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Energy needs and sustainable management of the energy cycle

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Abstract: The issue of sustainability of the energy policies is analised in its manifold facets. An overview is given about the trend of global energy needs and energy production, analysing the geographic distribution of consumptions and the share of energy sources, on the basis of the statistics and projections published by major agencies. The issue of sustainability of the energy cycle is finally addressed, highlighting how the use of biomasses as an energy source and of hydrogen as an energy carrier are among the most promising approaches.

Keywords: Sustainability; energy sources; renewable sources; energy carriers; hydrogen.

1. Introduction

Sustainability involves a web of environmental, economic and social factors and in the field of energy it clearly shows its complex interdisciplinary nature.

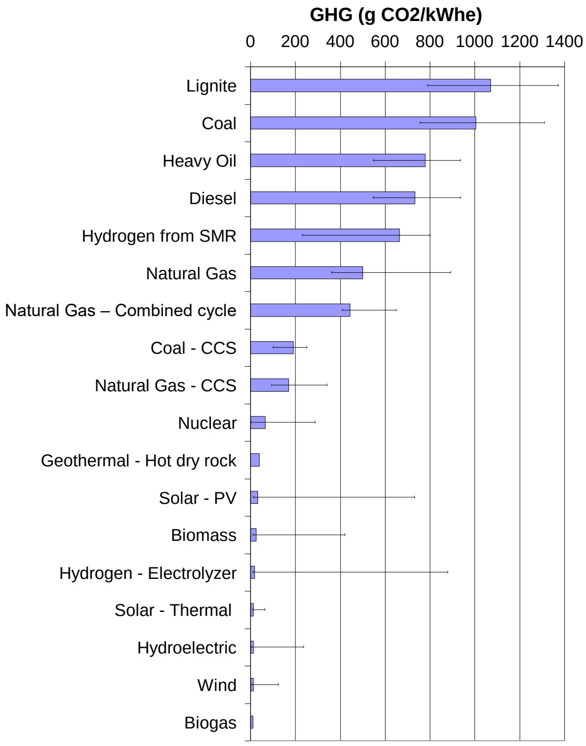
A major issue arises from the inescapable depletion of fossil fuels. Formidable challenges and dramatic choices will have to be faced to develop viable substitutes (e.g. with reference to revitalization of nuclear). Management of economic and social modifications in the countries more strongly linked to production and exploitation of fossil fuels also will be a matter of sustainability.

Another major issue arises from climate change and energy-related air pollution. It is well established that widespread exploitation of hydrocarbons is releasing Carbon Dioxide (CO2) at a rate higher than absorption by forests, oceans and other natural CO2 sinks and that this is a major cause of the global temperature increase which is prospected, but already perceived.

The Paris agreement on climate change, enforced in November 2016, mainly deals with energy policies. Low-carbon sources, and especially renewable energy sources are going to be developed, and this also rises an issue of affordability. Many countries are on track to achieve many of the targets set in their Agreement, but this will be enough to slow and not to stop the rise in CO2 emissions.

In fact the outlooks for sharp reduction of the emissions of Green House Gases (GHG), developed by several international organizations, clearly showed that the constraints about the quantity and quality of energy consumptions would be hardly accepted on a global scale, especially in the countries where economy is more strongly linked to large energy consumption and to exploitation of cheap fossil fuels.

Figure 1. Emissions of Green House Gases for selected energy sources. The histograms refer to average values, while the error bars correspond to the reported values. (*From* [1, 2, 3])



Indeed, in mature economies the use of hydrocarbons and the energy consumption generally could be limited with minor problems. For example it is possible to improve the energy efficiency of industrial processes, buildings and vehicles, or even to modify certain lifestyles in a perspective of eco-sustainability. Otherwise in emerging countries the availability of large amounts of low-cost energy is essential for industrial growth, which is a prerequisite for enabling access to wellness for populations so far deprived of it. Actually another issue of sustainability is energy access: today large swathes of the global population have no access to electricity (1.2billion people, mainly in rural areas of sub-Saharan Africa). Their number is going to reduce, but not to disappear in the next decades (they have been estimated to be still half a billion in 2040).

On the other hand the prospected regulatory policies, managing in a planned way the reduction of global production of fossil fuels, would have the potential to avoid sudden changes in availability of energy sources, as could arise in case of indefinite prosecution of current energy consumption patterns. Thus they have the potential to mitigate the related economic shocks. This is also a matter of sustainability, when it is intended in its widest meaning.

In the next section an overview is given about the trends of global energy needs and production on the basis of the statistics and projections published by major international organizations [4]-[7].

The share among energy sources, the geographic distribution of consumptions and their medium-term evolution scenarios are reported and analysed. Sustainability of some promising technologies is analysed and presented in Sec. 3.

2. Evolution of energy needs and regulation policies

According to the U.S. Energy Information Administration (EIA), to date the global energy production is about 14,500 Mtoe, and is mainly (54%) intended for the industrial sector [5].

The amount and quality of energy needs in the near future are the subject of great attention, as most anthropogenic CO2 is produced in the energy sector. Thus, several organizations like the International Energy Agency, IEA, provide long term outlooks, referred to different sets of assumptions about international policies, economic growth and investments in the energy sector.

A crucial role will be played by the technological improvements achieved both in energy production and in installations. They will be, in turn, affected by non-technological issues like the price of energy, depending on geopolitical factors such as the amount of oil produced by OPEC and the political stability in oil-producing countries. The price of oil is also doubly linked to the rate of economic growth: in the presence of stagnation, the low energy demand could lead to an oversupply that would limit the oil price (it could remain under 80 $/barrel until 2040) . In this scenario, the interest in the development of renewable energies and of the technologies for sustainability of energy consumption would be rather limited. In contrast, in the presence of a strong economic growth, the strong energy demand would push the price of oil, which could reach $ 150 / barrel in 2020 and $ 250 / barrel in 2040. Despite the economic prosperity, in this scenario the attention to energy policies could be much higher.

The reference scenario for IEA (New Policies Scenario) is based on already-announced policy commitments and plains terms of reduction of greenhouse-gas emissions and improvements of energy efficiency. With respect to the prosecution of current trends, it predicts some mitigation of environment modifications (global temperature increase around +4°C by 2035 instead of +6°C), indeed not sufficient to stop global temperature increase (energy-related carbon emissions would rise by 34% in 2040). The goal of stopping temperature increases, albeit in the second half of the century, would require more challenging energetic policies, like the 450 scenario. It is a set of policies intended to limit the concentration of net CO2 in the atmosphere to 450 ppm in 2035, in order to get a 50% chance to limit the temperature increase to + 2°C.

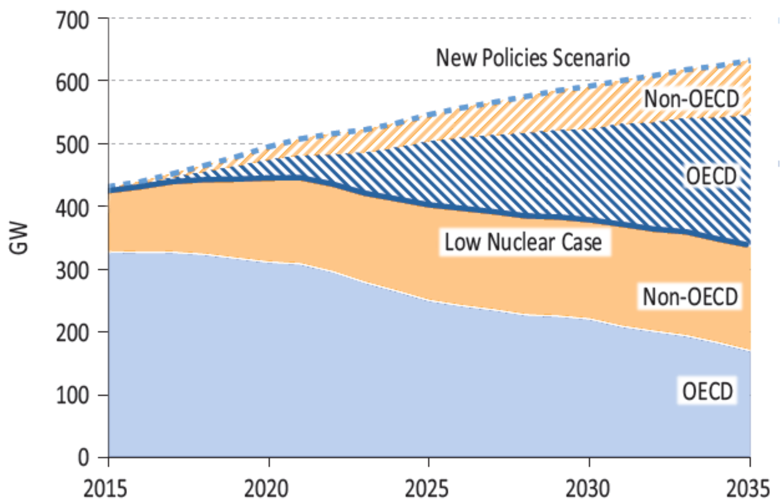
This level of global warming is the same agreed by the 196 countries participating at the2015 United Nations Climate Change Conference, COP 21, held in Paris [8]. They also pledged to make efforts to further lower the limit to 1.5 °C. This could anticipate the zero net CO2 to the period 2040 - 2060, but would require strong efforts for decarbonisation and larger investments (nearly double than in the reference scenario) in low-carbon energy sources, efficiency and Carbon Capture and Storage (CCS) systems [9], capable to capture the produced CO2 and confine it into suitable geological traps, e.g. in exhausted oil fields. However the global reduction of fossil fuels would take place only in the long term. Thus, for the sake of energy security, a large share (60%) of investments will be still devoted to oil, gas and coal extraction, in order to develop new fields in substitution of the existing, which are going to deplete.

Some countries (UE, Japan) are well underway to meet their climate pledges. The future policies of the US are somewhat uncertain, as the Clean Power Plan (CPP) enforced during the Obama Administration, capable to contribute to global carbon reduction by 2.5%, could be questioned by the new administration.

Reduction of use of fossil fuels will also require an increased contribution from nuclear power. Its relevance was demonstrated in 2011, when, after the Fukushima disaster, IEA developed a low-nuclear 450 scenario [10], with a share from nuclear nearly halved with respect to the Main Scenario. The contribution of renewable energies had to be increased, with implications for energy security. Larger costs were required for a wider deployment of CCS and other means to absorb the residual CO2 emissions. Limitations to the growth of energy consumption would be applied, with effects particularly evident in the economy of most developing countries.

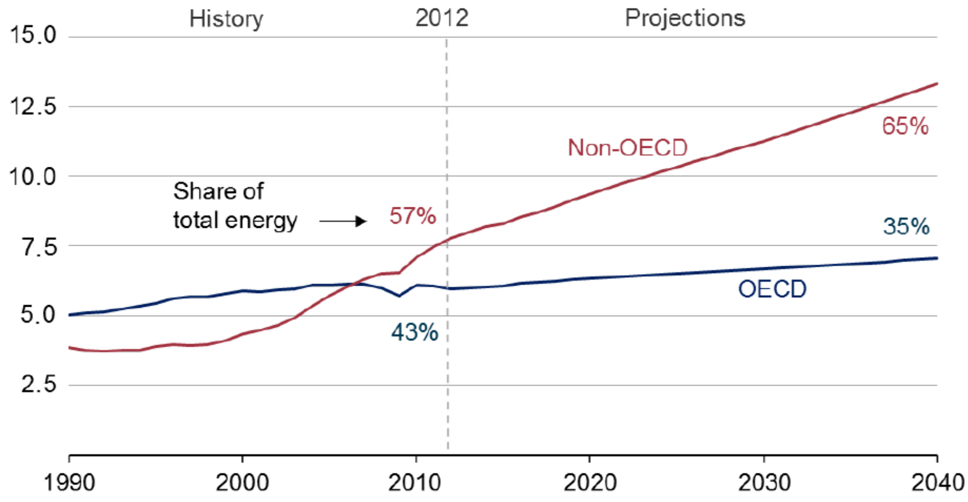
On the other hand, despite nuclear power is undoubtedly a low-carbon technology and cannot be neglected in a world where the main concerns arise from global warming and depletion of fossil fuels [2], its sustainability is largely questioned for the release of radioactive waste. Reprocessing techniques are available, but a small amount of radioactive end-product still is produced and has to be stored over a very-long term. Concrete structures were built with an expected life of 10,000 years (twice the Egyptian pyramids), but after this enormous amount of time the radioactivity will only be attenuated while the lethal potential of nuclear waste will only be partially mitigated. Even the idea of storing nuclear waste in deep geological cavities is not free from drawbacks [11], [12].

Figure 2. Projected growth of nuclear power capacity.
(*From IEA 2011* [10]).



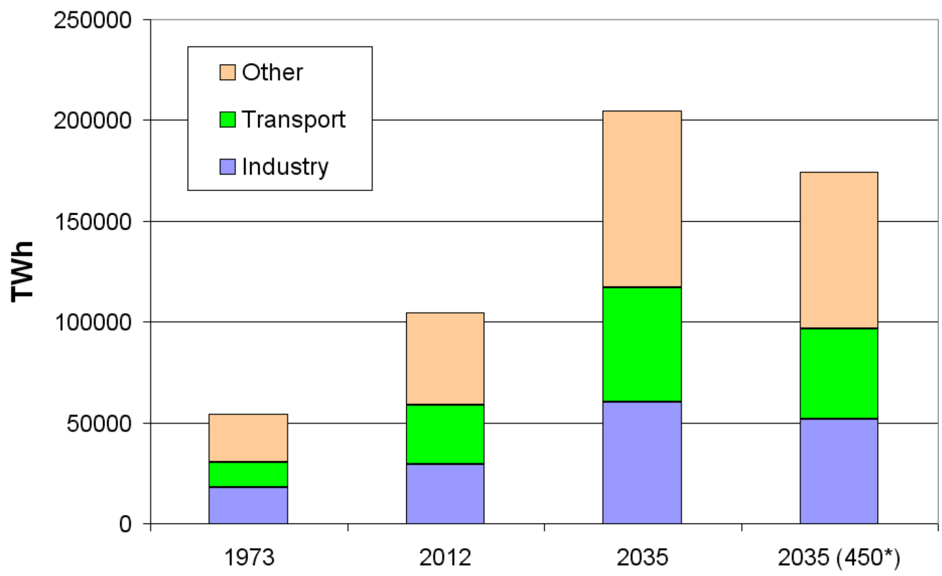
The outlooks about the future evolution of energy demand are affected by a wide margin of uncertainty, arising from several factors. It seems established that in the coming decades the geographical distribution of energy needs is going to undergo dramatic changes, with most increase (more than 80%) concentrated in a few non-OECD countries (Organisation for Economic Co-operation and Development, OECD) (OCSE in Italian), especially in China and India (see Fig. 3).

Figure 3. Projected growth in energy demand inside the OECD and outside it (Billion toe). (*From EIA 2016* [5]).



According to the main IEA scenario, the global energy demand will rise to 16,000 Mtoe in 2020 and then will continue rising with an average growth rate of about 1.4 % / year, driven by increase of population and economic activities. It will exceed 20,000 Mtoe in 2040, with the industry sector still accounting for 53-54% of the overall energy consumption (Fig. 4).

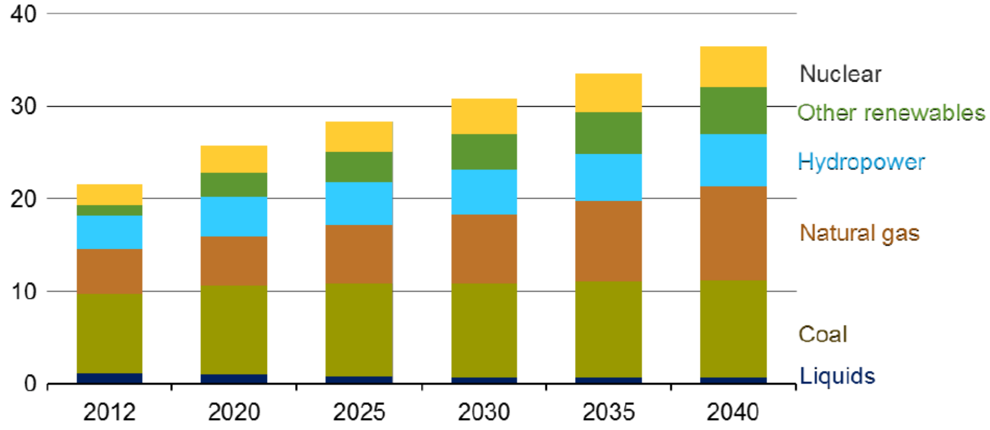
Figure 4. Growth in energy demand and share among the fields of use (billion toe). (*From EIA 2016* [5]).



Production of electrical energy is currently supported for about 75% from fossil fuels, for 10% from nuclear, for 10% from hydroelectricity and only for 5% from renewable sources. It is expected that global production of electricity will rise from the current 25 billion kWh to 37 billion kWh in 2040 (see Fig. 5). Nearly 25% of the increase in energy production is currently destined to electricity production. In perspective this share is going to rise to 40% in the main scenario and up to 85% in the 450 scenario. Only 15% of this increase will occur in OECD countries.

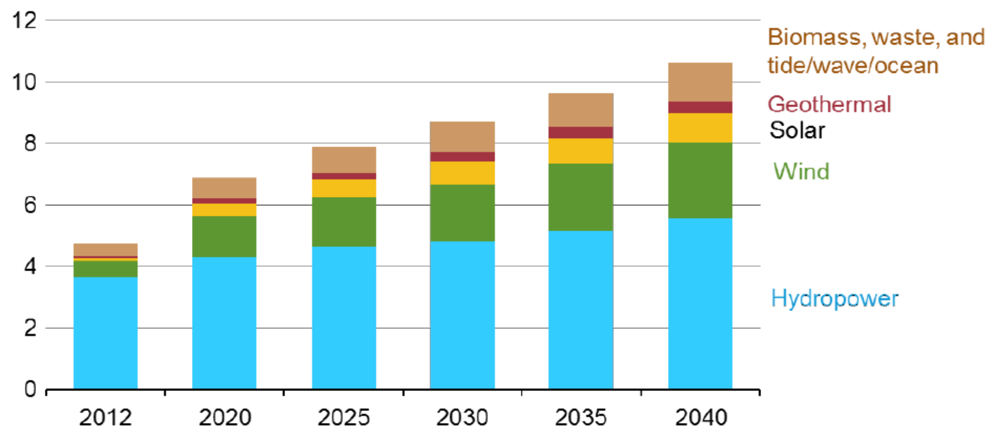
It will mostly take place in non-OECD Asia, notably in India and China. Thus, the environmental impact of energy production will be mostly determined by the energy policies taken in these countries.

Figure 5. Projected growth of electricity production from different energy sources (PWh). (*Source of data: EIA 2016* [5]).



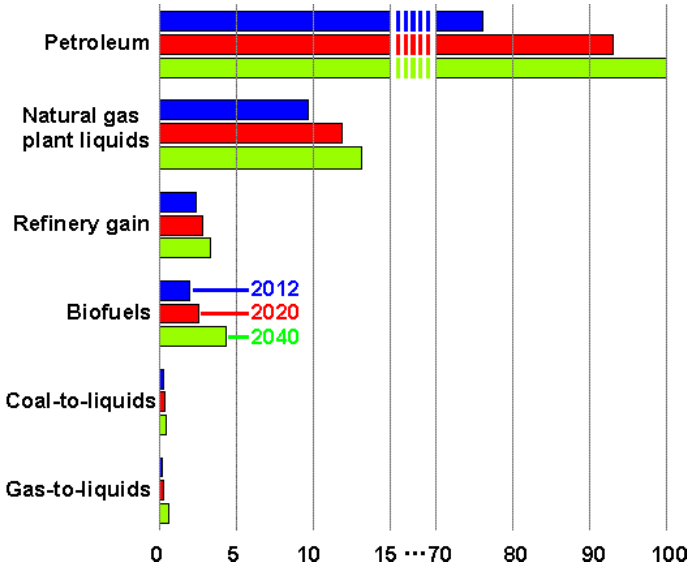
In the next few years the use of fossil fuels for electricity generation will continue to rise, especially supported by the introduction of shale gas [6], while consumption of coal will remain nearly stationary. It is also expected a strong increase of the share of renewables, mainly driven by wind farms (see Fig. 6), while hydroelectric production will grow at a smaller rate.

Figure 6. Projected growth of electricity production from renewable sources (PWh). *(Source of data: EIA 2016* [5].



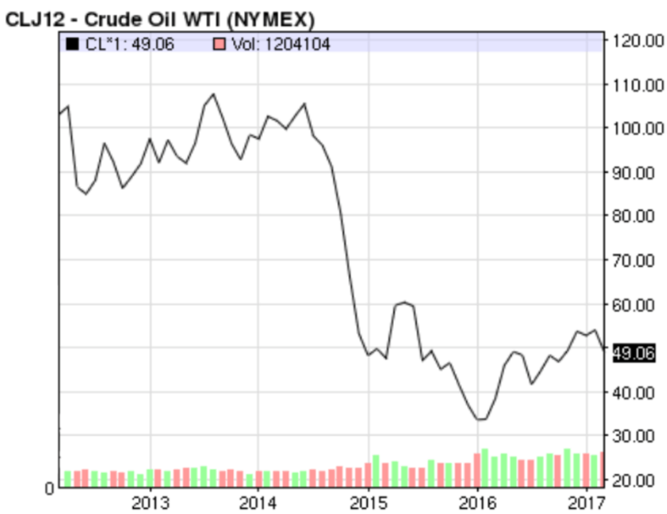
In the long term the consumption of oil and other liquid fuels (See Fig. 7) will be almost stable, as the increase in the developing countries will be compensated by drop of their consumption in the OCSE countries (-12mbd), where it will continue to be used mostly in petrolchemicals, aviation, freight. Production will take place mainly in middle-east but US will also contribute by the tight oil, extracted by hydraulic fragmentation from geologic formations of low permeability.

Figure 7. Production of liquid fuels by type (millions of barrels per day) (1 toe = 6,841 barrels). (*Source of data EIA 2016* [5]).



In general, the oil demand will also depend on economic trends, especially in the emerging countries, which in turn will be linked to a series of geopolitical factors that hardly can be traced back to a mathematical model. Indeed after the OPEC decided to reduce oil prices (dropped from over $100 per barrel in mid-2014 to below $40 in early-2016, see Fig. 8), a certain uncertainty arose about the payback times of the upstream investments to search and develop new oil fields. Thus after 2015 investments sharply dropped.

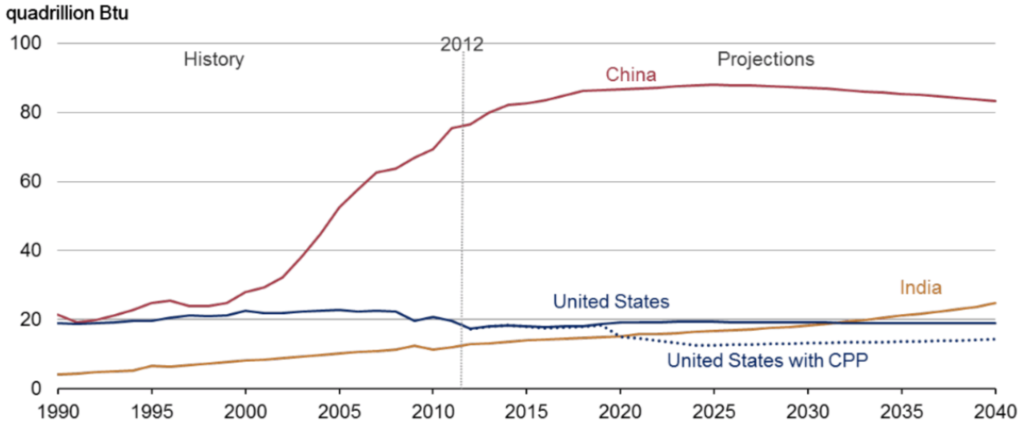
Figure 8. Price of crude oil in the last 5 years (US $) of liquid fuels by type (millions of barrels per day) (1 toe = 6,841 barrels). (*Source of data: Nasdaq* [13]).



This situation is harmful for energy security, as the existing fields are going to deplete and in the first 2020's a mismatch could happen between demand and production, with a new boom of prices and backslashes on the global energy market, only slightly mitigated by the tight oil produced in the US.

Coal plants are the largest source of energy-related CO2 emissions and will remain so in the next three decades, even if with a reduced share due to a larger exploitation of natural gas. Nevertheless, coal consumption is going to decrease only in higher-income economies (-60% in the EU, -40% in the USA), it going to reach a plateau in China, but it will continue to increase in emerging economies, especially in India, which cannot afford to neglect such a low-cost source.

Figure 9. Projected coal consumption in the largest coal consumers (quadrillion Btu) (Source of data: [5] and [14]).

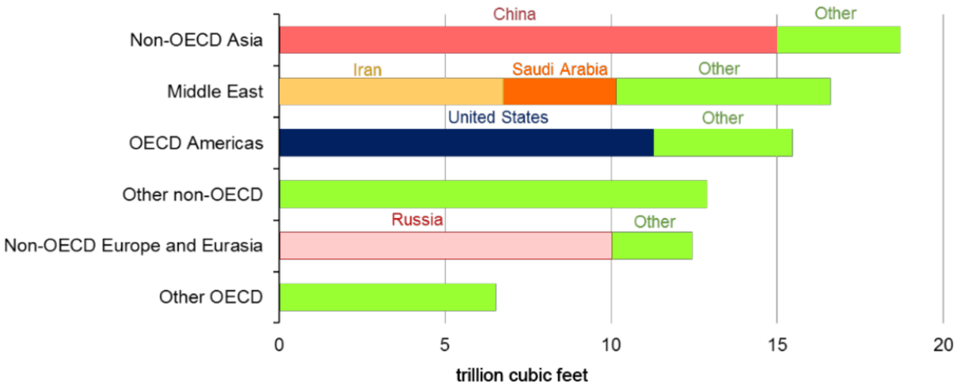


In fact, despite the rebound of coal prices observed in 2016, currently they are again decreasing and seem likely to level off at a values that make coal still economically competitive with natural gas.

Figure 10. Price of coal in the last 5 years (US $/t) (From [15]).

Among fossil fuels natural gas grows the fastest: in 2040 its production will be increased by 50% (nearly 1.5%/yr), supported by the production of non conventional gas [6], and will provide 28-29% of global consumption, with a share nearly equivalent to coal and renewable energy sources.

Figure 11. Projected natural gas production (trillion cubic feet)
(Source of data: [5]).



An interesting market development arises from the quick increase of production of Liquified Natural Gas (LNG, GPL). Allowing gas trading among countries not connected to specific infrastructures, it will promote the expansion of exporters like US and Australia and allow new actors to step into this market. The growth of natural gas will be mostly limited by the economical competition with other sources: despite the low carbon emissions, low capital costs and high operational flexibility of the gas-fired plants, the gap with costs of coal supplies limits their economical appeal.

Energy-related CO2 emissions stopped growing in 2014 and, despite the prosecution of use of fossil sources (Fig. 5), are going to drop from today's 515 gCO2/ kWh to 335 gCO2/ kWh in the Main scenario or 80 gCO2/ kWh in the 450 scenario. In OECD emissions the trend is sharply decreasing, as a result of increased deployment of renewables and enhanced efforts to increase energy efficiency.

In fact, improvements of energy efficiency are already accounted among the available energy sources [16]. Their potential can be fully understood by comparing the data on the global energy production (14500 Mtoe) with the final energy consumption (< 9000 Mtoe)[17]. For example: the average efficiency of the coal-fired and gas-fired thermal power plants around the world is about 33%, while the best plants currently in operation can provide an efficiency larger than 50%.

The different application fields will be affected by specific technological issues: for example, in the industrial field relevant advantages will be provided by improvements the process efficiencies; in the field of transport, they would arise by shifting a share of road freight traffic to rail or to ship; in private transport, by increasing the share of electric vehicles; in the residential field, improvements could arise by introduction of sustainability criteria in building construction and by more efficient air conditioning techniques.

Electricity consumption could be halved in a range of end-use applications (e.g. fans, pumps, compressors, refrigerators) simply by upgrading electric motors power supplies with inverter drives. At the current rates for electricity in Italy the cost of the new motors in industry at elevated degree of automation could be amortized within a few years. Moreover, it could be possible to reduce the losses along electricity distribution grids, which are very relevant (figure) in many countries: 2% in Europa, but larger than 5% in many countries and reaching record peaks in India, where, despite recent improvements, they are still close to 20%.

3. RENEWABLE SOURCES AND THE SUSTAINABLE MANAGEMENT OF THE CYCLE OF ENERGY

The cycle of energy begins when conversion plants are built, and also includes all preliminary stages for production of the materials and the components in use. It extends along entire service life of the plants, continues during their decommissioning and ends when the resulting materials are released into the environment [18]. Within this cycle, energy is extracted from the available primary sources and converted in the most suitable form (electrical, mechanical, thermal, ...) for the intended application, consuming energy produced from other plants and releasing both waste and entropy.

The perspective of sustainability pushes for energy sources characterized by cycles as near as possible to be closed, i.e. absorbing and releasing the smallest amounts of resources, and/or producing only end results which can be used as base resources for other cycles.

From a practical point of view, the feasibility of closed cycles is limited by the increase of entropy. On the other hand the Earth is not an isolated system, as it receives daily from the Sun a huge amount of energy, which can be exploited directly or indirectly to supply the most common renewable energy installations. (Not all renewables are connected to solar radiation, as for example geothermic and tidal energy arise from other sources).

Thus a large growth is expected for renewable sources (2.6%/yr, corresponding to 60% of new installations by 2040). Technological advances and economies of scale will also make them competitive even in the presence of reduced or null subsidies: prices of solar PV will drop by 40-70%, onshore wind by 10-15%. In the field of thermal generation, a large contribution will be given by thermal solar and biomasses. Inter alia, biomasses are characterized by the best approximation to a closed life cycle: in fact energy is produced releasing as a waste product CO2, which can be fixed in new plant species by photosynthesis and solar radiation, so that the process can be supplied indefinitely. The consumption of other resources is limited to the construction of conversion plants and energy distribution infrastructures, the transport of biomass to the facilities themselves and the energy transport to the user. Among other advantages, their installations can easily operate at variable power, with short response times, following the trend of energy demand.

Indeed, environmental sustainability of biomasses is the subject of a quite lively debate. Cultivation of the biomasses intended for energy production takes territory, and for this reason it is in competition with the crops intended for food production. Consequently the relevance of their contribution for global energy production is still debated. Other doubts on their use derive from the concern that the profitability of crops intended for energy production can boost deforestation and anthropization of wild lands, that otherwise should be protected as a shelter for biodiversity.

Among biomasses, an interesting development occurred for wood pellets, which are establishing as an energy source for heat generation in homes and small industries. Moreover, in countries like United Kingdom, Netherlands and Belgium, they are also widely used for utility-scale electricity generation.

Variable renewables (solar PV, wind tides, waves) show prominent periodic variations, both hourly and seasonal, superimposed to a large random component. In the energy systems where they provide a minor share, the balance between demand and production will be stabilized against their fluctuations by strengthening the grid, or arranging other power plants ready to dispatch at short notice.

Table 1. Storage technologies

Storage technology	Specific Energy (MJ/kg)	Energy density (MJ/liter)
Liquid hydrogen	141.86	8.491
Hydrogen (compressed at 700 bar)	141.86	1.3-1.6
Li-Ion batteries	0.4-0.9	0.9-2.7
Alcaline batteries	0.5	1.3
Lead batteries	0.17	0.56
Supercapacitors	0.01-0.04	0.06-0.05
Air (compressed at 200 bar)	0.5	0.14
Water (at an height of 100m)	0.001	0.001

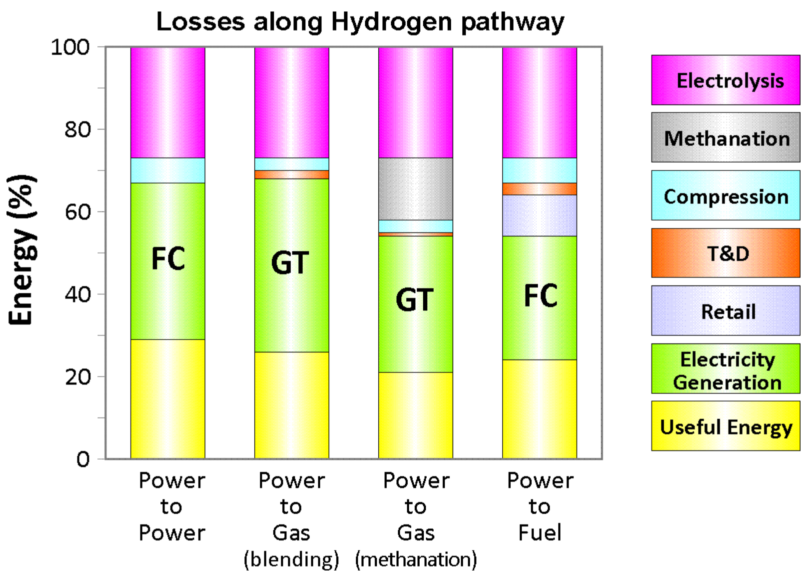
Otherwise, this approach is not feasible in the systems where their share is higher than 25%. First, in order to avoid that their fluctuations may affect energy security, an extra capacity has to be provided (at least 40% in EU). This, inturm will make their production to exceed demand for long periods (estimated 1/3 of time in EU and 1/5 of time in the US and India). Thus, it will be necessary to provide specific storage facilities for the surplus energy.

Various forms of energy can be used for storage: gravitational in hydroelectric reservoirs, electrochemical in batteries, electrostatic in supercapacitors, kinetic in flywheels, magnetic in SMES, potential in compressed-air tanks.

A very attractive approach is energy storage in the chemical bonds of hydrogen molecules [16],[17]. Hydrogen is easy to be transported, in tanks or via pipelines. It also allows long term storage, similarly to hydroelectricity and compressed air. Moreover, its specific energy (142MJ / kg) is by far the largest among the considered energy carriers.

On the other hand, energy density of H2 is considerably lower than that of fossil fuels (e.g. it is nearly 20% of that of natural gas, at the same pressure. Nevertheless it is comparable with other storage technologies, (V. Tab. 1) [19]. If hydrogen was used instead of electrochemical batteries,

Figure 12. Energy balance in the different hydrogen integration schemes. (FC: Fuel Cell, GT: Gas Turbine). (*Data form IEA 2015* [17]).



H2 could provide very relevant environmental benefits, avoiding use of toxic materials like Pb, Cd, or materials non abundant on the Earth crust, like Li.

The environmental impact of the life-cycle of hydrogen depends on the specific production process: electrolysis mainly consumes water and electricity, and can be entirely supplied from renewable sources.

However the strongest limitation in using hydrogen on a large scale consists in the low efficiency of the available processes, making available to the end user no more than 20 - 30% of the absorbed energy, as shown in Fig. 12.

4. CONCLUSIONS

Sustainability of energy cycles is an extremely complex issue, depending on a complex web of environmental, economic and social issues. The projections on energy consumption show that in the next two decades major changes will take place in energy consumption, in its geographical distribution and in the composition of the energy portfolio. Immediate promotion of policies for sustainability was agreed among 196 countries across the world at the Conference of Paris as it looks to be the only option to avoid, or at least to minimize, the shocks which could arise if current energy policies were not modified and the changes in energy policies would be dictated by uncontrollable events, such as abrupt change in availability of certain energy sources.

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