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Facing Global Challenges with Materials Innovation

FERNANDO RIZZO[1,2]

1.—Department of Chemical and Materials Engineering, Pontificia Universidade Catolica do Rio de Janeiro, Rio de Janeiro, Brazil. 2.—e-mail: rizzo@puc-rio.br

The path of society evolution has long been associated with a growing demand for natural resources and continuous environmental degradation. During the last decades, this pace has accelerated considerably, despite the general concern with the legacy being left for the next generations. Looking ahead, the predicted growth of the world population, and the improvement of life conditions in most regions, point to an increasing demand for energy generation, resulting in additional pressure on the Earth's sustainability. Materials have had a key role in decreasing the use of natural resources, by either improving efficiency of existing technologies or enabling the development of radical new ones. The greenhouse effect (CO_2 emissions) and the energy crisis are global challenges that can benefit from the development of new materials for the successful implementation of promising technologies and for the imperative replacement of fossil fuels by renewable sources.

INTRODUCTION

The Millennium Project[1] has updated annually, since 1996, the list of 15 Global Challenges (Fig. 1), which provide an adequate framework for the assessment of progress on the issues that raise most concern for the future of humanity.

They involve a variety of topics, including political, economic, social and environmental issues, offering a good yardstick to measure the evolution of mankind. Among them, several relate directly to aspects involving the use and development of materials, namely:

- How can sustainable development be achieved for all while addressing global climate change?
- How can population growth and resources be brought into balance?
- How can growing energy demands be met safely and efficiently?
- How can scientific and technological breakthroughs be accelerated to improve the human condition?

The first challenge has been the most discussed in the last decades, starting when the Club of Roma published, in 1972, the book *Limits to Growth*, expressing concern on the consequences of exponential economic and population growth in a world with finite resource supplies.[2] Subsequently, in 1987, when the Bruntland Commission produced its report *Our Common Future*,[3] the concern about global warming, deforestation, species loss and toxic wastes gave rise to the concept of "sustainable development", with its message that social and economic advance should not jeopardize the ability of future generations to meet their own needs. Since then, conferences and summits have been held periodically to discuss ways to mitigate the impact of progress and population growth on the planet environment, with limited success due to the resistance of some countries, notably some of the largest polluters, to comply with the decisions approved.

The continuous growth of the world population (Fig. 2) produces a steady pressure on the resources available in nature, due to the increasing need for potable water and food to sustain a growing population. From a geographical standpoint, the situation is in fact worse, since most of the population growth has a higher rate in developing or underdeveloped countries, where the living conditions are usually much lower. A recent report from the United Nations[4] predicts that, from now to 2050, half of the world's population growth will be concentrated in nine countries. With the exception of the United States, all the countries are in Asia and Africa.

A third issue to be considered is the world per capita energy consumption, which has steadily increased during the last centuries, as shown in

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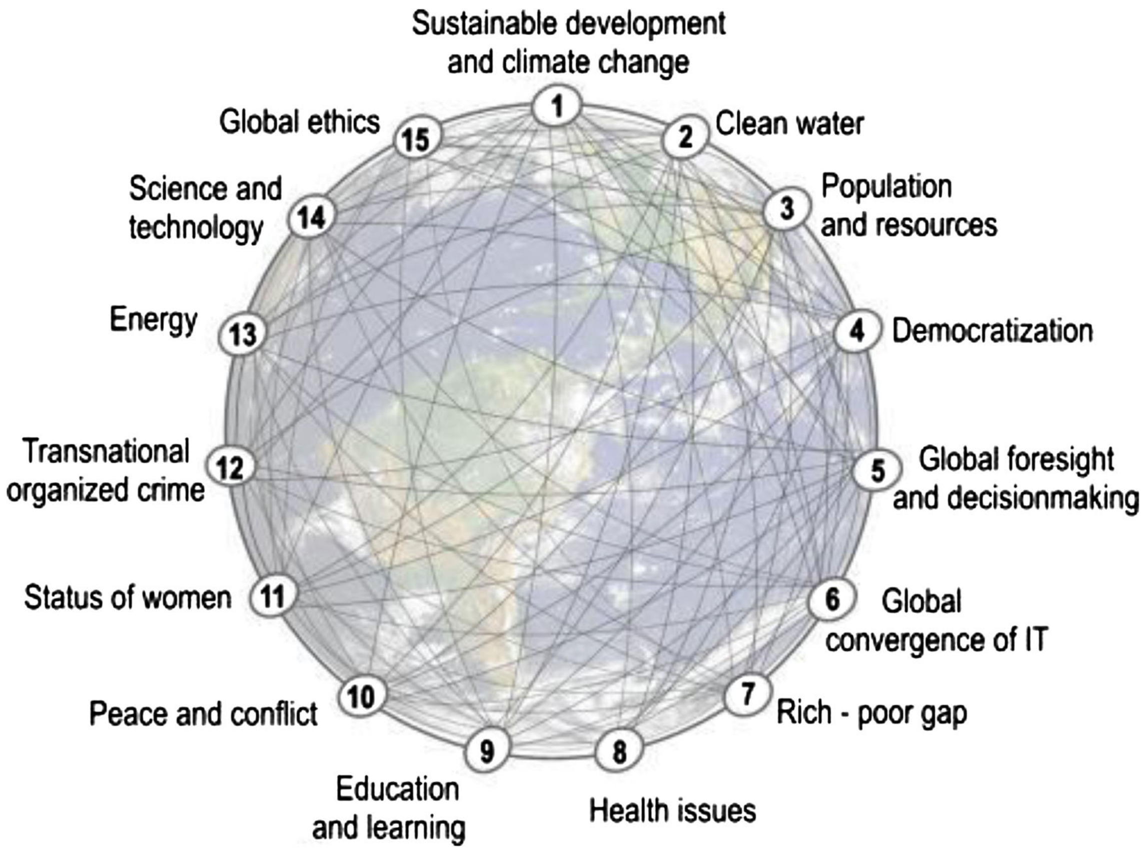

Fig. 1. The 15 Global Challenges—Millennium Project: Global Future Studies and Research.[1]

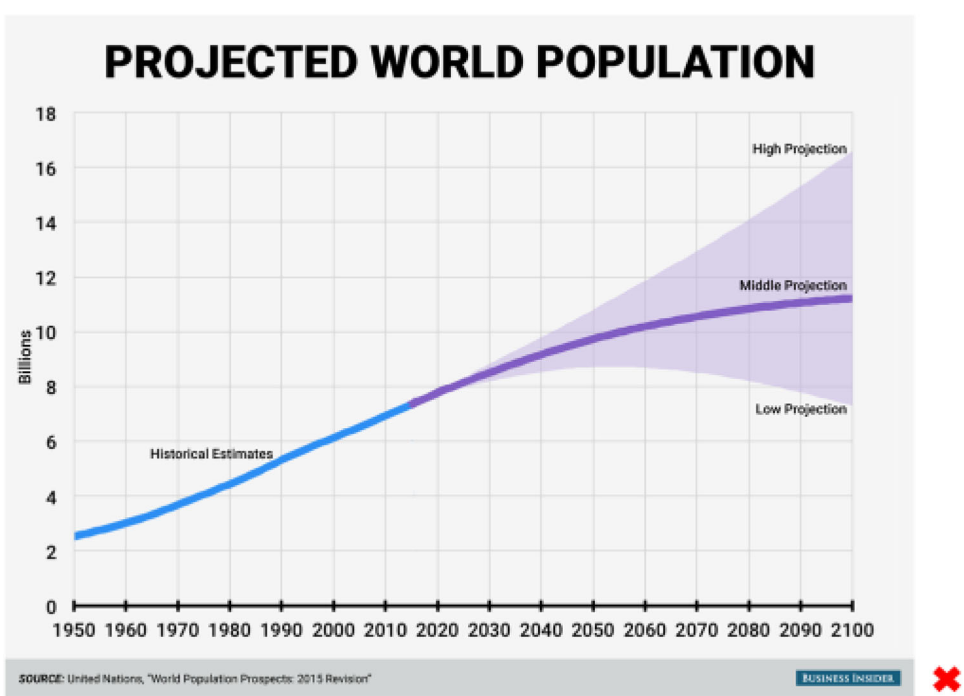

Fig. 2. Projected world population from 1950 to 2100. United Nations, World Population Prospects: The 2015 Revision.[4]

Fig. 3, and is expected to keep growing. even faster. The simultaneous population growth and increasing per capita energy consumption combine to produce a dramatic scenario, due to the geometric ratio of growth, if the "business as usual" trend is maintained.

The relationship between energy consumption and gross domestic product, presented in Fig. 4, indicates that most of the growth in energy consumption is expected to occur in the developing countries, which includes the most populous ones, such as China and India, as they succeed in raising the living standards of their populations.

The final concern has to do with the large participation of fossil fuels in the world energy generation, with its impact on the climate change due to the carbon dioxide (CO_2) emission. Despite the increase of renewable energy generation observed during the last decade, around 80% of the world energy matrix originates from fossil fuels (coal, oil and natural gas), as shown in Fig. 5, and this situation is expected to remain at least until 2030.

ENERGY GENERATION AND GLOBAL WARMING

Carbon dioxide emissions (CO_2) are a global concern due to their contribution to the greenhouse effect and, thus, to the temperature increase of the Earth's atmosphere. Carbon dioxide emissions have different sources, such as industrial processes, use of fossil fuel (largest global emissions source) and change in land use. In Brazil, the large amount of energy generation based on renewable sources, such as hydropower and biofuels (Fig. 6) makes its energy matrix compatible with the proposed scenario of lower carbon emissions, recently approved in the Paris Agreement, aiming to reduce the global warming temperature to below 2°C by 2050. In addition, the growth of wind and solar photovoltaic generation observed in the country during the last few years suggests a tendency to increase even further the share of renewable generation in the near future.

Looking at the world's energy-related CO_2 emissions, most specialists predict the same trend of reduction in fossil fuel generation in the future, their

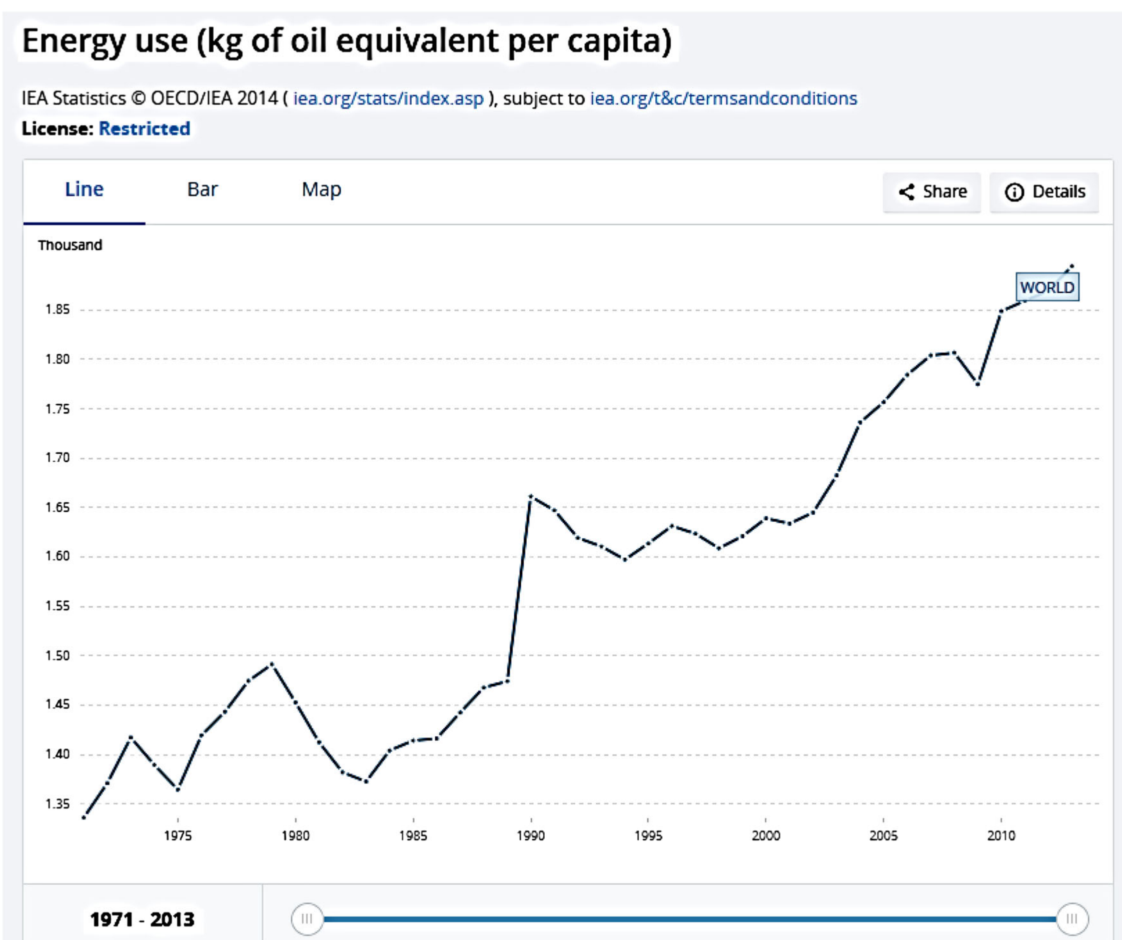

Fig. 3. Evolution of energy consumption per capita. IEA Statistics OECD.[5]

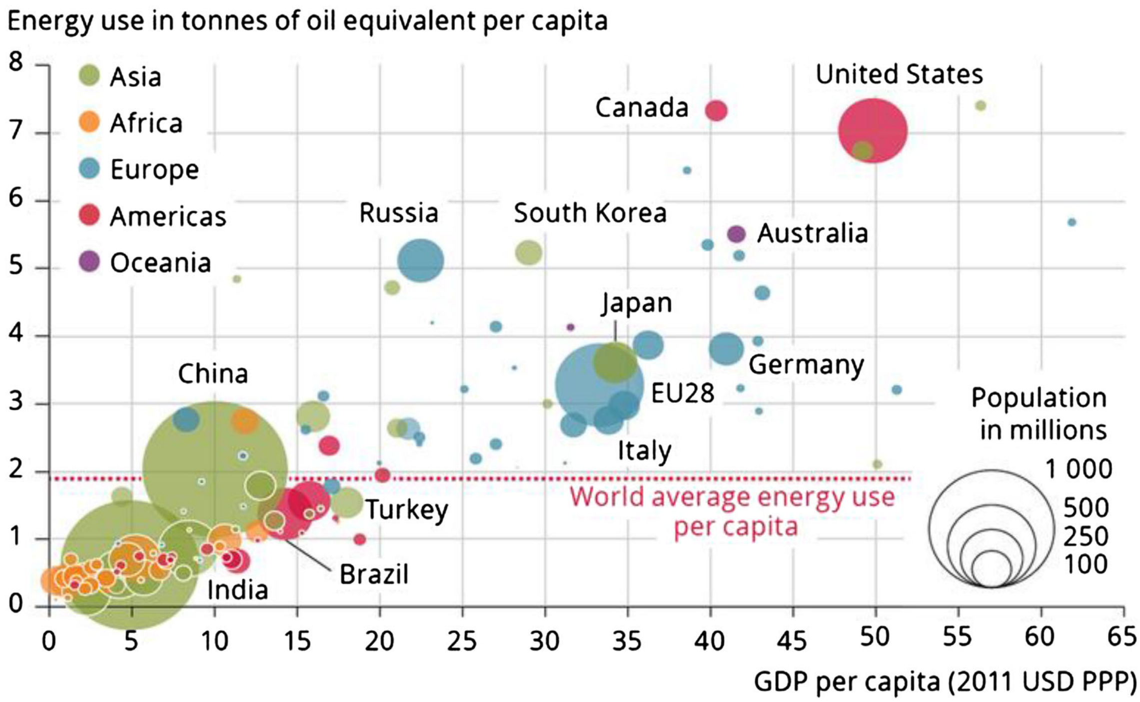

Fig. 4. Per capita energy consumption versus gross domestic product. European Environment Agency, 2011.[6]

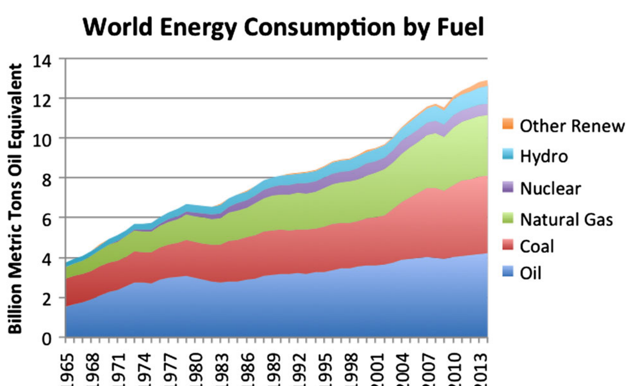

Fig. 5. World energy consumption by fuel.[7]

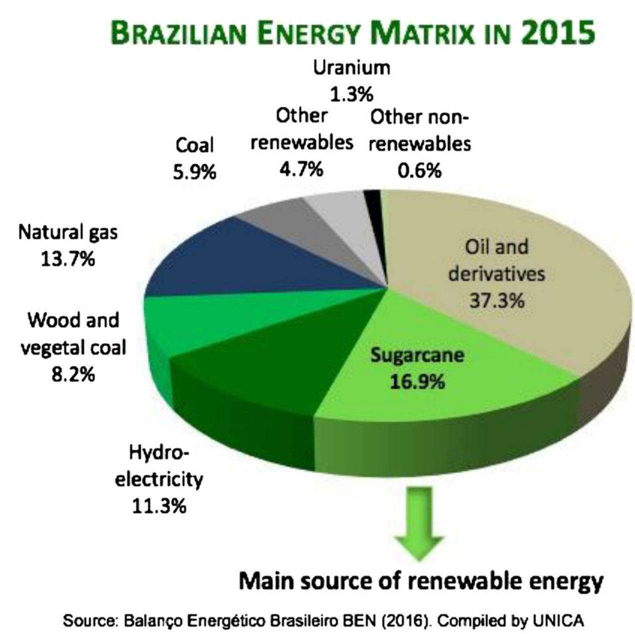

Fig. 6. Matrix of energy generation in Brazil.[8]

predictions only differing with respect to when the turning point will occur. This will depend, of course, on the effectiveness of governments in enabling the transition to a low-carbon society, and on the successful introduction of energy technology innovations. Several technologies are expected to play key roles in reducing CO_2 emissions by improving the efficiency gain, among them: electricity savings (such as solid-state lighting and electric vehicles), fuel switching, and carbon capture and storage. Up to 40% reduction of CO_2 emissions from the power sector could be achieved by 2050 from these technologies.[9] Another significant reduction is predicted to come from nuclear and renewable sources, such as wind, solar, hydro and biomass.

However, until this objective becomes a reality, fossil fuels will be responsible for the larger share of energy generation. Therefore, technologies to reduce their impact on the climate during the next decades are necessary. Carbon capture and storage (CCS) is a technology developed to mitigate the impact resulting from the use of fossil fuels, particularly coal, which emits more CO_2 among all fossil fuels. In the 450 scenario, it is estimated that emissions will peak around 2020 and declines significantly to reach in 2035 values close to those in 1990.[10]

Carbon capture in a power plant can be divided into three categories: post-combustion, pre-combustion and oxyfuel. The post-combustion process is used in conventional coal-fired power plants, and CO_2 is separated at the end of the process, which uses low temperatures and can retrofit existing power plants.[11]

In the pre-combustion process, used in Integrated gasification combined cycle (IGCC) power plants, a syngas bearing CO, CO_2 and H_2 is produced and then CO is transformed in CO_2 by water gas shift reaction, and then separated from H_2. The process has good economic and plant efficiency characteristics, but the power plant is costly to construct and the system is more complicated to operate than conventional boilers.[12]

Oxyfuel is a process developed to be used in new coal-fired power plants together with CCS, producing energy with zero CO_2 emissions. In this process, flue gas at the end of the process contains only water vapor and CO_2, which is compressed to be sold or stored.[11,12] The oxyfuel process works fundamentally by removal of molecular nitrogen prior to gas injection into the boiler. Gas injection in the boiler is a mixture of O_2 and flue gas containing basically CO_2 and H_2O. Recirculation of flue gas, with prior ash removal, is essential to control burner temperature.[11,13] With high CO_2 concentration, it is easy and cheap to separate SO_2 and H_2O from the flue gas before this is compressed. A minor quantity of SO_x, NO_x and Hg is also removed in the gas compression in order to obtain the purity necessary to further flue gas use.[14–16]

Oxyfuel is more expensive than post-combustion, but it is the most energy- and cost-efficient of all carbon capture technologies, due to its small boiler volume and to flue gas cleaning systems.[11,13] The process is being studied, and pilot plans, like the Callide Oxyfuel Project in Central Queensland, Australia, is the world's first project, successfully demonstrating how oxyfuel and carbon capture technology can be applied to existing power stations to generate electricity from coal with low emissions.[17]

The use of CCS and the development of (advanced) ultra-supercritical power plants will allow energy production from coal with zero or near zero CO_2 emissions. In ultra-supercritical power plants and advanced ultra-supercritical power plants, the temperature used in the process is higher than that currently used, and efficiency can grow from 33% at present to more than 50%.[18,19] Ultra-supercritical power plants work at higher temperatures and pressures, increasing efficiency and decreasing CO_2 emission. The introduction of ultra-supercritical power plants is also essential to the development and use of CCS in an economically viable way, to compensate for the energy consumed to separate and compress the CO_2, decreasing the overall efficiency. A very recent and promising technology also using CCS is the Allam cycle. In this case, supercritical CO_2 drives the turbine, the gas pressure drops, and it turns into a normal gas. The CO_2 is repressurized and returned to the front end of the loop, in a highly recuperated cycle that can achieve efficiencies near 60%. The cycle can use a variety of fuels, including natural gas, coal or biomass.[20] This is one area where the implementation of novel technologies has been dependent on the successful development of new materials to withstand increasingly demanding conditions.[21]

The change in gases and working temperatures of the new power plants has forced the development of new alloys and feasibility studies on how existing commercial alloys behave at higher temperatures and atmospheres containing water vapor,[22–26] CO_2,[27,28] and also under conditions characteristic of the oxyfuel process.[29–34] All these studies have attempted to increase the ferritic and martensitic steels temperature range of use, instead of employing more expensive nickel alloys. At temperatures above 700°C, nickel alloys are the main materials studied for use in power plant applications. Corrosion resistance is a property analyzed in the material selection for high-temperature applications, but the mechanical properties of the materials are more important, especially the resistance to creep.[35]

CONCLUSIONS

Materials have been a fundamental factor in the history of civilization and can be associated with the steady progress of society over the centuries, as well as with significant jumps in the evolution of mankind. During the last 50 years, the combination of population growth with the increase in energy consumption have resulted in a rise of CO_2 emissions, enhancing the greenhouse effect and contributing to global warming.

This situation is aggravated by the large fraction (around 80%) of energy generation using fossil fuels. Despite the significant growth of renewable sources, such as wind and solar photovoltaic, the predominance of fossil fuel generation should last until around 2030. Therefore, carbon capture and sequestration, as well as an increase in efficiency, will be necessary to reduce CO_2 emissions and guarantee global warming below 2°C by 2050, as agreed in the Paris Agreement.

Development of materials to withstand higher temperatures and CO_2-rich atmospheres is necessary to improve the overall efficiency of the processes. Research is presently underway in several laboratories to contribute to this endeavor.

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