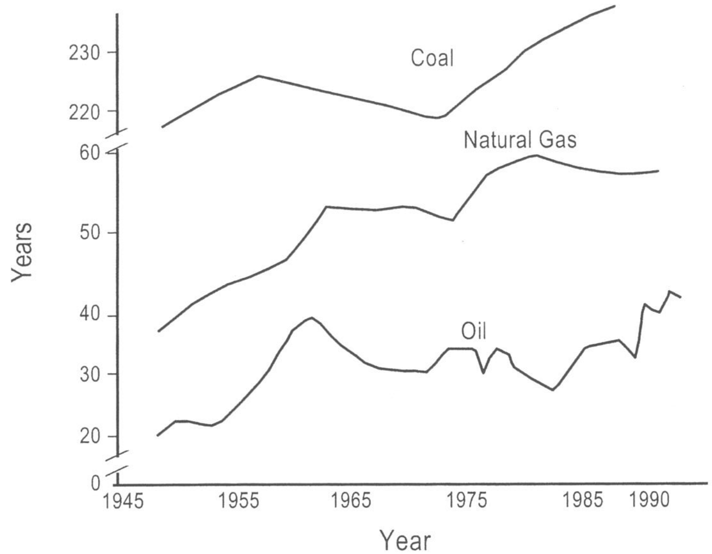

Fig. 2.4 Residual life forecast of energy resources.

standing that there is a real depletion of energy resources and that human action is required before adverse effects become irreversible [20].

Figure 2.4 shows also that each of these energy resources became significantly scarcer during the 1970s. The situation reversed during the 1980s as new reserves were discovered. Nevertheless, the alarming realisation of the depletion of energy resources and the coincidental energy crisis in the 1970s left a lasting imprint and far reaching implications on future economic growth, proving that scarcity of resources and economic growth are closely interrelated. To be sure, it has not been proven that the short term scarcity fluctuation of energy resources has substantial implications on long term economic growth. However, the need for active involvement in the allocation of scarce, non-renewable energy resources and the potential negative effects of uncontrolled consumption on economic growth has become evident.

2.3.2 *Environment*

The use of primary energy resources is a major source of CO_2 emissions [21–24]. Because fossil fuels have been shown to be economical, in recent years more than 88% of primary energy in the world has been generated from fossil fuels. However, the exhaust gases from combusted fuels have accumulated to such an extent that the global environment is being seriously damaged. The accumulated amount of CO_2

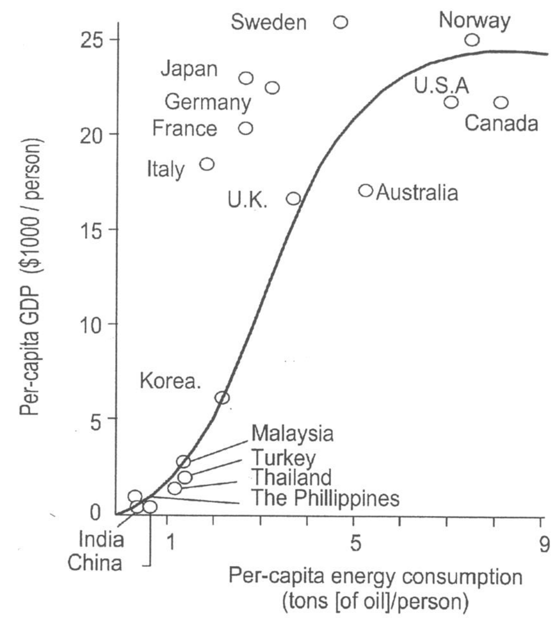

Fig. 2.5 Correlation between income per capita and energy consumption levels per capita of selected industrialised and developing countries (Source: Herman Daly, Steady-state Economics, Washington, Island Press, 1991).

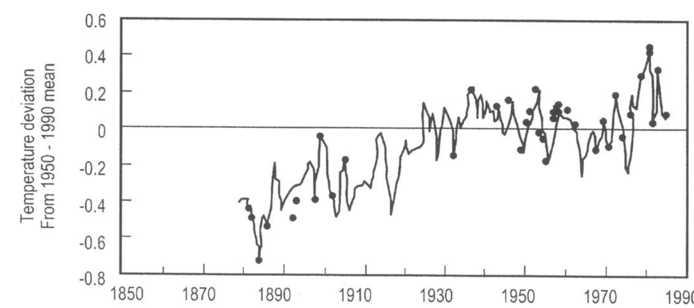

Fig. 2.6 Global warming trend 1900–1990.

in the atmosphere is estimated at about 2.75×10^{12} t. The global warming trend from 1900 to 1997 is shown in Figure 2.6 [25]. The future trend of carbon dioxide concentration in the atmosphere can be seen in Figure 2.8.

Obviously, further increases of CO_2 emissions will lead to disastrous effects on the environment. Emissions of SO_2, NOx and suspended particulate matter will further contribute to this.

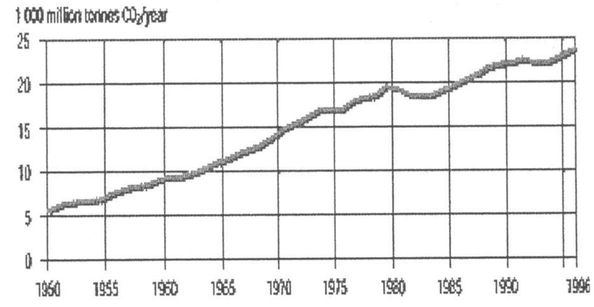

Fig. 2.7 Cumulative CO_2 production.

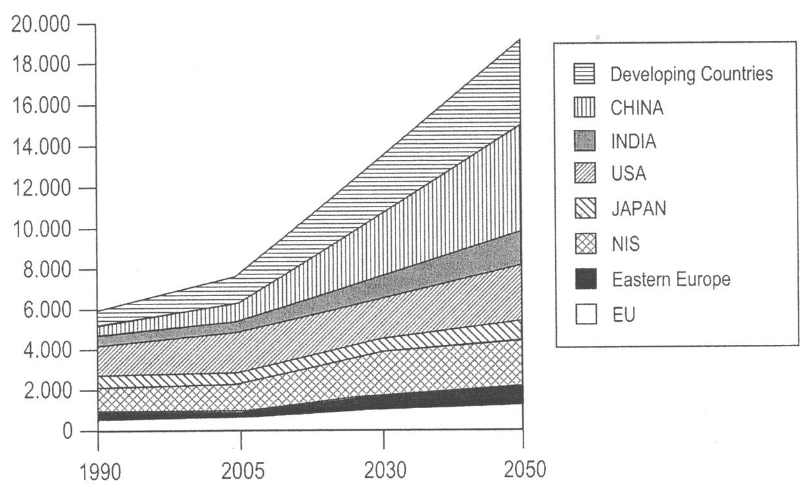

Fig. 2.8 Forecast for CO_2 emission.

On the world scale, coal will continue to be a major source of fuel for electric power generation. Many developing countries, such as China and India, will continue to use inexpensive, abundant, indigenous coal to meet growing domestic energy needs. As the economy of developing countries continues to expand, the use of coal worldwide is greatly increasing. The major long-term environmental concerns regarding the use of coal have changed from acid rain to greenhouse gas emissions – primarily carbon dioxide from combustion. Coal is expected to continue to dominate China's energy picture in the future. The share of coal in primary energy consumption is forecast to be no less than 70% during the period 1995–2010. In 1993 China produced a total of 1114 billion (10^9) tonnes of coal, in 2000 1.5 trillion (10^{12}), and in 2010 it will be 2 trillion. Since China is the third largest energy consumer in the

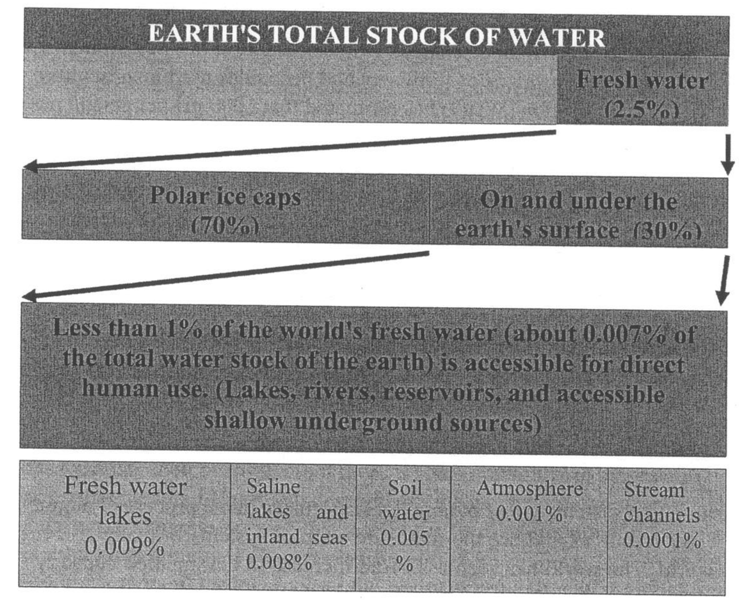

Fig. 2.9 Global stock of water.

world after the USA and Russia, its contribution to the global accumulation of CO_2 will be substantial unless adequate mitigation strategies are adopted. The example of China is instructive in the assessment of the future needs of developing countries and their accelerated economic development.

2.3.3 Water

The sustainability of desalination systems, an essential component of human-made or built capital, is discussed in this section with respect to its important contribution to life support systems. Figure 2.9 shows the distribution of the global stock of water [26, 27].

Of the total global water stock, 97.5% is saline and only 2.5% is freshwater. Approximately 70% of this global freshwater stock is locked in polar icecaps and a major part of the remaining 30% lies in remote underground aquifers. In effect, only a miniscule fraction of the freshwater available in rivers, lakes and reservoirs (less than 1% of total freshwater, or 0.007% of the total global water stock) is readily accessible for direct human use. Furthermore, the spatial and temporal distribution of the freshwater stocks and flows is hugely uneven. Hydrologists estimate the average annual flow of all the world's rivers to be about 41,000 km^3/yr. Less than a third of this potential resource can be harnessed for human needs. This is further reduced by pollution such as discharges from industrial processes, drainage from mines and leaching of residues of fertilisers and pesticides used in agriculture. The World Health Organization (WHO) has estimated that 1000 m^3 per person per year is the benchmark level below which chronic water scarcity is considered to impede development and harm human health.

Several countries are technically in a situation of water scarcity, i.e., with less than 1000 m^3 of renewable water per head of population per year. Water shortage is predicted to increase significantly, mainly as a result of population increase.

The Dublin Statement of January 1992 on "Water and Sustainable Development" and the subsequent Rio Earth Summit Agenda 21, Chapter 18, "Protection of the quality and supply of freshwater resources", are most relevant to the present context since desalination augments fresh water resources. Chapter 30 of Agenda 21 is also important in the context of desalination as it draws the attention of leaders of business and industry, including international corporations and their representative organisations, to their critical role in helping the world achieve the goals for sustainable development.

Desalination systems are of paramount importance in the process of augmenting fresh water resources and are the main life support systems in many arid regions of the world. The world has seen a 22-fold increase in desalination capacity since 1972 and the figure continues to rise. In 1997 the total desalination capacity was 22,730,000 m^3 of fresh water per day. That represents a doubling in global capacity over 10 years and a 22-fold increase over 25 years. Yet desalinated seawater represents only about one thousandth of the fresh water used worldwide. Desalinated water costs several times more than the water supplied by conventional means. The countries in the Arabian Gulf Region heavily subsidise the costs to render it affordable. In some of these countries, water is subsidised so heavily that users make little effort to curb their use. Water consumption would be greatly reduced if the price were closer to the true cost of production.

2.4 Sustainability Definitions

Over the past few years "sustainability" has become a popular buzzword in the discussion of the use of resources and environmental policy. Before any further discussion of the subject, it is necessary to define and properly assess the term we are going to use. So, what is sustainability? Among the definitions most often adopted are the following:

a. World Commission on Environment and Development (Brundtland Commission) [28] "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs".
b. Agenda 21, Chapter 35 [29]
"Development requires taking long-term perspectives, integrating local and regional effects of global change into the development process, and using the best scientific and traditional knowledge available".
c. Council of Academies of Engineering and Technological Sciences [30]
"It means the balancing of economic, social, environmental and technological consideration, as well as the incorporation of a set of ethical values".
d. Earth Chapter [31]
"The protection of the environment is essential for human well-being and the enjoyment of fundamental rights, and as such requires the exercise of corresponding fundamental duties".
e. Thomas Jefferson, September 6 1889 [32]
"Then I say the Earth belongs to each generation during its course, fully and in its right no generation can contract debts greater than may be paid during the course of its existence".

All five definitions emphasise a specific aspect of sustainability. Definitions (a) and (e) imply that each generation must bequeath enough natural capital for future generations to satisfy their needs. Even if there is some ambiguity in these definitions, it is implied that we should leave our descendants the wherewithal to survive and meet their own needs. There is no specification for the form or amount of these resources as it is difficult to anticipate future scenarios.

Definitions (b) and (c) incorporate the political requirement at global, regional and local levels to stimulate the United Nations, governments and local authorities to plan development programmes in accordance with scientific and technological knowledge. Note the inclusion in definition (c) of the ethical aspect of actions to be taken to meet sustainable development. Definition (d) reflects also religious beliefs which assume responsibilities and duties toward nature and Earth.

2.5 Sustainability Concept

Sustainable development encompasses economic, social, and ecological perspectives of conservation and change. The WCED definition of sustainability (a) is based on the ethical imperative of equity within and between generations. Moreover, apart from meeting the basic needs of all, sustainable development implies sustaining the natural life-support systems on Earth, and extending to all the opportunity to satisfy their aspirations for a better life. Hence, sustainable development is more precisely defined as "a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations" [33, 34].

This definition involves an important transformation and extension of the ecologically based concept of physical sustainability to the social and economic context of development. Thus, the terms of sustainability cannot be defined exclusively from an environmental point of view or on the basis of attitudes. Rather, the challenge is to define consistent and operational terms of sustainability from the perspective of an integrated social, ecological, and economic system. This gives rise to two fundamental issues that need to be clearly distinguished before integrating normative and positive issues in an overall framework.

The first issue is concerned with the objectives of sustainable development; that is, "what should be sustained" and "what kinds of development are preferred". These are normative questions that involve value judgements about society's objectives with respect to social, economic, and ecological system goals. These value judgements are usefully expressed in terms of a social welfare function, which allows an evaluation of trade-offs among the different system goals.

The second issue deals with the positive aspect of sustainable development; that is, the feasibility problem of "what can be sustained" and "what kind of system we can devise". It requires an understanding of how the different systems interact and evolve, and how they could be managed. Formally, this can be represented in a dynamic model by a set of differential equations and additional constraints. The entire set of feasible combinations of social, economic and ecological states describes the inter-temporal transformation space of the economy in the broadest sense [35–37].

2.6 Sustainability Measurement

Measuring sustainability is a major issue in planning and realisation of sustainable development. The development of a tool that reliably measures sustainability is a prerequisite for identifying non-sustainable processes, informing designers of the quality of products and monitoring impacts on the social environment. The multiplicity of indicators and measuring tools being developed in this fast-growing field shows the importance of the conceptual and methodological work in this area. The development and selection of indicators require parameters related to the reliability, appropriateness, practicality and limitations of measurement [38–42].

In order to cope with the complexity of sustainability-related issues for different systems, the indicators have to reflect the wholeness of the system as well as the interaction of its subsystems. Consequently, indicators have to measure the intensity of the interactions between elements of the systems and between the system and its environment. From this point of view, there is a need for indicator sets related to the interaction processes that allow an assessment of the complex relationship of every system and its environment.

2.6.1 Characteristics of effective indicators

Indicators can be useful as proxies or substitutes for measuring conditions that are so complex that there is no direct measurement. For instance, it is hard to measure the "quality of life in my town" because there are many different things that make up quality of life and people may have different opinions about which conditions

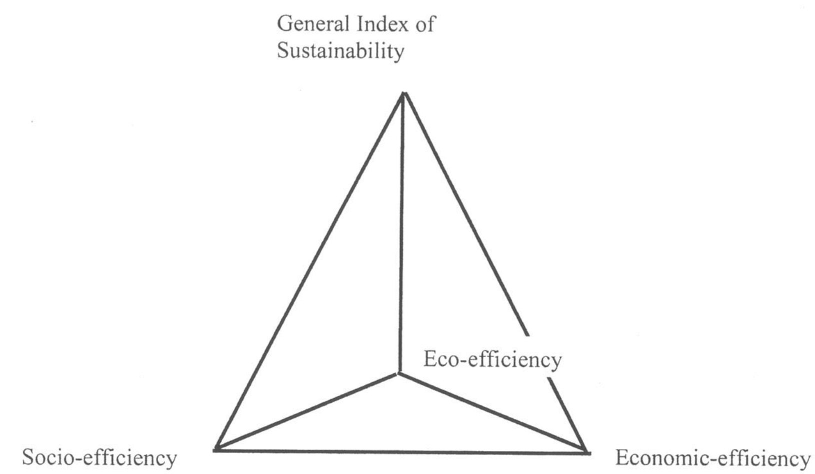

Fig. 2.10 General index of sustainability.

count most. A simple substitute indicator is "The number of people moving into the town compared to the number moving out".

Sustainability can be presented in the form of a triangle pyramid, where every corner on the base represents one of the efficiencies to be included in the assessment of any system. The fourth corner represents the Sustainability Index value (Figure 2.10). The Sustainability Index is obtained when a balance is found between the issues of all three efficiencies reflecting imposed constraints. In order to obtain the Sustainability Index for the option under consideration the weighting coefficient for the efficiencies has to be determined. The decision-making theory is used to calculate weighting coefficients. Non-numerical constraints are generated to represent constraints between the criteria.

The interactions between the three aspects of sustainability emphasise that sustainable development is not a static concept which can be easily translated and quantified. It is a dynamic concept, the result of a process of social learning involving many actors. For instance, in order to know which system is more sustainable it is necessary to formulate shared visions about the value of non-economic elements like biodiversity or cultural heritage. Because these visions and the underlying eco and social values change over time, it is imperative to consider all three aspects of sustainability as a continuous process, including the process of social learning and the environmental global change.

For the assessment of the system , attention will be focused on the three efficiency definitions.

2.6.2 *Economic Efficiency*

The traditional method for assessment of systems is based on the econometric justification of the use of capital needed for unit production. This method has been the basis of the decision-making process in the selection of systems; it has been a driving force for development of economic welfare in industrial societies. One of the basic assumptions of this method was that of the abundance of resources. With the development of the notion that scarcity of resources imposes limits on the use of resources it has been realised that, in addition to the limits of resources, there are other limits which play an important role in the decision-making process. Indicators for economic efficiency assessment are: investment cost including material cost, fuel cost, thermal efficiency and operation and maintenance cost. These indicators are a result of the optimisation procedure adopted for the respective optimisation function and respective design parameter of the system.

2.6.3 *Ecological Efficiency*

Following recognition of the adverse effect of combustion products on the environment, new indicators have been introduced in the decision-making procedure for system selection. The Kyoto Protocol has imposed local, regional and global limits of emission of CO_2, which should be incorporated in the design, operation and selection of new energy systems. This has led to the development and introduction of indicators for the ecological aspects of any energy system.

Indicators for ecological efficiency assessment include the concentration of combustion product species which are considered to have an adverse effect on the local, regional and global environment. Ecological efficiency is evaluated by the monitoring and assessment of those indicators which affect the quality of the environment.

2.6.4 *Social Efficiency*

The social aspect of any human endeavour is of paramount importance in the selection of possible options. It has become evident that the social aspect of any engineering system is an important part of its total quality. Criteria which assess the social aspect of a system are therefore as important as the economic and environment criteria. To formulate social criteria it is necessary to create a system of indicators of sustainable development which provide a reference for the respective type of system, and which may be used in the numerical evaluation of the system.

Indicators for social efficiency assessment are: job opportunity, diversity of qualifications, community benefits and consequences for local safety. The job opportunity indicator takes into consideration the number of jobs created by the respective system.

2.7 Sustainability Index Definition

The decision-making process comprises several steps that need to be followed in order to obtain a mathematical tool for the assessment of the rating among the options under consideration [43–46]. The first step in the preparation of data for the multi-criteria sustainability assessment is arithmetisation of the data. This step consists of the formation of particular membership functions $q_1(x_1),\ldots,q_m(x_m)$. For every indicator x_i we have

1. to fix two values $\min(i)$, $\max(i)$;
2. to indicate if the function $q_i(x_i)$ is decreasing or increasing when argument x_i is increasing;
3. to choose the value of the exponent λ for the increasing and decreasing functions $q_i(x_i)$ in the formula

$$q_i(x_i) = \begin{cases} 0 & \text{if} \quad x_i \le \min(i) \\ \left(\dfrac{x_i - \min(i)}{\max(i) - \min(i)}\right)^{\lambda} & \text{if} \quad \min(i) < x_i \le \max(i) \\ 1 & \text{if} \quad x_i > \max(i) \end{cases}$$

The functions $q_1(x_1),\ldots,q_m(x_m)$ indicate the formation process is being completed with a matrix $(q_i^{(j)})$, $i=1,\ldots,m$, $j=1,\ldots,k$, where element $q_i^{(j)}$ is a value of i-th particular criterion for j-th option. In this analysis it is assumed that the functions $q_1(x_1),\ldots,q_m(x_m)$ are linear. In our case when there are four indicators q_1, q_2, q_3 and q_4, the membership functions are adapted as the decreasing functions. There is no constraint as regards to increasing or decreasing functions. They are defined in accordance with the indicators values.

The general index method comprises the formation of an aggregative function with the weighted arithmetic mean as the synthesising function defined as

$$Q(q;w) = \sum_{i=1}^{m} w_i q_i,$$

where w_i presents the weight-coefficients elements of vector $\mathbf{w}$ and q_i presents the indicators of specific criteria.

In order to define the weight-coefficient vector, the randomisation of uncertainty is introduced. Randomisation produces stochastics with realisations from corresponding sets of functions and a random weight-vector. It is assumed that the measurement of the weight coefficients is accurate to within a step $h = 1/n$, with n being a positive integer. In this case the infinite set of all possible vectors may be approximated by the finite set $W(m,n)$ of all possible weight vectors with discrete components.

Table 2.2 Energy system indicators.

	Efficiency %	Instalation USD/kW	Elect. cost c/kWh	CO_2 $kgCO_2/kWh$	Area km^2/kW
Coal	43	1000	5.4	0.82	0.04
Solar Thermal	15	3500	17	0.10	0.08
Geothermal	8	2500	8	0.06	0.03
Biomass	1	2500	14	1.18	5.20
Nuclear	33	2300	4	0.025	0.01
PV Solar	10	4500	75	0.1	0.12
Wind	28	1100	7	0.02	0.79
Ocean	3	10000	25	0.02	0.28
Hydro	80	2000	8	0.04	0.13
Gas	38	650	4	0.38	0.04

For non-numeric, inexact and incomplete information $I = OI \cup II$, where OI is ordinal information and II is incomplete information, is used for the reduction of the set $W(m,n)$ of all possible vectors **w** to obtain the discrete components set $W(I;n,m)$, defining a number of constraints reflecting non-numeric information about mutual relations among the criteria under consideration.

2.7.1 Multi-Criteria Assessment of Energy Systems

As the non-numerical information we will impose a condition that should define the mutual relation of the individual criteria. This will give us the possibility to introduce a qualitative measure of the relations among the criteria.

As an example for the multi-criteria assessment of energy system we will take a number of energy system options with respective values for the five indicators including economic, environment and social indices [46]. Options of energy systems are defined with respective indicators (see Table 2.2).

The group of cases is designed to give priority to a single indicator with other indicators having the same values. Each case will represent a different set of the priority of criteria as they are used in the definition General Index of Sustainability. Among the cases which are designed with the preference of single options are:

CASE 1 Efficiency > Investment = Elect. Cost > CO_2 = Area

In this case, priority is given to the efficiency criteria of the energy system. As shown, the efficiency of systems with different basic principles is not a very realistic indicator to use for comparison of the system. This suggests that in the evaluation of efficiency criteria it would be better to use the relative value of the efficiency for each system. For example, for the heat conversion system the Carnot efficiency should be used as the absolute efficiency.

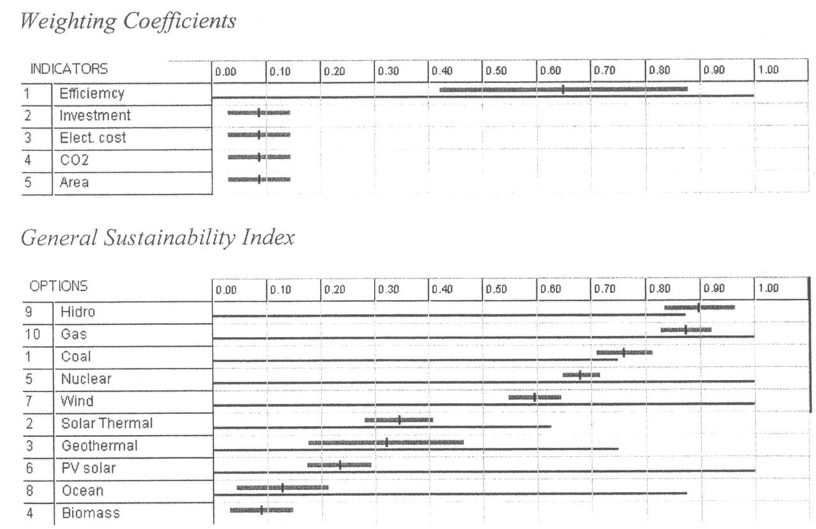

Fig. 2.11 Case 1: Sustainability index and weighting coefficients.

CASE 2 Investment > Efficiency = Elect. Cost > CO_2 = Area

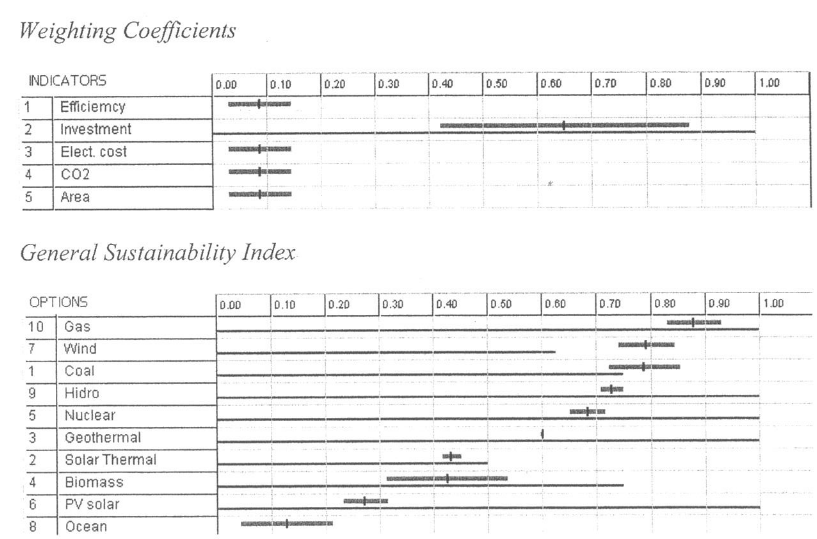

Fig. 2.12 Case 2: Sustainability index and weighting coefficients.

The change in priority from the efficiency criteria to the investment cost criteria has led to a drastic change in the priority list. Gas, wind and coal energy systems form a single group with the General Index of Sustainability being only marginally different among themselves. It is of interest to notice that the effect of single criteria can be so strong as to bring into the picture a different priority list. From the values for probability of dominance in this case it is evident that this case does not have high certainty.

CASE 3 Elect. Cost > Efficiency = Investment = CO_2 = Area

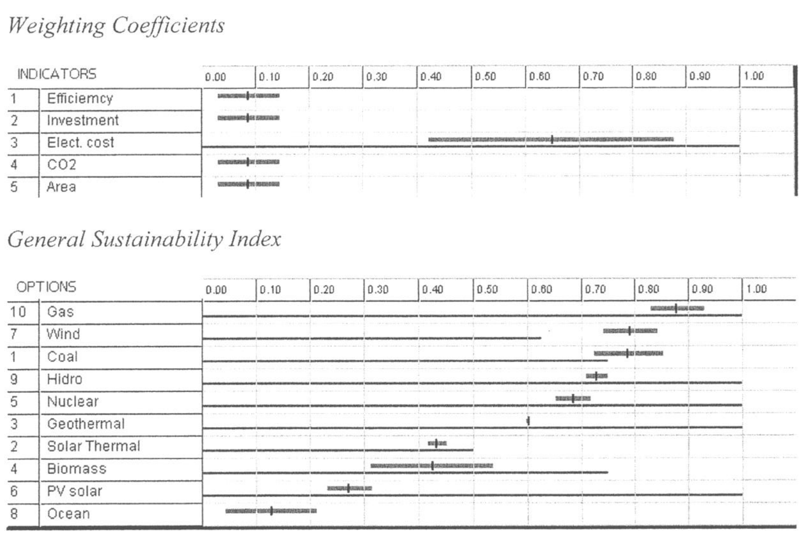

Fig. 2.13 Case 3: Sustainability index and weighting coefficients.

With priority given to the electricity cost criteria we obtain two groups of options: gas, wind, coal, hydro and nuclear make up the first group; geothermal, solar thermal, biomass, PV solar and ocean power plants make up the second group.

CASE 4 CO_2 > Efficiency = Investment = Elect. Cost = Area
Environment criteria measured by CO_2 affects only the coal and biomass options. All other options are presented in a single group with marginal differences.

This example of the evaluation of the priority rating among selected options of energy systems illustrates the method for obtaining an option rating based on the multi-criteria decision-making procedure. It is noted that the analysis is based on non-numerical information as the criteria for the design of cases which result in the respective rating among the options.

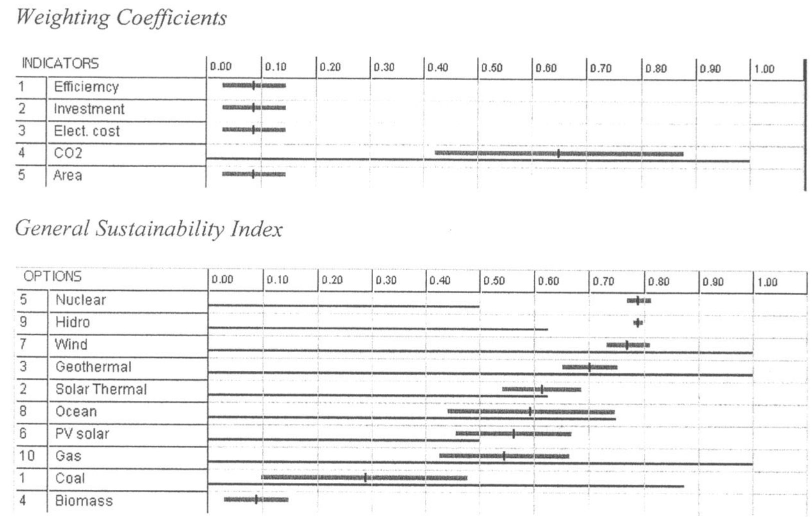

Fig. 2.14 Case 4: Sustainability index and weighting coefficients.

The selection of the group of cases illustrates an evaluation of the options with constraints, with the possibility of having a predetermined relation between indicators. Even though this analysis is based on a limited number of considered cases, it can be noticed that the priority of the rating list is the result of the respective relation among the criteria under consideration. In the group of cases, it can be noticed that the option which is the first on the rating list is closely related to the respective indicator priority and its value. If priority is given to a single criterion, with the other criteria having a respective value of indicators for each individual option, it may affect the rating list of the options. If the efficiency criteria are given priority there are changes in the rating list compared to the single criteria rating, and priority is obtained for hydro, coal, and gas options. The same can be noticed if priority is given to the other indicators. For the case of the Investment Indicator priority, gas, wind and coal power plants are the first on the rating list of the options under consideration. For the case of the Electricity Cost Indicator priority, the first places on the priority list are the gas and nuclear options. If the CO_2 Production Indicator and Area Indicator are given priority, the gas and nuclear power plants are rated in first place. A special case is designed with criteria that introduce a relation among individual Indicators. Besides the changes in the first place on the rating list, it can be noticed that there are changes in the rating among options. Options with renewable energy power plants have gained a higher place on the rating list in comparison with the case with an equal weighting factor for all indicators.

2.8 Conclusions

Sustainability assessment of power plants is immanent to the development of future energy strategy. It implies the need to verify a multi-criteria analysis of potential options. In this respect it is of interest to introduce a new methodology for evaluation of the power plant options under consideration. This article aims at emphasising the importance and potential of the sustainability notion in meeting the present needs of modern society. Starting from current definitions of sustainability and showing their close relation to the historical definition, it has been proven that our global society has borne in mind the need for the preservation of commodities for future generations. Sustainability has been introduced as a property of a complex system. With its multi-dimensional scope, a new method is required for the evaluation of this complex system.

The energy system is a typical example of a complex system with multi-criteria assessment. The need for a respective methodology has been conceptualised and introduced. The demonstration of the method has been presented for a specific number of energy systems, taking into consideration a number of criteria with respective indicators.

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