SUSTAINABILITY CHALLENGES FOR FUTURE ENERGY SYSTEMS

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Abstract - Sustainability is the comprehensive paradigm on the basis of which it is possible to assess the perspectives of future evolution of all anthropogenic activities, including energy system exploitation and relations with the environment. This paper discusses some conceptual aspects concerning the many components that must be taken into account in order to address sustainability issues properly. These components belong to different fields of knowledge and application, ranging from technical and economic issues to a wider set of entries including production organization and quality, risk management, ecology, social, equity and diversity issues. Energy efficiency and climate change concepts are recalled to provide indications on the current status and envisioned perspectives in the corresponding areas. The discussion is then widened to address the critical points emerging in the definition of sustainability indicators. Specific references are made to recent scientific papers and regulatory documents of the European Union and various international organizations.

Key words: efficiency, energy systems, environment, indicators, sustainable development.

1. INTRODUCTION

Energy efficiency and sustainability are key concepts in today's energy systems. The recent evolution towards designing and exploiting sustainable energy systems has given birth to a broad set of studies addressing technical, economic and environmental issues. In many cases, the related research has been carried out by setting the main focus on one of these issues, while the other ones have been either neglected or introduced in simplified forms, for instance as additional constraints. Nowadays, a new trend is emerging towards the integrated study of the multi-disciplinary aspects related to the energy sector. Besides the always relevant impact of economics, now strengthened by the emergence of energy markets, these aspects include the development and application of advanced technologies (also for combined production of different energy vectors), the strong push towards compliance of environmental constraints, and the more and more pronounced impact of consumer preferences.

The new trend has the natural consequence of enhancing the interactions among different scientific areas and worlds. The sharing of concepts, problem formulations and solution methods adopted in different fields of knowledge is increasing on the one hand the complexity of the studies, but is providing on the other hand significant inputs to handle various kinds of complexity in an effective and coordinated way.

Incorporation of the different aspects within a single framework is a challenging task, first of all due to the need for identifying the nature of this framework. The current direction is to interpret the evolution of the human activities and their relations with the environment in terms of *sustainability*. The term sustainability has been defined in different ways along the years. The general concept refers to the possibility of preserving quantity and quality of the human heritage and natural reserves, allowing the new generations to access them and to benefit from their exploitation [1][2].

A corollary is the definition of *sustainable development* as the development that satisfies the present needs and tends to improve the quality of life without impairing the possibility for future generations to satisfy their needs. The concept of sustainability is then linked to all aspects of our lives, requiring an enlarged view of the problems of each specific sector.

The "three-E" rule (encompassing Ecology, Equity and Economy) is a key factor commonly used for studying how to maintain an economic development consistent with social equity and environmental equilibrium. The Universal Declaration on Cultural Diversity [3] has added to the three-E's a fourth dimension of cultural diversity, highlighting the value of differences to promote changes and to avoid stereotyping solutions and practices in any field or sector.

The remainder of this paper recalls energy efficiency and climate change concepts, providing indications on the current status and envisioned perspectives in the related areas. The discussion is then widened to address the critical points emerging in the definition of sustainability indicators, defined by taking into account the formulation of specific problems from different fields of research in a consistent way. Specific references are made to recent scientific papers and regulatory documents of the European Union and various international organizations.

2. ENERGY EFFICIENCY AND MANAGEMENT ASPECTS

2.1. Energy efficiency and costs

Qualitatively, a system is *energetically efficient* if it consumes a reduced amount of energy to carry out its mission. In more practical terms, the energy efficiency of

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a system is not evaluated in absolute terms, but it comes down from *comparing* the performance of different systems, either among them or against a conventional system taken as reference. Thus, the best system in energy efficiency terms is the one that consumes less energy to provide the *same useful output* with respect to all other systems to which it is compared.

However, this kind of definition of energy efficiency is merely technical and is not directly related to costs. Energy efficiency and overall costs (e.g., for investment, operation and maintenance) are typically conflicting objectives, being it necessary to increase the costs to get energy efficiency benefits. In some cases, for instance in the presence of constant fuel supply prices, the link between *operation* costs and energy efficiency could be more direct, being it possible to decrease the fuel supply costs by increasing energy efficiency. Yet, if the fuel supply prices are variable in time, this link becomes less direct. In fact, considering the same energy consumption, for instance a consumption of short duration occurring within a single period with low fuel prices would be more convenient than a consumption in a longer period in which the fuel price is partially higher.

2.2. Advances on energy management

Effective energy management is one of the keys to enhance efficiency and to promote sustainability of energy applications in all sectors of activity. The relevant figures are the *energy manager*, responsible for the conservation and rational use of energy, and the *energy auditors* who control that the recommended practices are actually and correctly implemented. In the European Union, the Directive 2002/91/EC (Art. 10) indicates that in the Member States the certification and the elaboration of recommendations have to be carried out in an independent way by qualified and recognized experts. Furthermore, according to the Directive 2006/32/EC (Art. 8) the Member States ensure, where necessary, appropriate qualification and certification systems for the providers of energy services, energy analyses and means for energy efficiency improvement. Concerning *energy audit* practices, the European standard "*Energy efficiency services – Definitions and requirements*", is in course of preparation (and is currently at the stage of project standard prEN 15900:2009).

In 2003, CEN and CENELEC created the Advisory Joint Working Group (JWG) "Energy Management" to define the current status of the technical standards and to assess the need for releasing new standards concerning energy management. After the analysis of national reports on legislation and technical standards in force or under preparation, the JWG prepared some recommendations highlighting priorities referred to energy service companies (ESCo), energy managers and experts, energy management systems (EMS), and energy efficiency and savings calculations. In 2006, two Task Forces were created, namely, the CEN/CLC-Task Force 189 -"Energy Management" to develop standards on ESCo, energy managers and experts and EMS, and the CEN/CLC-Task Force 190 to develop standards on energy efficiency and savings calculations. Furthermore, the CEN/CLC-Sector Forum on Energy Management continued the activity of the previous JWG. In 2009 the EN 16001:2009 "*Energy management systems*" was issued to extend the fields covered by standards with respect to the ISO 9001 "*Quality management systems - Requirements*" and the ISO 14001 "*Environmental management systems*" [4].

The EN 16001:2009 is based on the principle of continual improvement, according to which the energy policy requirements affect planning, implementation and operation strategies, whose application results are subject to a process with checking, preventive and correcting actions (also on the basis of monitoring and measurement results) within an internal audit. The audit results are then subject to management review to determine the energy policy update.

2.3. Energy efficiency in buildings and industrial applications

Improving energy efficiency is a classical objective. However, the ways for achieving improvements highly depend on availability of technical solutions at acceptable costs. The presence of incentives set up by regulatory bodies and legislation can be highly beneficial to direct the decision of the users towards upgrading their systems, overcoming the bent for leaving the situation as it stands.

In *buildings*, the current trends refer to reducing specific consumption (kWh/m^2) and increasing local energy production (in particular from renewable sources). More specifically (Fig. 1), the reduction in the specific energy consumption, initially very low due to some inertia to change the current situation, can be envisioned to become more steep as a result of the application of specific regulation and/or market conditions, also with incentives to technology modernization. After a massive introduction of new and more efficient solutions, again the specific consumption reduction in time could become less pronounced. Concerning local energy production, the initial situation has almost no local generation, and the expected trend is to progressively increase the installation of local generation units. Conceptually, following the trends indicated in Fig. 1, it is possible to qualitatively envision a *break-even* condition, corresponding to the equality between total energy input to and output from the building. Beyond this break-even condition, the building could even become a net energy producer. However, this global analysis makes no distinction among the different forms of energy. As such, the break-even condition does not mean that the building is energetically independent of any energy source at any time. While a net production of electricity is likely to be envisioned, in particular in some hours of the day, for the other energy vectors the situation is far more complex, also depending on the activity carried out inside the building. Examples of buildings requiring very low amount of energy for space heating or cooling are the *passive houses* developed according to the concepts first introduced by Adamson and Feist in 1988, leading to successive applications [5].

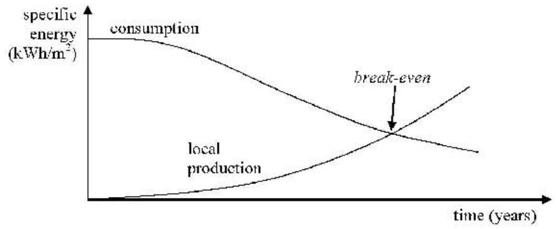

Fig. 1. Qualitative evolution of specific energy consumption and local production in buildings.

More specifically, the perspectives to *reduce energy consumption* in buildings are based on a number of items, such as:

- modernization of the *envelopes* (thermal isolation, windows, natural ventilation in summertime, protection to summer solar radiation, exploitation of the winter solar radiation, etc.);
- energetic *qualification* of the buildings and development of architectural solutions to increase natural lighting inside the buildings, study of effective strategies of air exchange within the ambient, energy management through effective variation in time of the reference temperatures of the control systems; in particular, *energy certification* of buildings is addressed by the European Directives 2002/91/EC and 2006/32/EC, with the objective of establishing quality levels depending on the total energy consumption expressed in kWh/(m^2*year);
- use of high-efficiency *boilers* and *air conditioning* systems (substitution of earlier technologies with most efficient ones and adoption of energy management systems for a more rational energy usage, with timers and control based on climatic variables);
- modernization of *lighting* systems (with elimination of incandescent bulb lamp in the EU since 2011, use of high-efficiency lamps and lighting control systems);
- modernization of the *white appliances* (e.g., use of class A+ appliances);
- accurate *maintenance* of appliances and equipment according to the requirements of standards and good practices;
- *education* of the users towards more sustainable behaviour, by enhancing the users' knowledge on the most convenient nodes of operation of the set of appliances with relatively high consumption, assisting the users in the choice of the most suitable tariff option according to their needs, stressing the importance of correct maintenance of equipment and installations, and making the users aware of the importance to avoid keeping the devices in stand-by mode when not used.

The perspectives to *increase local energy production* refer to electricity (from photovoltaic systems, or micro-wind where applicable), heat (from solar thermal systems), combined production of electricity and heat through micro-cogeneration systems, use of heat pumps for production of heat from electricity or cooling from heat, multi-generation solutions with internal recovery of different forms of energy to increase global system efficiency, waste exploitation for energy use, and in perspective the possible integration of electric and hybrid vehicles in the energy system. Further benefits may come from effective management of the local production systems and from the revision of the energy supply contracts.

However, the way to ensure proper sustainability is long. In order to meet the sustainability objectives by 2050, the primary energy consumption per capita in the residential and tertiary sectors should reduce to about one half in the EU-27 and to less than one fourth in the U.S.. In practice, the increase in the energy per capita occurred in over 140 years should be reabsorbed in the next forty years. This scenario is worsened by the population increase and by the trend towards increasing the share of population who will live in large urban areas or megalopolies with millions of inhabitants. Development and management of these urban areas, not only in energy terms, is one of the key challenges to be addressed to ensure a sustainable future for humanity.

In *industrial applications*, the variety of solutions makes it necessary to identify the specific energy characteristics of each application to study the most efficient way to address energy efficiency issues. The perspectives mainly refer to the use of new and more efficient technologies (starting from electric motors), the restructuring of the production processes (with particular attention to energy management issues and adoption of adequate control systems), fuel replacement and development of suitable techniques for managing combined production from different energy vectors.

Significant benefits on enhancing energy efficiency through primary energy saving, accompanied with reductions in network losses and GHG emissions, can be obtained by exploiting combined production of different energy vectors, from cogeneration or multi-generation, managing the energy vectors within the local energy system and interacting with external energy networks [6][7][8]. As such, promoting high-efficiency cogeneration based on useful heat demand has been considered a priority in the European Union. Efficient use of cogeneration has the further benefits of contributing to enhance energy supply security (also through resource diversification and international cooperation) and to increase competition through new entities entering the market as vendors of technologies, energy suppliers or managers. On these aspects, the Directive 2004/8/EC [9] deals with *high-efficiency cogeneration* as simultaneous generation in one process of thermal energy and electrical and/or mechanical energy, providing primary energy saving with respect to the separate production of the same energy outputs (evaluated through conventional reference efficiencies [10]). The Directive 2004/8/EC also recalls the attention on the maintenance of the cogeneration units in order to obtain durable benefits. The provenience of high-efficiency cogeneration can be indicated by a guarantee of origin, that has to remain separate from the possibility of exchanging energy efficiency certificates in the corresponding markets [11].

3. THE ROLE OF ENVIRONMENT

3.1. Environmental issues

Environment is one of the key components of sustainability. Many aspects referred to environment are recalled on any sustainability criterion or analysis. Among them, ecology and climate change are most addressed.

Concerning the phenomena occurring in the atmosphere leading to climate change, the major issues are related to two aspects of different nature, that have to be addressed in a distinct way:

- *ozone layer depletion*: in the stratosphere (second layer of the atmosphere over the ground, with altitudes from about 8-20 km up to about 50 km), the ozone layer protecting the Earth from the harmful effects of the ultraviolet rays UV-B coming from the Sun can be damaged by substances containing chlorine and fluorine;
- *global warming* (*greenhouse effect*), due to the effect of some gases that allow the solar radiation to enter the atmosphere, but maintain within the atmosphere the radiation emitted by the ground surface after its warming, or diffuse, absorb and re-emit the infrared radiation (as heat).

3.1.1. Ozone layer depletion

The measures to reduce the phenomena leading to ozone layer depletion have been indicated in the Montreal Protocol, an international treaty signed on 16 September 1987, in force since 1 January 1989 and successively updated. The Montreal Protocol establishes the reduction in the production and use of substances containing chlorine and fluorine, defining seven categories of halocarbons and setting up for each category an action plan to dispose of or eliminate the substances, with precise temporal deadlines. For instance, chlorofluorocarbons (CFCs) used in refrigeration systems as cooling agents must be totally phased out before 2030. The Montreal Protocol has been actuated in the EU in 1994 with the Regulation 3093/94/EC, then substituted in the year 2000 by the Regulation 2037/00/EC. Among the other measures, the CFC phase-out limit has been anticipated to 1 January 2015.

3.1.2. Global warming

The variations in the average temperatures of the globe in the post-industrial era show an unprecedented trend to increase with respect to pre-industrial values. Looking at the individual years, the average temperatures show either increase or reduction with respect to the previous year, but the main aspect is the global increase trend shown for the 5-year or 10-year average temperatures [12].

In 1998 the United Nations formed the Intergovernmental Panel on Climate Change (IPCC), with components of the World Meteorological Organization (WMO) and of the United Nations Environment Programme (UNEP). In 2007, the IPCC together with Al Gore received the Nobel prize for Peace.

Among the results obtained, in 1990 the IPCC indicated that also CO_2 contributes to the natural global warming. In 1995, the IPCC defined the Global Warming Potential (*GWP*) of the greenhouse gases (GHG), measuring the contribution of the GHGs to the greenhouse effect. The GHG list includes Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6).

Technically, the *GWP* is the integration in a time period of the radiant impact (expressed by the level of atmospheric damage) produced by the release of 1 kg of gas. The *GWP* is expressed in relative terms with respect to the one of CO_2. Among the GHGs, the SF_6 has the highest GWP (24900), also with a duration of about 3200 years before its elimination.

However, notwithstanding SF_6 is the worst-ranked GHG, owing to its particularly stable molecular structure that leads to very effective absorption of the infrared radiation as heat, SF_6 does *not* contribute to the ozone layer depletion. In fact, due to its spectrum of ultraviolet rays absorption, SF_6 can be activated only at distances from the ground over about 60 km (in the mesosphere), higher than the about 50 km limit of the stratosphere in which the ozone layer does exist. Furthermore, SF_6 does not contain the main element responsible of the ozone destruction (chlorine). These aspects make the conceptual differences among ozone layer depletion and global warming more evident.

A specific aspect concerning global warming is the main interest to CO_2 as harmful GHG, even though its *GWP* is largely lower than the one of other GHGs. In particular, the GHG effect of SF_6 has to be evaluated by taking into account that the concentration of the SF_6 used in the world is currently very low (even though it increases of some per cent each year). Estimations of the global warming due to SF_6 by 2100 indicate a temperature increase lower than 0.02°C [13]. Conversely, estimates of IPCC and other organizations indicate significant increases in the average temperature of the globe also in the case of drastic reductions of CO_2 emissions in the next future (Table 1). In particular, even with a reduction of over 60% of the emissions in the year 2050 with respect to the year 2000, an average temperature increase over 2°C is expected. The problem is the *persistence* of the GHGs in the atmosphere for very long time periods (centuries or thousands of years), according to which no GHG decay is expected in the next centuries and the problems are then caused by *cumulative* emissions. In practice, the anthropogenic CO_2 (and GHG) emitted in the post-industrial period has been excessively high with respect to the amount of CO_2 absorbed in the natural cycles, thus affecting the natural equilibrium existing in the pre-industrial era and creating an unbalance towards global warming.

Table 1. CO_2 emissions and global warming.

CO_2 emissions increase in the year 2050 with respect to the year 2000	*global average temperature increase [°C]*
-85% ÷ -60%	2.0 ÷ 2.4
-60% ÷ -30%	2.4 ÷ 2.8
-30% ÷ +5%	2.8 ÷ 3.2
+5% ÷ +60%	3.2 ÷ 4.0

From Table 1 it is evident that the situation remains highly problematic even by drastically reducing the CO_2 emissions in the next future. The solution has to be addressed by establishing effective measures for emission reduction and a path to apply these measures in a relatively fast way.

3.2. Climate change and international treaties

The framework set up by the United Nations to address climate change issues resulted in the Kyoto Protocol, approved in December 1997 by a number of Parties [14]. The Kyoto Protocol contains quantitative actions to reduce GHG emissions. In particular, Article 20 states that each Party is commended to study and activate policies aimed at:

- improving energy efficiency in various sectors of the economy;
- avoiding GHG formation by promoting eco-compatible agriculture and controlled use of forestry;
- researching, implementing and improving the technologies for using renewable resources and for abating CO_2 and acoustic pollution;
- progressively reducing or eliminating market imperfections, withdrawing incentives, fiscal discounts and funding to the sectors with high CO_2 production;
- promoting measures for limiting the anthropogenic GHG emissions produced by human activities.

The Kyoto Protocol indicated a GHG emission reduction target for the period 2008-2012 of at least 5% with respect to the levels of the year 1990. For this purposes, a number of nations (indicated in the Annex I) were applied a cap on GHG emissions, expressed in per cent with respect to the values of 1990. Cap values equal to or higher than 100% indicate that the conditions imposed are satisfied. The mechanism leading to emission reduction is based on the definition of Assigned Amount Units (AAUs), each of which corresponds to 1 tonne of equivalent CO_2. The global emission limit defines the maximum number of AAUs assigned. Globally, the emissions in the nations considered must not exceed the maximum number of AAUs assigned. The AAUs have then been partitioned among the territories. For instance, for the European Union with 15 Member States (EU-15), in 1997 the assignment was of 3924 Mt of equivalent CO_2.

The rationale for global warming reduction is that the problem is indeed considered on the *global* scale, so that any measure adopted in any part of the globe is considered to lead to positive effects.

Besides the national measures for obtaining emission reduction, the Kyoto Protocol established the possibility of inserting in the GHG emission balance a maximum amount of emissions due to natural CO_2 sequestration by means of carbon sinks (e.g., forests), as well as the possibility of adopting market-based emission trading mechanisms in the forms of Clean Development Mechanisms and Joint Implementation (producing credits based on the environmental benefits obtainable though actions carried out in developing countries, subject to specific approval).

In synthesis, besides the AAUs, different marketable solutions have been introduced to respect the emission reduction obligations:

- RMU (*Removal Unit*) assigned on the basis of the GHG absorbed by means of activities of Land-Use, Land-Use Change and Forestry (LULUCF);
- ERU (*Emission Reduction Unit*), obtainable through Joint Implementation in the Annex I countries;
- CER (*Certified Emission Reduction*), obtainable by actuating Clean Development Mechanisms in the countries not included in the Annex I.

The European Environment Agency (EEA) report [15] indicates that not all EU-15 countries reduced the emissions per capita by 2008. The overall emission reduction per capita was 6.2%, while the EU-15 target is 8% reduction by 2012.

The Technology Perspectives 2008 document of the International Energy Agency (IEA) [16] updated the numbers of a problematic situation and expresses some hopes for signing a new treaty with wide international cooperation during the Copenhagen meeting (November 2009). However, the Copenhagen meeting put into evidence a situation with enormous problems and failed in finding out suitable solutions. As a matter of fact, during the Copenhagen meeting it was clear that the expected growth in the energy demand to and over 2030 will prevailingly occur in China, India and countries not belonging to the Organisation for Economic Co-operation and Development (OECD), while the expected demand in OECD countries will experience (relatively) a very limited growth. The CO_2 emissions will substantially grow in the non-OECD countries as well. The major issue is that non-OECD countries start from a level of industrialization and modernization much lower than the OECD ones, and are not likely to stop their growth until reaching better welfare conditions, to some extents comparable with the ones of the OECD countries. On the other side, to balance the demand growth in the other part of the world, the OECD countries should renounce to most of their welfare and abate their consumption drastically. As such, no agreed response has been found in the Copenhagen meeting. This situation clearly emerges as a global sustainability issue.

In climate change terms, the IEA total CO_2 emission forecasting show that, starting from the 2005 levels, the expected trend with no additional measure activated (baseline case) would lead to a significant increase of the equivalent CO_2 emissions in 2050. This situation is clearly not sustainable in terms of growth of the average temperature of the globe. A reasonably minimum objective has been indicated in limiting the average global temperature rise to 2°C to 2050. This corresponds to the scenario called 450, in which the concentration of equivalent CO_2 in the atmosphere in 2050 does not exceed 450 ppm and the total amount of emissions does not exceed 14 Gt of equivalent CO_2. This objective (also identified as Blue map) could be reached by applying starting from today a strategy composed of different types of solutions, whose impact in the scenario 450 has been estimated. These solutions include the adoption of carbon capture and storage (CCS) systems (that could indicatively provide 9% of the emission reduction from the industry and transformation sector, and another 10% of the reduction in the power generation sector), nuclear power (6% of the reduction), renewable sources (21%), efficiency improvement and fuel switching in power

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generation (7%), end-use fuel switching (11%), and efficiency improvement in end-use electricity (12%) and end-use fuel (24%).

3.3. The EU Emission Trading System

The Kyoto Protocol decisions have been adopted in the European Union through the Directive 2003/87/EC, in force since 2005, introducing the emission trading system (EU ETS). This Directive contains an agreement for burden sharing. Each EU-15 country has been assigned a permission (European Union Allocation, EAU). Each EAU corresponds to 1 tonne of equivalent CO_2.

The EU ETS system has been ruled in two phases, the first one covering the period 2005-2007, and the second one covering the period 2008-2012. EAUs are used in the first phase. In the second phase, the EAUs are converted into AAUs, and the other market schemes are made consistent with the Kyoto Protocol indications.

The EU ETS adopts a *cap and trade* strategy, with definition of the environmental objectives and of the maximum amount (*cap*) of allowed emissions, corresponding to the release of the emission allowances, also giving the possibility of buying and selling the emission allowances in a dedicated market (*trade*).

3.4. Climate and energy: the European Union strategy

Recent activities of the European Union produced the *climate-energy package* (also known as 20-20 to 2020) defined on 12 December 2008. This package set up the objectives to be reached to 2020 by the EU-27, consisting of:

- unilateral decision of reducing GHG emissions of 20% with respect to the ones at year 1990, with possible upgrade to 30% in case of approving further international agreements;
- reach the production of 20% of the final energy consumption by means of renewable energy sources (RES);
- guarantee that at least 10% of the fuel consumed in transport is formed by bio-fuel.

In order to reach these objectives, energy efficiency improvements are necessary. The related objective (initially included in the Action Plan for energy efficiency as 20% reduction in energy consumption by 2020 [17]) has not been included in the final version of the Directive, being implicitly included in the other objectives.

The climate-energy package contains various proposals of Directives, among which the revision of the EU ETS, the rulemaking for CO_2 reduction outside the ETS borders in the EU-27, based on effort-sharing rather than burden-sharing principles [18], and other Directives on RES with bio-fuels, CCS, CO_2 emissions of vehicles and environmental quality of fuels.

The UE ETS system in its current version involves about ten thousand industrial plants, among which power plants, refineries and steel factories, summing up about one half of the CO_2 emissions in the EU. In the revision of the EU ETS, the issues addressed are the extension of the field of application from CO_2 to other GHG and to all the main fonts of industrial emission, the substitution of the national plans of assignment with auction mechanisms or free assignment with unique rules for the whole EU, the reduction of the rights introduced in the market each year to reduce the emissions covered by ETS by 2020 of 21% with respect to the 2005 levels. Furthermore, an integral auction mechanism is foreseen for the electricity generation sector, responsible of the largest part of the emissions, already at the starting of the new system in 2013, while for the others productive sectors the transition to the integral auction should be gradual, up to its full usage in 2020.

3.5. Emission reduction in multi-generation systems

In thermally-driven applications, the energy efficiency benefits of exploiting combined production of different energy vectors (cogeneration and multi-generation) may also correspond to environmental benefits [19]-[23]. A basic distinction occurs between the *global* emissions of pollutants considered on the overall scale such as GHGs, and the *local* emissions of pollutants impacting on various receptors, and in particular on the human health, within a delimited zone (for instance, an urban area). These two types of emissions call for specific modelling, for instance, by using the emission factor model based on the output-related specific emissions of pollutant (g/kWh) [19]-[21] to formulate suitable emission balances [24]. Explicit consideration of emission reduction benefits that can be obtained through combined production of different energy vectors is still lacking in international regulations [25]. However, dedicated indicators have been formulated by exploiting formal analogies between energy efficiency and emission reduction [26][27].

4. ENERGY, ENVIRONMENT AND SUSTAINABILITY INDICATORS

4.1. Environmental indicators

In 2002 the European Council characterized some environmental indicators to be included in overall structural indicators aimed at verifying the strategy to make the EU economy competitive, dynamic and capable to ensure a sustainable growth [28]. These indicators are partitioned into four groups, namely:

1. indicators for which in 2002 there are available and reliable data;
2. indicators for which the data available in 2002 are incomplete or not updated;
3. indicators with data identifiable but of difficult future application because of inadequate sources, data unavailable on an annual basis or high costs required for data collection;
4. indicators for which data are unclear and further methodological or other developments are needed.

For instance, group 1 includes total GHG emissions (per capita, by sector and by unit of Gross Domestic Product, GDP), energy consumption per type of energy transfer, exposure of the urban population to air pollution (ozone and particulate matter), emissions of air pollutants like ozone precursors (CO, CH_4, NO_X and volatile organic compounds), particulate matter and SO_2, sustainability of fishing for selected species and areas with organic farming. Furthermore, group 2 contains indicators referred to transport, municipal waste, recycling, protected areas for biodiversity, and concentrations and balance of further substances. Group 3 includes indicators related to investment in transport, hazardous waste, recycling, water-related issues, natural resource productivity, pesticide use and evolution of land use. Finally, group 4 addresses entries related to transport noise, journey length and external cost internalization, waste prevention, toxic materials, biodiversity, material valorisation, intensity of primary material use, and others.

The report concludes by stating that a detailed work programme for the production of the indicators will be developed in the next stage. Priority will be given to the production of indicators feasible in 2002 and those feasible in 2002 but incomplete.

4.2. Sharing energy, environment and information concepts

Studies and analyses on sustainable development are carried out on multiple dimensions. In the energy sectors, a first line of debate refers to the future of the energy sources [29][30], considering the deployment of the various sources with particular attention to the future role of renewable energy [31]-[33] and to the perspectives for energy use in developing countries [34]. Dedicated analyses refer to the expansion of the electricity sector [35][36], with integration of biomass production [37], decentralized electricity generation [38][39] and emergent storage solutions such as Plug-in Hybrid Electric Vehicles (PHEVs) [40].

In a wider way, energy system analyses also encompass extensive concepts of exergy [41], external costs [42][43], life cycle assessment (LCA) [44], quality assurance [45], risk and asset management and other aspects characterizing the economic growth [46][47].

A further direction to generalize the approaches to address energy system sustainability is indicated in [48], extending the energy system analyses by adding to the energy flows referred to the technical equipment all other energy flows concerning human societies, also including those referred to nutrition of humans and domesticated animals. Other perspectives depend on the possibility of providing energy services with less energy consumption [49] especially in the countries under fast development, that can immediately benefit from applying new solutions without paying replacement costs. Furthermore, information technologies will certainly play a significant role in terms of sustainability [50], notwithstanding their use can raise problems concerning energy supply [51]. Relevant benefits are expected from exploiting information theory concepts to formulate sustainability indices [52] and using *pervasive computing* [53][54] for extended monitoring of human and environmental data, and for widening worldwide communications. The challenges for making pervasive computing effective refer to reaching the largest part of the human communities and natural areas, avoiding at the same time excessive amount of information delivered, intrusiveness and privacy violation.

Energy supply sustainability has to be evaluated by resorting to the definition of envisioned scenarios and to the adoption of suitable metrics and indicators [55]-[57] also applied to policy-making [58][59]. The width of the horizons to be analyzed in highly uncertain conditions makes conventional analyses based on individual criteria insufficient to represent the variety of options and scenarios. For this purpose, suitable solutions can be obtained by applying *multi-criteria* formulations [45][60]-[62].

4.3. Sustainability indicators

The first sustainability indicator has been formulated by Dow Jones in 1999, to evaluate the financial performance of the best companies having sustainability as objective [63]. This indicator is formed by merging a set of criteria belonging to three dimensions (economic, environment and social). Weighting factors are applied to each criterion, For instance, in the economic dimension the main criteria are Codes of Conduct / Compliance / Corruption&Bribery (6% weight), Corporate Governance (6%), and Risk & Crisis Management (6%). In the environmental dimension, the main criterion is Environmental Reporting (from public data) (3% weight). In the social dimension, the main criteria are Corporate Citizenship/ Philanthropy (3% weight), Labour Practice Indicators (5%), Human Capital Development (5.5%), Social Reporting (from public data) (3%), and Talent Attraction & Retention (5.5%). For each dimension, other industry specific criteria can be added, with weighting factors depending on Industry.

The definition and use of sustainability indicators is a complex and challenging task [64] and is not exempt from criticisms, for instance because some indicators are limited to the available information or to a few individual aspects, or search for global characterizations based on the "three-E"s that do not preserve the fourth dimension of diversity among cultural groups, or are unable to link causes with outcomes [65]. Additional criticism based on resilience (capacity of the system to adapt to stresses and changes and transform itself to reach better states) is raised in [66]. Application of the principles, approaches and methodologies to be used require identification of a careful balance between the various entries and testing of the effectiveness of this balance on a broad spectrum of applications and scenarios [67]-[70].

Sustainable development deals with global issues such as implementation in regional scale [71], the need for ensuring global security [72], and overall social acceptance of technologies and solutions [73][74]. The complex equilibrium between the various aspects involved in sustainability analyses requires macro-level modelling of the impacts envisioned in properly defined scenarios [75][76]. The individual aspects of sustainable development need to be synthesized into suitable indicators. While translating technical, economic and to some extent environmental aspects into quantitative indicators may be a relatively easy task due to the type of variables involved, other indicators expressing ecological

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[77] and social aspects [78] are more challenging to be formulated, including aspects of energy availability, political stability, as well as various forms of risks and quality of life.

5. INTERNATIONAL ORGANIZATIONS AND ACTIVITIES

5.1. Broader sustainability concepts

The overall view on sustainability includes various concepts borrowed by different fields of knowledge and activity. Energy systems studies cannot leave out of consideration organizational, social and political aspects. Valuable inputs to understand and apply this broader view are provided by recent activities of various international organizations. For instance, the International Organization for Standardization (ISO) has recently released the publication ISO 9004:2009 "*Managing for the sustained success of an organization - A quality management approach*" [79]. The elaboration of this publication has taken as models the underlying principles of the companies that survived in the market for at least half a century, passing through different stages of technological evolution, life cycles of the products, applications of organization and management concepts, and different administrations. The synthesis of these underlying principles is deemed useful to indicate possible keys for the sustainable success of an organization capable to satisfy needs and expectations of all stakeholders (also including, besides management and personnel, the clients, suppliers, authorities, labour organizations, and so forth), by providing adequate responses and by maintaining equilibrium during time.

The ISO is also completing the definition of the standard ISO 26000 *Guide on social responsibility*, aiming at creating awareness of every type of organization on the impact of their activity on the society and on the environment. The final goal is that all activities have to be carried out by respecting legislation and ethical behaviour, and by making them consistent with the interests of the society and of sustainable development. The draft of the standard ISO 26000 has been approved on 14 February 2010 to be written in the Final Draft International Standard (FDIS) version, the last step before publishing it as official international standard.

5.2. European documents on sustainability

The European Union (EU) strategy for sustainable development has been adopted in 2001 and has been revised in 2006 and 2007. The main aspects are economics, society, environment and international relations, recalling the three-E's plus cultural diversity items mentioned in the Introduction. The EU strategy includes among other issues the integration of the environmental aspects in the European policies impacting on the environment. The main documents can be retrieved in [80]-[82].

The strategies for integration of the environment include internal politics (for energy, economics and markets, environment, industry, transport and administration), external politics (environment and cooperation in external relationships) and actions in particular geographic regions (urban and coast areas).

Furthermore, the EU contributes to the world sustainable development by funding actions aimed at establishing a global agreement for sustainable development, according to the main objectives established by the General Assembly of the United Nations in the year 2000 [83]. The actions proposed for reaching these objectives are to progress towards the objectives of giving a public aid for development, reduce poverty in the least developed countries, and participate in the debate to offer worldwide public goods. The EU has confirmed in November 2005 that the objectives of its development politics include reduction of poverty in the world in the framework of sustainable development [84].

The instruments for supporting sustainable development include the definition of environmental indicators, a strategy for sustainable use of the natural resources, a strategy for waste prevention and recycling, an action plan for technologies consistent with the environment, a framework programme for innovation and competitiveness (period 2007-2013), a programme for ecologic and competitive small and medium enterprises, the promotion of social responsibility of entrepreneurship, an agenda for sustainable and competitive European tourism, and a worldwide fund for promotion of energy efficiency and renewable resources.

6. CONCLUSIONS

Energy systems have been generally addressed in the past by looking at the individual characteristics of each system, mainly on the technical and economic points of view. The emergence of energy markets has then strengthened the focus on economics and in particular on profitability issues. More recently, environmental considerations have become crucial. The inclusion of environmental aspects has widened the scope of the analyses, creating the need for formulating and solving multi-objective problems. Alternatively, the objectives have comprehensively formulated been in economic terms, also embedding environmental aspects and more generally internalizing the external costs as the costs of activities having an impact on the society but not included in the economic balance of the subject who determines them. All these extensions increase complexity of the problem formulations and require more refined tools for their solutions, such as multi-criteria analyses. Sustainability is the common term used today to address future developments. Besides energy, environment and economics, further aspects concerning production organization and quality, risk and asset management, social issues, equity and ecology have to be integrated within a comprehensive framework. The international organizations are already providing directives, guidelines and recommendations to cover the broad aspects of the future evolutions of the human activities, indicating the main concepts and directions to be followed. The main challenges for scientists and engineers are to find suitable formulations to address all these aspects in a quantitative way, identifying and assessing suitable solutions to ensure a truly sustainable development for today's and future generations.

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