Renewable Energies

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The Future of Energy Supply: Challenges and Opportunities

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Dealing with Change

"Questions are never indiscrete, answers sometimes are."
Oscar Wilde

Each generation is confronted with new challenges and new opportunities. In a restricted system like the Earth, however, opportunities discovered and exploited by a generation can cause challenges to the subsequent ones. Fossil fuels have offered astounding opportunities during the 20th century in the rich countries of the western world, but now mankind has to face the challenges arising from fossil-fuel exploitation. The proven reserves of fossil fuels are progressively decreasing,[1] and their continued use produces harmful effects, such as pollution that threatens human health and greenhouse gases associated with global warming. Currently the world's growing thirst for oil amounts to almost 1000 barrels a second,[2] which means about 2 liters a day per each person living on the Earth (Figure 1).[3] The current global energy consumption is equivalent to 13 terawatts (TW), that is, a steady 13 trillion watts of power demand. How long can we keep running this road?

Figure 1. In this 1970 picture, an average American family is surrounded by the barrels of oil they consume annually. Now this consumption is about 40% higher.

"Currently the world's growing thirst for oil amounts to almost 1000 barrels a second."

Energy is the most important issue of the 21st century. Here is the fundamental challenge we face, here are many vital and entangled questions that we are called to answer. Can well-being, or even happiness, be identified with the highest possible amount of per capita energy consumption? Should we progressively stop burning fossil fuels? Can scientists find an energy source capable of replacing fossil fuels? Can chemistry help in solving the energy problem? Will it be possible for all the Earth's inhabitants to reach the standard of living of developed countries without devastating the planet? Will science and technology alone take us to where we need to be in the next few decades? Should we, citizens of the western world, change our lifestyle and shift to innovative social and economic paradigms? Can people living in poor countries improve their quality of life?

Forty years ago, looking at the first photos of the Earth seen from space, we fully realized that our planet is a spaceship that travels without any destination in the infinity of the universe. As passengers of this spaceship we are deeply interested in finding solutions to the energy crisis. As parents, we wish to leave our planet in a good shape for the benefit of future generations. As scientists, we do have the duty to contribute to the discussion on the impending energy crisis. As chemists, we can help improving energy technologies and, hopefully, finding scientific breakthroughs capable of solving the energy problem at its root. Finally, as citizens of the affluent part of the world, first class passengers of spaceship Earth, we should ask ourselves how can we really help passengers now traveling in much worse compartments of this spaceship. We know that our lifestyle, based on consumerism, may cause disparities. Disparity is, indeed, the most prominent characteristic among the Earth's inhabitants and, in the long run, the most dangerous problem. Finding a correct solution to the energy crisis could offer the opportunity to reduce disparity and create a more peaceful world. Our

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generation will ultimately be defined by how we live up to the energy challenge.

"Our generation will ultimately be defined by how we live up to the energy challenge."

An Unsustainable Growth in an Unequal World

"My grandmother used to say: there are but two families in the world, have-much and have-little."
Miguel de Cervantes, Don Quixote

Energy is the number one but, by no means, the unique problem for humanity. Food, water, health, environment, education, population, war, democracy are other important problems. It can be noted that all of them, perhaps except for democracy, are strictly dependent on the availability of energy.[4] It is easy to understand that a hospital consumes a huge quantity of energy. Perhaps it is more difficult to reckon the colossal amount of energy embodied in and consumed by a stealth bomber. Modern agriculture, which provides any kind of food and delicacies to Western consumers, is one of the most energy intensive human activities. For example, the energy of 7 liters of oil is needed to produce 1 kg of beef. Some people say that modern industrial agriculture is, in fact, the use of land to turn oil and gas into food.

Excluding the light coming from the Sun, the Earth is a closed system. The second law of thermodynamics states that, in a closed system, there are limitations that cannot be overcome; apparently, several economists are not acquainted with this simple principle. We must never forget that human economy vitally depends on the planet's natural capital (e.g. oxygen, water, biodiversity, etc). Fortunately, part of this capital is regenerated for free by the direct and indirect action of sunlight on the biosphere, but drawing on the natural capital beyond its regenerative capacity results in depletion of the capital stock. Humanity's load corresponded to 70% of the capacity of the global biosphere in 1961, and grew to 100% in the 1980s and to 120% in 1999.[5] This statistic simply means that we are living above our possibilities. Furthermore, we make extensive use of resources that cannot be regenerated by the biosphere. This is not only the case of fossil fuels, that are irremediably consumed when used, but also that of metals.[6] Clearly, spaceship Earth has a limited carrying capacity. It has been calculated that if all the world's 6.5 billion inhabitants were to live at current North American ecological standards, we should look around for another two Earths to accommodate them.[5] Of course also Europe is heavily contributing to unsustainable Earth exploitation: European terrestrial biosphere absorbs only 10% of Europe's anthropogenic CO_2 production.[7]

Known and Hidden Costs of Energy

"The struggle for existence is the struggle for available energy"
Ludwig Boltzmann

What is energy? The answer is not simple. We might apply to energy what Saint Augustine argued about time (Confessions, XI, 14): "*What is time? If nobody asks me, I know; if I wish to explain to him who asks, I know not.*"

Energy is an ubiquitous entity looking like heat, electricity, motion that, unnoticed, shapes and drives every single instant of our life (Figure 2). However, even the most educated people of developed countries do not care much about its importance. There is indeed a big disproportion between the extensive use we make of energy and the scarce knowledge we have of it. This situation is not good for a society willing to become *knowledge-based* as Europe is supposed to do.[8]

"There is a big disproportion between the extensive use we make of energy and the scarce knowledge we have of it."

If you ask simple questions to common people, for example, How energy is produced? How much energy do you consume? What is the cost of electricity? How can you save energy? you will most likely get poor answers. As educators we should ask ourselves: how energy is taught in our schools and universities?

In recent years the price of energy has substantially increased; the common belief is that energy is now extremely expensive. But can we really complain? The current "high" price of the most valuable energy source, oil, is around \$70/barrel, that is, \$0.44/liter. Hence, crude oil is cheaper than some mineral waters one can find on the supermarket shelves. Currently, the cost of petrol in a gas station in Europe (ca. €1.3 L^{-1}) is

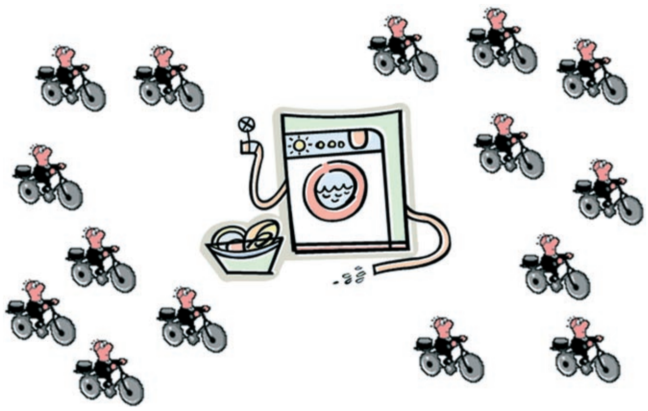


Figure 2. The power at the disposal of energy-affluent people: to run a TV set the continuous muscular work of 2 people would be needed, while for a complete cycle with an energy-efficient washing machine the number is increased to 15. To take-off a fully loaded Boeing 747, 1.6 million "energy slaves" would be required. These examples give an idea of how much energy we use.

lower than that of water in a restaurant. Thus it is still cheaper for a car to drink than for a human being.[9]

Our energy bonanza, however, comes at a price that is not paid directly by individuals or by energy companies, but by the society as a whole in terms of socio-economic and environmental damage. For instance, in Europe health care for people injured by car accidents (i.e., energy intensive transportation) is paid with public money and this contributes to burden national budgets. The hidden costs of energy ("externalities") deal with short term negative impacts related to the discovery, extraction, distribution, and conversion of power resources as well as long-term effects, such as health damage arising from air-pollution exposure.[10,11] Externalities are probably the greatest taboo of the energy puzzle. Some side-effects of energy consumptions are transmitted to future generations (e.g., nuclear waste); others, in the form of huge military costs related to securing energy supply, further burden our society. In this regard it is sufficient to recall that the first Persian Gulf War (PGW I, 1990–1991) cost approximately $80 billion, most likely a tiny value if compared to the unknown cost of the ongoing PGW II (Figure 3). Even in peace time there is a gigantic security machine operating to safeguard key energy corridors and facilities (pipelines, sea routes, refineries, etc.) and these costs are not directly charged on the oil barrel.

"Some side-effects of energy consumption are transmitted to future generations; others, burden our society."

Europe is leading the way to establish a scientifically sound account of energy externalities.[12] The European Union (EU) has recently estimated the extra-cost of electricity production by different sources. For example, electricity generated by coal in Germany implies an extra cost of 0.73€ cents per kWh, that is, 10-times higher than wind energy.[13] From these and related data it becomes clear that, if externalities were included in energy accounting, some renewable technologies would be already competitive with traditional technologies on a purely economic basis.

Probably the heavier externality that big energy consumers are inflicting to all of the citizens of the world is the forcing of the carbon cycle that fosters global warming. The amount of carbon we are injecting in the air (ca. 7 Gt/year) looks little if compared to the naturally occurring exchange between the biosphere and the atmosphere (ca. 200 Gt/year). However this is enough, on the long term, to steadily increase CO_2 concentration (+30% since industrial revolution), alter the Earth's radiation balance, and trigger artificial climate variations that overlap with natural oscillations.[14] The most likely scenarios imply an increase of extreme weather events, such as top scale hurricanes, droughts, heavy precipitations, heat waves. Of course, the most exposed to the "external" effects related to climate-change are deprived people, as shown in the aftermath of Katrina in New Orleans. In other words, affluent energy consumers will mainly generate the damage, the poor will suffer most.

Figure 3. The so-called "energy strategic ellipse", an area stretching from Arabian Peninsula to Western Siberia, where about 70% of the world's proven oil and gas reserves are concentrated.

Energy and Quality of Life

> *"You can never get enough of what you don't need to make you happy"*
> Eric Hoffer

Energy is embodied in any type of goods and is needed to produce any kind of service. This is the reason why it takes energy to improve people's standard of living. Since more energy yields more goods and more services, one could believe that the well-being of people increases with increasing consumption of energy. This, however, is not always the case. The quality of life is highly correlated with energy consumption during basic economic development, but it is almost completely uncorrelated once countries are industrialized.[11]

"The quality of life is almost completely uncorrelated with energy consumption once countries are industrialized."

When the per capita energy consumption reaches a value of about 2.6 ton of oil equivalents (toe) per year there is no further improvement. There is in fact a strict parallelism between overconsumption of energy and food. The nation with the highest number of overweight or obese people (USA: 130 million, or 64%) is also the one with the highest energy consumption per capita (8 toe per year). An American consumes as much energy as 2 European, 10 Chinese, 20 Indian, or 30 African people.[11] Calories are both biologically and socially healthy only as long as they stay within the narrow range that separates enough from too much.[15] Over a definite threshold, energy inputs increase inefficiency of personal life (obesity) as well as of social life (traffic jams), cause more waste, boost medical expenses and, last but not least, increase inequality.

As soon as a black-out takes place in a country, for whatever reason, the solution proposed by most politicians and economists is that of making new power plants. This, for example, was the case for the nationwide black-out that occurred in Italy on a Saturday night in September 2003, when the power demand was less than 30 % of the national capacity production. The wisest decision to take in front of any "energy crisis" in developed countries is not that of increasing energy supply, but that of reducing energy demand. It is not difficult to demonstrate that affluent countries can cut the energy consumption by 25 % at virtually no sacrifice for people.[16] Since a substantial amount of the consumed energy is embodied in industrial products, avoiding production of useless things and increasing the lifetime of products would save a lot of energy.

"The wisest decision to take in any energy crisis in developed countries is that of reducing energy demand."

Unfortunately this goal does not fit with the mantra of endless economic growth.

Fossil Fuels

"Is fossil solar energy the only one that may be used in modern life civilization? That is the question"
Giacomo Ciamician

Oil is the most valuable commodity in world trade. It can be estimated that, at current prices, roughly six billion dollars a day change hands in worldwide petroleum transactions.[17] We currently consume 85 million barrels of oil a day and demand is growing mainly as a result of increasing car ownership in Asian countries. If China and India, with now less than 20 cars for 1000 people, should reach the car saturation level of European countries (about 700 cars per 1000 people), their automotive fleet would need 28 million barrels of oil a day, that is, almost three times the current production of Saudi Arabia.

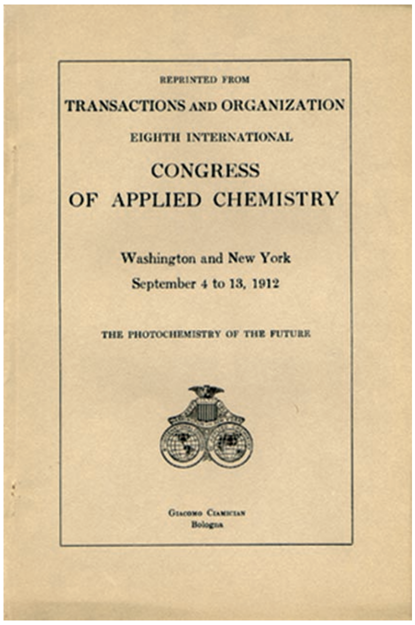
Our oil-addicted civilization is going to face a problem that might change the energy scenario dramatically, the so-called oil peak.[18] Starting from early 20th century the demand of oil has steadily increased and the supply has always been able to cope with such a demand: we needed more oil and we extracted it easily. There will come a time, however, in which the supply will not be able to satisfy the ever increasing demand. That day the oil reserves will not be exhausted, but the golden age of "easy oil" will be over. The pessimists believe that we are now at the oil peak, the optimists[19] shift it 30 years later. Actually, even if the latter are right, the oil peak problem will not be moved too far away: after all, the babies today will be still young in 30 years time.

Oil is the ideal fuel since, being liquid, it is easy to extract and transport. For some applications oil is practically impossible to replace: can we conceive to run a Boeing-747 Jumbo Jet with solid or gas fuels?

The gas peak is expected to occur later than oil peak. However, the shortage in the supply of Russian natural gas to Europe in winter 2006 has shown that the distribution infrastructure of this valuable energy source is rigid and fragile. We should also consider that in the future a substantial share of Russian gas could take the direction south to developing Asian countries. The distribution problem can be limited, in principle, by building liquid natural gas (LNG) tankers and regasification terminals. These infrastructures, however, are extremely expensive and imply severe security issues. This is probably the reason why most California LNG terminals were built off the Mexican coast.[20] The risk of accident is limited, but … you never know.

Coal is the most abundant and dirtiest of fossil fuels. Basically, the problem of coal in the next 100 years is not availability, but environmental sustainability. Just to give a visual impression, a standard 1000 MW plant consumes a 100-trainloads of coal a day. The trend in the use of the most greenhouse-intensive fuel is in conflict with ongoing efforts for a world-scale climate policy. In the hope to mitigate the climate impact of coal, considerable resources are being invested on projects for coal gasification and carbon sequestration underground. The latter technology, that aims at capturing CO_2 from stationary sources (e.g., power plant flue gases) thereby preventing its release in the atmosphere, encounters a wealth of environmental, technical, economical, and political obstacles.[21,22] Coal has another significant drawback: in many cases it requires someone digging it underground, which is not exactly the easiest job one can dream of. Probably, the lowest vocation rate for this career is found among the biggest energy consumers of affluent countries.

In conclusion, it is clear that, sooner or later, we will face an energy transition from fossil fuels to some kind of renewable energy source (Figure 4),[23]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THE PHOTOCHEMISTRY OF THE FUTURE

Giacomo Ciamician
Bologna

Figure 4. The famous paper "*The Photochemistry of the Future*" also published in *Science* by Giacomo Ciamician in 1912 (ref. [23]), where he pointed out the need for an energy transition from fossils to renewables. One century later this call is more urgent than ever.

Nuclear Energy

"The nuclear power industry remains as safe as a chocolate factory"
The Economist, March 29th 1986 (4 weeks before the Chernobyl catastrophe)

Nuclear energy can be obtained by fission or fusion. While fission is largely used to produce electrical energy, fusion is still at the level of preliminary laboratory experiments[24] (except for bombs). The most technically advanced nations have recently joined to launch a project called ITER that should demonstrate by 2050 the possibility to use nuclear fusion for civil purposes. It is difficult to forecast whether this project, which is extremely complex and very expensive (about 10 billion €, which means approximately 2 € for each person on the Earth) will be successful.

Presently there are 441 operating fission power plants in the world. In the next few years this number will likely decrease because, while waiting for new planning and regulation clearance, the 26 plants that are now under construction will hardly replace the oldest reactors close to decommissioning.[25] Development of fission nuclear energy faces a number of difficulties. In principle, modern reactors are safe, but people cannot forget the Chernobyl accident, whose terrible material and psychological consequences are still difficult to evaluate. The problem of safe disposal of nuclear waste has not yet been solved even in the United States, in spite of the huge effort to construct a national deposit in the Yucca Mountain,[26] whereas leaving nuclear deposits radioactive for thousands of years to future generations raises moral concern. Civil nuclear energy is tightly and ambiguously linked with weaponry technology (see the current Iran affair) and proliferation of nuclear weapons is the last thing we need on our fragile spaceship Earth. Nuclear plants are primary targets for terrorists and are hugely expensive to build, safeguard, and decommission.

"Civil nuclear energy is tightly and ambiguously linked with weaponry technology."

The development of nuclear energy has been heavily subsidized in different ways. In U.S., for example, the Price–Anderson act poses a cap of $200 million on the cost of private insurance, that would otherwise be prohibitive. When required, resources are ultimately provided by taxpayers. Observers note that it is questionable if any nuclear plants would have been constructed in the U.S. without this support.[10]

To contribute significantly to our future energy needs, nuclear energy should provide 10 TW of power for an extended period of time. Production of such a large amount of energy would require 10000 one-gigawatt-electric (1-GW_e) nuclear fission plants which means that a new power plant should be constructed somewhere every other day for the next 50 years.[27,28] Once that level of deployment was reached, the terrestrial uranium resource base would be exhausted in 10 years. Spent fuel should then be reprocessed and breeder reactor technology should be developed and disseminated to countries wishing to meet their additional energy demand in this way.[29] Conventional fuel reprocessing, however, requires the separation of plutonium from radioactive material, making much easier plutonium stealing for atomic weapons. The Bush administration has recently asked Congress to provide $40 billion start-up funding for an ambitious program called Global Nuclear Energy Partnership (GNEP) that aims at launching an improved nuclear recycling process.[29] If the project were successful, by 2025 the U.S. and its partners would provide fresh nuclear fuel and small nuclear reactors to developing nations. In return, these user nations would agree not to build uranium enrichment and to give back spent fuels to the original supplier for reprocessing. This kind of initiative, however, would render developing countries heavily depend on foreign technology and their political freedom could be substantially compromised.

Solar Energy

"Life is a water mill: the effect produced by the falling water
is achieved by the rays of the sun.
Without the sun the wheel of life cannot be kept going.
But we have to investigate more closely which circumstances and laws of Nature bring about this remarkable transformation
of the sunrays into food and warmth."
Wilhelm Ostwald

As mentioned before, spaceship Earth is a closed system. We are lucky, however, to have an inexhaustible energy flow coming from the sun and deposited on the surface of the Earth: 120000 TW of electromagnetic radiation. It is a quantity of energy far exceeding human needs. Covering 0.16% of the land of the Earth with 10% efficient solar conversion systems would provide 20 TW of power (Figure 5),[30] nearly twice the world's consumption rate of fossil energy and the equivalent of 20000 1-GW_e nuclear fission plants.

Solar energy has enormous potential as a clean, abundant, and economical energy source, but cannot be employed as such; it must be captured and con-

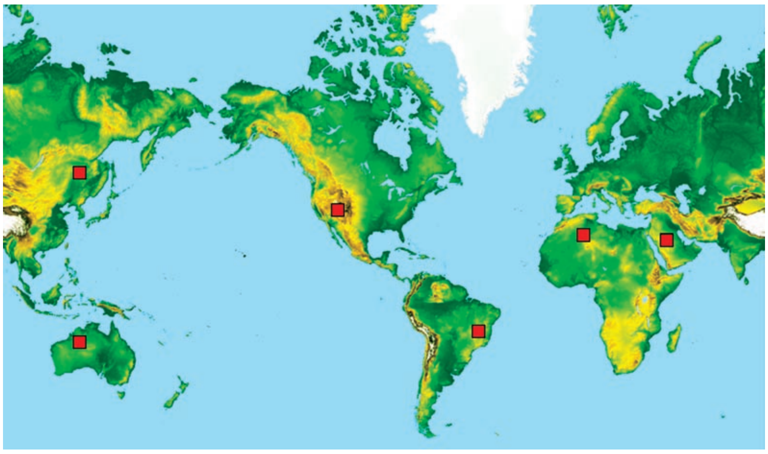

Figure 5. The production of 20 TW of power, the world's mid-century projected demand, would require covering 0.16% of Earth's land (red squares) with 10%-efficient solar panels (courtesy of Prof. Nathan Lewis, Caltech, Pasadena).

verted into useful forms of energy. Since solar energy is diffuse (ca. 170 $W m^{-2}$) and intermittent, conversion should involve concentration and storage. Currently, none of the many routes used to convert solar energy into heat, electricity, and fuel is competitive with fossil fuels at today's world market price. However, if the "external" costs of energy from fossil fuels were considered, the cost comparison would give quite different results.

Some scientists believe that in the future it will be possible to collect energy from the space by solar power satellites (SPS) and then send microwave power beams back to Earth. We will not consider these futuristic applications in the following.

Solar Thermal Conversion

The most broad-scale way of making use of solar energy is that of solar thermal collectors, in which a liquid is heated to supply hot water for direct use or home heating. These systems are very simple and do not need sunlight concentration. The market for solar thermal collectors grew some 50 % between 2001 and 2004. The EU accounts for 13 % (1.6 million square meters installed in 2004).[31] The highest density of solar thermal systems is in Israel (740 m^2 per 1000 inhabitants; in Germany, it is tentimes less), where most buildings are required by law to have solar hot-water collectors. The 110 million square meters of installed collector area (77 thermal gigawatts, GW_{th}, of heat production capacity) worldwide correspond to almost 40 million households, about 2.5 % of the roughly 1.6 billion households that exist worldwide.[31] It is important to point out that, contrary to common perception, over 50 % of energy use in modern houses is spent in the most trivial fashion: warm up water for heating, washing, and cooking. Hence wide diffusion of solar thermal conversion would substantially alleviate the energy and environmental bill of the residential sector.

It has been estimated that in 2004 the use of solar energy in the place of fossil fuels to obtain hot water has avoided production of 25–30 million tons of CO_2. A number of major cities around the world, lead by Barcelona and Oxford, have enacted ordinances requiring solar thermal systems in new buildings, with very significant results. An important improvement of solar thermal conversion would be to construct systems capable of accumulating heat during the day, storing it in an embedded phase transition, and release it in a controlled manner.

> ***"Over 50% of energy use in modern houses is spent in warming up water for heating, washing, and cooking."***

The Sun's energy can also be converted into high-temperature heat by using mirrors to concentrate the radiation. Once the sunlight is concentrated, heat can be converted into electricity by heat engines or used for thermochemical processes such as methane reforming and metal oxide reduction.[28] After a stagnant period which lasted until a few years ago, high-temperature solar thermal systems have recently regained interest. Spain's market is emerging and some developing countries have planned projects.[31] Breakthrough directions are materials that can withstand the high temperatures and corrosive chemical environments in solar furnaces.

Solar Electricity

Solar electricity can be produced from photovoltaic (PV) cells and related devices, or from high-temperature systems. The first method is by far the most promising for diffuse electricity production. PV cells have many applications. They are particularly well suited to situations where electrical power from the grid is unavailable. About 1.6 billion people still do not have access to electricity and a substantial portion of the world's poor lives in areas where the cost of extending the electric grid is prohibitive. In developed countries, solar cells (in the form of modules or solar panels) on building roofs can be connected through an inverter to the electricity grid in a net metering arrangement (grid-connected PV systems). From 2002 to 2004, grid-connected solar photovoltaics grew by 60 % per year, to cover more than 400000 rooftops (of which 200000 in Japan, and 150000 in Germany).[31]

In conventional PV cells electrons and holes created by absorption of photons with energies above the semiconductor band gap lose their excess energy as heat. The thermodynamic limit for energy conversion efficiency under these conditions is 31 %. In principle, this limit can be overcome by second-generation systems made of semiconductor p–n junctions arranged in tandem configuration (multijunction solar cells).[28]

The most common, first-generation PV cells, consisting of single-crystalline silicon, have efficiencies between 5 and 15 %, a lifetime of about 30 years and a cost for grid-connected electricity of about 0.20–0.40 $/kWh, to be compared to electric grid supplies from fossil fuels, which vary between 0.03 (off-peak, developed country) and 0.80 $/kWh (rural electrification).[31] The energy payback time of a solar cell is of the order of 2–4 years and in its lifetime a cell may produce electricity with a value of something in the order of 10 times its cost of production.[28] Total world cumulated installed capacity of PV amounted to 1.8 GW in 2004.[31]

Solar electricity is already cost-competitive with fossil and nuclear electricity if externalities are taken into consideration. Furthermore, it can reasonably be expected that an intense research effort in this field will produce new concepts, designs, materials, and technologies capable of increasing cell efficiency and reducing cost.

During the past decade, solid-state PV cells based on molecular-based organic systems like those used in video display technology have been developed. Their energy conversion efficiency is still low (less than 5 %), but they offer great potential for construction of low-cost, lightweight, large-area, flexible solar cells. The development of high-efficiency organic solar cells could lead to solar conversion paints that would allow extensive capture and conversion of solar energy.[28]

Solar energy can be converted into electrical power also by photoelectrochemical cells based on a semiconductor electrode in contact with an electrolyte containing an electron relay. The most stable, and therefore most used semiconductor is TiO_2 which, however, does not absorb much of the sunlight because its band gap is too high (3.0 eV, ca. 410 nm). To overcome this problem, dye molecules are adsorbed onto thin films of sintered nanocrystalline particles of TiO_2.[32] The dye molecules, when excited by sunlight, inject electrons into the TiO_2, producing the charge-separation process. These dye-sensitized solar cells are attractive because of the low cost of TiO_2 and the potential simplicity of their manufacturing process. Laboratory scale devices of 11 % efficiency have been demonstrated, but larger modules are much less efficient.

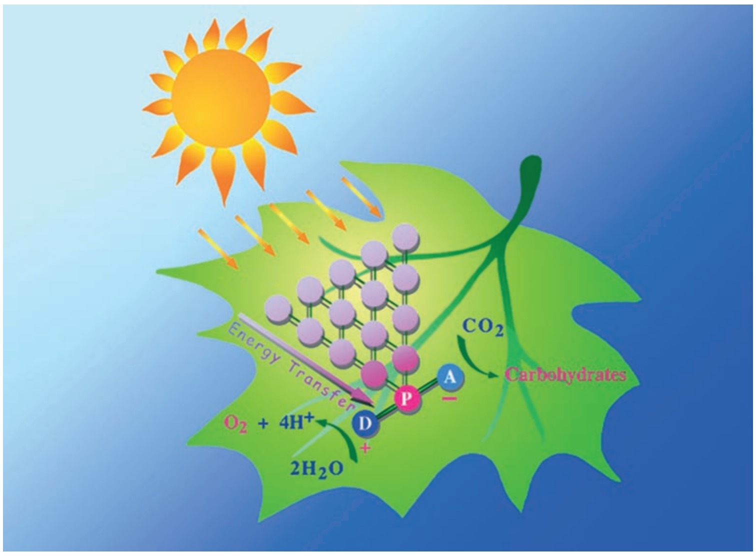

Figure 6. A very simplified sketch representing key processes in natural photosynthesis: solar light harvesting by pigments, energy transfer to the reaction center, charge separation, production of carbohydrates and oxygen (courtesy of Dr. Lella Serroni, University of Messina). D donor, A acceptor, P photosensitizer.

Solar Fuels

Liquid fuels are the best form of energy since they can be stored and transported. Because of the intermittent nature of solar energy, its conversion into useful chemical fuels is even more advisable. Solar electricity can be converted into chemical fuels through the electrolysis of water to produce H_2 and O_2, but it is a very expensive method. Therefore, direct production of fuels from sunlight (perhaps including methanol)[33] would be much more advantageous.

Natural photosynthesis: Natural photosynthesis converts sunlight into fuels, producing biomass and, over geological time, fossil fuels. Fossil fuel production rate, however, is about 500,000-times slower than our current consumption rates. The maximum potential photosynthetic conversion of sunlight to chemical energy is about 6.7 %, but only a fraction of this is realized. Globally, only 0.3 % of the solar energy falling on land is stored in plant matter, and only a fraction of this can be harvested.[11] Improving upon the efficiency of natural photosynthesis would of course be a very important result. To reach this goal, elucidation of the molecular basis of the overall process is essential (Figure 6). In photosynthetic organisms, light is harvested by antenna systems consisting of pigment-protein complexes. The captured excitation energy is then transferred to reaction center (RC) proteins, where it is converted by an excited-state electron-transfer process into electrochemical potential energy. The quantum efficiency of the charge-separation process is close to 100 %. The resulting oxidizing and reducing equivalents are then transported, by subsequent thermal electron-transfer steps, to catalytic sites, where they are used to oxidize water and produce fuels, such as carbohydrates.

Artificial photosynthesis: The need and possibility to achieve artificial photosynthesis[34] was anticipated by the Italian chemist Giacomo Ciamician (Figure 7) about one century ago:[23] "*Where vegetation is rich, photochemis-*

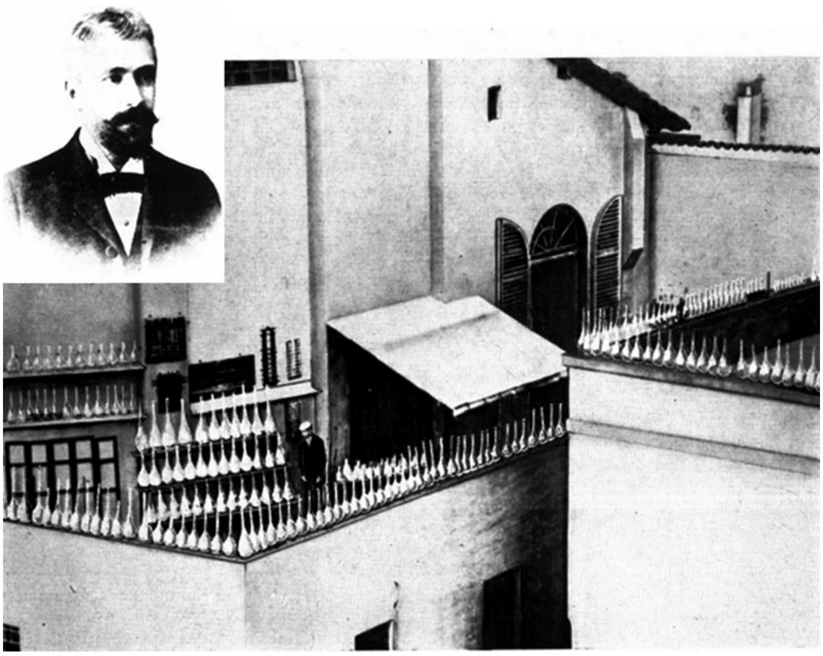

Figure 7. Giacomo Ciamician, pioneer of photochemistry and prophet of the energy transition, while watching his flasks under solar irradiation on the roof of his laboratory at the University of Bologna, Italy, circa 1910.

try may be left to the plants and, by rational cultivation, solar radiation may be used for industrial purposes. In the desert regions, unsuitable to any kind of cultivation, photochemistry will artificially put their solar energy to practical uses. On the arid lands there will spring up industrial colonies without smoke and without smokestacks; forests of glass tubes will extend over the plants and glass buildings will rise everywhere; inside of these will take place the photochemical processes that hitherto have been the guarded secret of the plants, but that will have been mastered by human industry which will know how to make them bear even more abundant fruit than nature, for nature is not in a hurry and mankind is. And if in a distant future the supply of coal becomes completely exhausted, civilization will not be checked by that, for life and civilization will continue as long as the sun shines!".

The efficient production of clean solar fuels would indeed represent the most important breakthrough of modern science. Although this task presents many scientific challenges, some results so far obtained are encouraging.[35]

"The efficient production of clean solar fuels would represent the most important breakthrough of modern science."

For solar fuel production to be economically and environmentally attractive, the fuels must be formed from abundant, inexpensive raw materials such as water and carbon dioxide. Water should be split into molecular hydrogen and molecular oxygen,[36] and carbon dioxide in aqueous solution should be reduced to ethanol with the concomitant generation of dioxygen. These are the two reactions on which research is presently focused. The best way to construct artificial photosynthetic systems for the practical production of solar fuels is that of mimicking the molecular and supramolecular organization of the natural photosynthetic process: light harvesting should lead to charge separation, that must be followed by charge transport to deliver the oxidizing and reducing equivalents to catalytic sites where oxygen evolution and hydrogen evolution (or CO_2 reduction) should separately occur. While some progress has been made on each aspect of artificial photosynthesis, integration of the various components in a working system has not yet been achieved (Figure 8).[37]

Difficulties arise because formation of hydrogen and oxygen from water (as well as reduction of CO_2) are multi-electron processes, whereas light absorption is a one-photon process that results in a one-electron charge-separation process. Therefore catalysts are necessary to couple single photon events to processes capable of accumulating the redox equivalents needed for fuel production. Efficient catalysts, particularly for oxygen generation, however, have not yet been found. The recent discovery of the structure of the oxygen evolving center of natural photosynthesis[38] may help in designing efficient artificial catalytic systems.

More successful has been the study of hybrid natural–artificial systems, for example, the construction of a proton pump using an artificial donor–acceptor triad and ATP synthase incorporated in a liposome.[39]

Fuels from biomass: Biomass has been, and continues to be, an important resource for energy production particularly in developing countries where it is often used to provide energy in small-scale industries and more generally as fuel-wood in stoves causing severe health problems.[40] Substantial energy production from biomass requires very large areas of cultivable land, and huge amounts of water. It has been estimated that, at current consumption rate, the substitution of a mere 5% of gasoline and diesel fuels for Europe and U.S. would claim about 20% of their cultivable land.[41]

In the industrial countries, biomass is employed to produce heat and electricity using mainly solid biomass, or to obtain liquid fuels, such as ethanol and biodiesel, from crops (33 billion liters in 2004, about 3% of the 1200 billion liters of gasoline consumed globally).[31] Ethanol is extracted from sugarcane in Brazil and from corn in the U.S. The Brazil cane–ethanol system converts 33% of the harvested primary energy into ethanol[42] providing, in 2004, 44% of all (non-diesel) motor-vehicle fuel consumed as pure ethanol (E95) or a 25%-ethanol/75% gasoline blend (E25). More than half of all new cars sold in Brazil are flexible-fuel vehicles

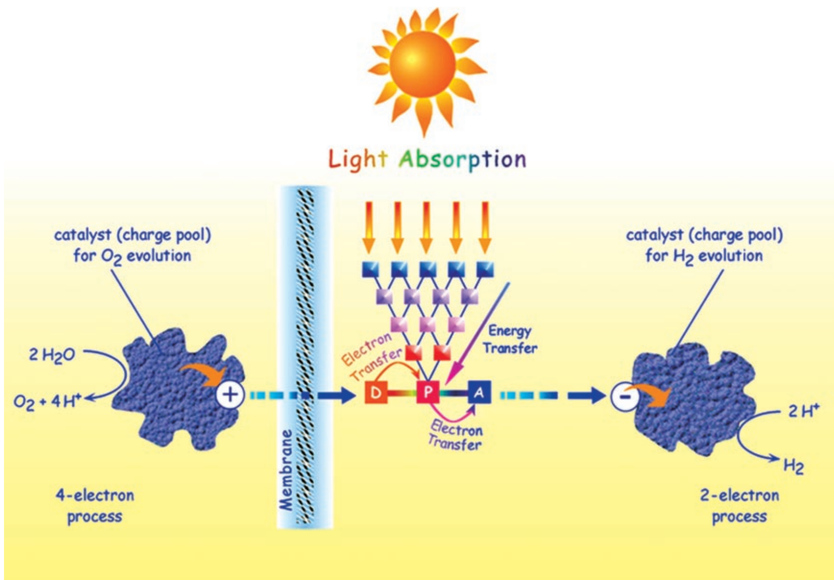

Figure 8. A very simplified sketch representing key processes in artificial photosynthesis: solar light harvesting by molecular antennas, energy transfer to a reaction center, charge separation, water splitting with production of hydrogen and oxygen on the two sides of a membrane (adapted from ref [37]).

that run with pure ethanol or the ethanol/gasoline blend. Use of ethanol as E85 and E10 blends (that is 85% or 10% ethanol) is increasing in the U.S., where the corn–ethanol system is reported to convert 54% of the harvested primary energy.[43] Mandates for blending biofuels into vehicle fuels have been appearing in several countries including India and China. In Europe, several countries produce biodiesel and provide tax exemption for this fuel. In Germany, biodiesel production grow by 50% in 2004. EU has a biofuels target of 5.75% for 2010. Notably, the net energy gain in the production of biodiesel from soybeans is substantially higher than that of bioethanol from corn.[44]

Current research directions on biomass focus on 1) increasing cellulose-to-sugar conversion for the production of ethanol,[16,45] and 2) gasification technologies to produce synthesis-gas (syngas), a mixture of CO and H_2 for use in fuel-forming reactions.[28]

Wind, Hydro, and Other Renewables

“Praised be You my Lord with all Your creatures,
especially Sir Brother Sun,
Who brings the day and through whom You give us light.
And he is beautiful and radiant with great splendor.
Praised be you, my Lord, through Brother Wind,
Praised be You, my Lord, through Sister Water,
Praised be You, my Lord, through Sister Mother Earth,”
Saint Francis, Canticle of the Creatures

Wind

Producing electricity by wind implies a number of hard-to-rival advantages such as 1) guaranteed perpetual zero cost of the primary “fuel”; 2) no emissions in the atmosphere or heat to dissipate; 3) a relatively simple technology; 4) short times of construction and wide tunability of installed capacity from a few kW to hundreds of MW. Inevitably, the price of wind-made electricity will continue to decrease on the long term, making it a stronger and stronger competitor for traditional technologies. Disadvantages are related to the natural variability of winds, the distance between wind farms and consumption centers, and aesthetic and ecological objections. The total amount of globally extractable wind power has been estimated to be 2–6 TW_e.[30]

The wind-power market is concentrated in a few primary countries, with Spain, Germany, India, U.S., and Italy leading expansion in 2004, but new large-scale commercial markets are taking the first steps in several countries such as Russia, China, and Brazil. The wind-power industry produced more than 6000 wind turbines in 2004, at an average size of 1.25 MW each.[31] According to the European Wind Energy Association,[46] by the end of the current decade 75000 MW of wind turbines will be installed in Europe, able to satisfy the residential electricity need of almost 200 million European citizens. The vast European wind-energy potential, in principle, would be able to satisfy all our electricity needs.

Hydroelectric Energy

Hydrogeneration is one of the oldest technologies for electricity production, thus it is easier to evaluate advantages and disadvantages.[16] Among the latter, invasivity comes first. The land occupied by the world hydroelectric infrastructure is estimated to be roughly 300000 km^2 (approximately the area of Italy), although hydroelectric plants provide just 3% of world total primary energy supply (TPES).[47] The construction of big dams has caused the forced displacement of 40-to-80 million (usually poor) people in developing countries during the 20th century, with unaccountable social and economic penalties. Reservoirs have often inundated archeological sites as well as many unique natural ecosystems and life in downstream rivers (e.g., the Colorado) has often been dramatically affected. Recently it has also been shown that water reservoirs can be significant sources of CO_2 and CH_4 from decaying vegetation. Despite these drawbacks, hydroelectric power exhibits many important advantages such as 1) the lowest operating cost and a longer plant lifetime than any other mode of electricity production; 2) easy harvesting of potential energy for peak electricity demand, available within seconds; 3) reliable supply of irrigation and drinking water; 4) protection against recurrent, and sometimes destructive, floods. In principle the Earth untapped hydro potential is simply huge, however only a small fraction of it can be utilized in a sustainable fashion from an economic and environmental standpoint. According to recent estimates, the remaining exploitable hydroelectric resource is less than 0.5 TW.[28]

As far as Europe is concerned, the potential for new big hydroelectric plants is minimal, but small size and widely distributed facilities can give a significant contribution to tomorrow’s energy mix. This situation is also true for developing countries where tens of millions of rural homes already receive power from small hydroelectric plants, mostly in China.[16,31]

Other Renewables

Mother nature donates us a few other options to draw energy from our Earth spaceship. The most important of these is probably geothermal energy, related to the heat stored in the depths of our progressively cooling planet. In some selected areas, as demonstrated in Italy over a century ago, underground thermal energy can be extracted and used as heat or converted into electricity. Geothermal direct-heat utilization capacity has nearly doubled from 2000 to 2005 (13 GW_{th} increase), with at least 13 countries using geothermal heat for the first time.[31] The total geothermal energy at the surface of the Earth, integrated over all the land area of the continents, is 12 TW, of which only a small fraction could practically be extracted. The global potential electric energy generated in this way could cover 3–5% of current consumption, which is certainly interesting especially for regions of the planet where exploiting geothermal energy is practical.[16]

Other, minor energy resources could be obtained by taking advantage of the ocean and lake temperature gradients, currents, and waves, while the Earth–Moon gravitational energy can be exploited in some selected coastal areas of the northern hemisphere where tides move large volumes of sea water in a relatively short time. The cumulative energy in all tides and ocean currents in the world amounts to less than 2 TW. However, in our quest for an increasingly diversified energy portfolio, they must be carefully considered, especially on the local scale. A recent interesting example is the use of the deep cold waters of Lake Ontario to provide air-conditioning to thousands of Toronto's offices and houses.[48]

The Hydrogen Economy

> *"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable … . Water will be the coal of the future"*
>
> Jules Verne, The Mysterious Island

According to media and press it seems that the energy problem will shortly be solved by hydrogen (Figure 9), that sometimes is described as a fuel obtainable for free from water.

Figure 9. A hydrogen fuel-cell bus in Iceland. The water splitting and recombination reactions are figuratively represented by the opening and closing of the door.

Policy-makers have strongly biased opinions on the hydrogen issue.[49] Most scientists believe that the shift to a hydrogen economy will not occur soon and might also not occur at all unless a large research effort is set up to overcome several scientific and technological obstacles.[49–52]

Combustion of molecular hydrogen, H_2, with oxygen produces heat and water, and combination of molecular hydrogen and oxygen in a fuel cell generates electricity, heat, and water. Clearly, if hydrogen could promptly replace oil, both the energy and the environmental problems of our planet would have been solved. Unfortunately, however, there is no molecular hydrogen on the Earth. Molecular hydrogen cannot be "mined", but it has to be "manufactured", starting from hydrogen rich compounds, by using energy. Therefore, hydrogen is not an alternative fuel, but a secondary form of energy. This is the central (but not unique) problem of hydrogen economy. Like electricity, hydrogen must be produced by using fossil, nuclear, or renewable energy and then it can be used as an energy vector, with the advantage, with respect to electricity, that it can be stored.

> ***"According to the media it seems that the energy problem will shortly be solved by hydrogen."***

Although a proper *use* of hydrogen is not expected to cause big environmental problems, one cannot say that hydrogen is a "clean" form of energy. In fact, hydrogen is "clean" or "dirty" depending of the primary energy form used to produce it. Hydrogen obtained by spending fossil fuels or nuclear energy incorporates all the problems of using those primary energy sources. Burning fossil fuels in remote regions to produce hydrogen as a clean fuel for metropolitan areas would be an ineffective solution, owing to the transboundary nature of atmospheric pollution.[53]

Clearly, clean hydrogen can only be obtained by exploiting renewable energies, and this can be done, in principle, through the intermediate production of electricity (e.g., by wind or photovoltaic cells) followed by water electrolysis, or by photochemical water splitting.

Growth and Potential of Renewable Energies

> *"The only way to discover the limits of the possible is to go beyond them into the impossible"*
>
> Arthur C. Clarke

In the last few years, the use of renewable energies has grown rapidly. From 2000 to 2004, the average annual growth rate was: grid-connected solar PV 60 %, wind power 28 %, biodiesel 25 %, solar hot water/heating 17 %, off-grid solar PV 17 %, geothermal heat capacity 13 %, and ethanol 11 %.[31] Such a generalized increase in all the fields of renewable energies is very important since it allows each country to construct a diversified energy portfolio.

Solar water heaters are fully competitive with conventional water heaters; ethanol in Brazil is competitive with gasoline; hydro, geothermal, and some forms of biomass power generation are already competitive with power from fossil fuels (2–4 $cents/kWh) and nuclear energy 4–6 $cents/kWh; wind power is competitive at good sites, and solar PV power is expected to become competitive before 2010 even in developed countries at high insolation regions.

While waiting for progress in solar-fuel production, solar thermal and solar electricity can already supply a noticeable amount of energy. China's target for solar thermal is to reach 230 million square meters by 2015, more than twice the amount of worldwide collectors today. Solar thermal conversion can indeed replace much of the heat now supplied by burning fossil fuels and biomass.

Solar electricity can be profitably exploited in developing as well as developed countries. By 2005, more than 2 million households in developing countries have received electricity from solar home systems. An idea of how necessary development in this field is and how huge this market is, comes from the estimate that 350 million households worldwide do not have access to central power networks. The spreading of decentralized electricity generation systems could eliminate the need to build up an extensive and costly transmission grid, in the same way as mobile telecommunications has allowed the leapfrogging of cabled telephone lines in some developing regions of the world.

In some developed countries, demand for grid-connected PV systems outstrips production. Solar PV is indeed one of the world's fastest growing, most profitable industries. Chinese module production capacity doubled during 2004. India's primary solar PV manufacturer expanded production capacity from 8 MW in 2001 to 38 MW in 2004. Large production is expected from new plants installed in the Philippines, Thailand, and other countries. Substantial, but not sufficient, increase in production is taking place also in Europe, where at the end of 2004 the top two producers were Q Cell in Germany (75 MW) and Isofoton in Spain (53 MW).[31]

The harnessing wind energy is also increasing worldwide. Considering the current level of deployment of on-shore and off-shore wind farms, especially in Europe, it is outdated to consider them as "alternative" energy stations.

In new buildings, solar thermal and PV systems can be integrated and incorporated into roof and walls. Blending of small wind turbines with PV and/or solar heaters is also possible. Standardized "plug and play" full-scale household off-grid PV systems are produced and shipping containers with integrated systems consisting of PV modules, small turbines, and advanced batteries are also available. Indeed, the sophistication of many segments of the renewable-energy industry increases year by year.

At least 48 countries worldwide, including all 25 EU and 14 developing countries, have now some type of renewable-energy promotion policy. For example, an European Solar Thermal Technology Platform has just been created to promote and ease the development of industries with high technological potential.[54] European renewable-energy targets are 21 % electricity and 12 % total energy by 2010. Large commercial banks, venture-capital investors, and leading global companies are strongly interested in renewable energies, whose growth is supported by at least 150 marked facilitation organizations. More than 1.7 million jobs have been estimated to be directly involved in renewable energies in 2004, including 400 000 jobs in the Brazil ethanol industry, 250 000 jobs in the China solar hot-water industry, 130 000 jobs in Germany from all renewables, and 15 000 jobs in the European wind industry.[31] Detailed studies are available on the estimation of direct jobs that can be created by the development of the various kinds of renewables.

There is strong evidence that solar and other renewable energies can take off with great benefit for people and the environment. Policy can play a fundamental role to support this development. Key points are durability and reliability of political support and direct involvement of local authorities. A variety of renewable-energy promotion policies have been adopted in farsighted countries.

In spite of such a fast growth, the contribution of renewable energy to the overall energy supply is still very low. Renewables (excluding hydroelectric) provide 0.5 % of world TPES and 2 % of world electricity;[55] more than one third of the latter share is produced in Europe.[56] There is a need to accelerate the development of renewable energies, but this acceleration can only be based on scientific research. If suitable research projects are launched and supported, a wealth of more efficient and less expensive materials to construct systems for solar energy conversion into heat and electricity can reasonably be expected in a few years and production of solar fuels by artificial photosynthesis is a likely achievement in the long run. As pointed out by the Basic Energy Science Workshop on Solar Energy Utilization in April 2005,[28] research in solar-energy conversion lies at the crossroads where physics, chemistry, and biology meet nanoscience. Science's greatest advances have always occurred on the frontiers, at the crossroads of different disciplines, where the most profound questions are posed. Solving the energy problem is indeed a great question that needs to be tackled by an interdisciplinary scientific effort. Since great questions often make good science,[57] research aimed at solving the energy problem will also lead to abundant positive outcomes in other fields.

"Research aimed at solving the energy problem will also lead to abundant positive outcomes in other fields."

Answers to Fundamental Questions

> *"Better to expect the foreseeable than be caught out by the unexpected"*
> André Isaac

At the beginning of this essay we pointed out that the energy problem is entwined with many other social issues, and that we need to know the answers to several entangled questions before taking decisions that could heavily affect our lives and, even more so, those of our children and grandchildren. After the above discussion, we are in the position to propose some answers that are, of course, as much entangled as the corresponding questions.

Can well-being, or even happiness, be identified with the highest amount of per-capita energy consumption? NO. Increase in energy consumption helps material development, but in developed countries it does not help people to solve their nonmaterial problems. We have to change the paradigm that governs our energy policy. The energy crisis in a wealthy society cannot be overwhelmed by increasing energy production. To expand our happiness we should make room for our nonmaterial values and to human relationships.

Should we progressively stop burning fossil fuels? YES, for three important reasons: 1) fossil fuels are a not renewable energy source that is going to exhaust; 2) use of fossil fuels causes severe problems to human health and irreversible damages to the environment; 3) fossil fuels should be preserved as raw material for the chemical industry. Energy from fossil fuels should progressively be used only for creating the conditions for a smooth transition toward the development of new energy sources.

Can scientists find an energy source capable of replacing fossil fuels? YES. There are two abundant energy sources, solar energy (that broadly speaking includes the other renewable energies) and nuclear energy. These two forms of energy are completely different not only for technical reasons, but also from the social viewpoint.

Nuclear energy obtained by the presently available technology (fission) is neither clean nor inexhaustible. Furthermore, it is a very concentrated form of energy that has to be produced under strict technical, political, and military control because of its high capital cost, possible catastrophic accidents, difficulty to dispose wastes, misuse of nuclear material, proliferation of nuclear armaments. Development of nuclear energy will favor energy overuse, increase disparities among rich and poor nations, and lead to a more fragile world.

Solar energy is abundant and inexhaustible. It can be exploited all over the world by a variety of friendly, but still relatively expensive technologies, some of which are very simple. Solar energy is a diluted and diffuse form of energy, which can be transformed without fearing big accidents, misuse, and military applications. Being not concentrated, solar energy will discourage energy overuse and reduce pressure on the consumption of the Earth's other resources; being diffuse all over the world (Figure 10), it will reduce disparities among the world's nations. Most poor countries have abundant solar energy and development of related technologies can contribute to poverty alleviation.

Can chemistry help in solving the energy problem? YES. The three conversion routes of solar energy (solar heat, solar electricity, solar fuel) require special materials and two of them involve chemical processes. New material systems, guided by the interplay between rational design and experimental screening, can greatly improve the performance of light absorbers, energy converters, and energy-storing systems. Chemistry can play a key role in improving any kind of energy-related technology and can even find novel solutions. Finding a breakthrough for solving the energy crisis is indeed the "grand challenge" of chemistry.[27,28,57]

Will it be possible for all Earth's inhabitants to reach the standard of living of developed countries without devastating the planet? NO. Even if, as expected, the population growth will soon reach a plateau, there are not enough resources for all people to live at the level reached today by developed countries. To keep a decent level of life we will be forced to exploit sunlight for recycling the most important raw materials.

Will science and technology alone take us to where we need to be in the next few decades? NO. Even if science and technology will fully succeed in taking advantage of solar energy, we should never forget that spaceship Earth, except for solar energy, is a closed system and that we are already using the natural capital beyond its regenerative capacity. Therefore, there is a need to reduce our pressure on the Earth and to recycle resources as much as we can, especially in view of population growth. We must become aware that the Earth is not an open place in which we live, but a closed system which we belong to and whose destiny we share.[59]

Should we, citizens of the western world, change our lifestyle and shift to innovative social and economic paradigms? YES. We should change our lifestyle for two reasons. First, the notion of endless economic expansion cannot be maintained because it contradicts the second principle of thermodynamics. Second, we know that our lifestyle, based on consumerism, increases disparities.

In affluent countries we live in societies where the concepts of "enough" and "too much" have been removed. At most, we agree on the need of increasing efficiency of energy consumption. Higher efficiency, however, will not lead us towards the promised land of sustainability because not only is efficiency still consumption, but it can even increase consumption. For example, if we increase energy efficiency of some cars, consumers will presumably use the saved money to buy other items, perhaps more dangerous from a sustainability viewpoint (e.g., faster cars). To live in the third millennium, we need new thinking and new ways of perceiving world's problems. We need to overcome the logic of efficiency and enter a logic of sufficiency to attain ecological stability.[60]

"In affluent countries the concepts of 'enough' and 'too much' have been removed."

Can people of poor countries improve their well-being? YES, they can.

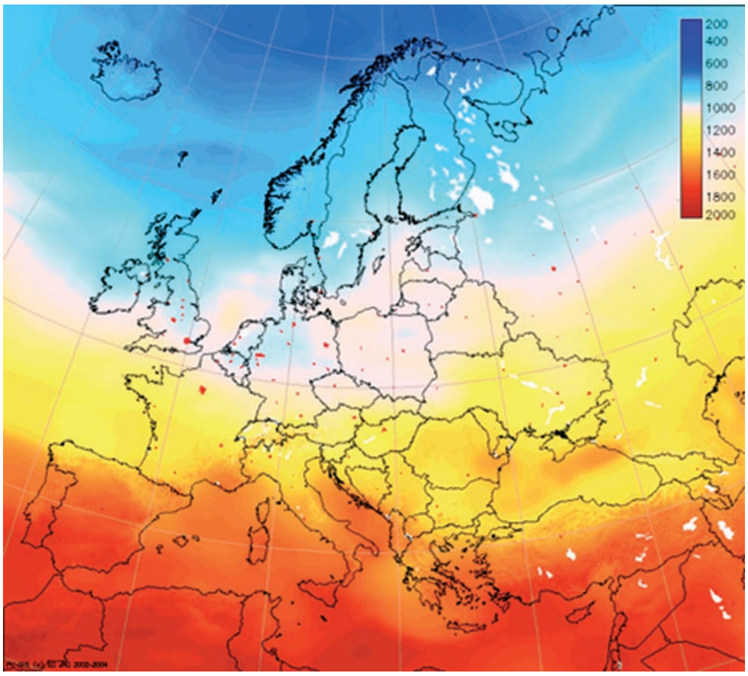

Figure 10. Yearly sum of solar irradiation on horizontal surface in Europe in $kWh\,m^{-2}$; there is only a factor of 1.6 between the values for Rome and London (data from European Commission Joint Research Center). Isolated red dots are major metropolitan areas.

What is not clear is whether we wish to help. To contribute to this effort, we should change somewhat our lifestyle. Between 2002 and 2030, consumption in U.S./Canada is expected to increase by 5.7 mbpd (million barrel of oil equivalent per day) as a result of a population increase of 88 million. By comparison, a population increase in India of 383 million will be responsible for an additional 1.4 mbpd, or an increase in China of 164 million will be responsible for an additional 1.5 mbpd.[61]

To diminish the huge disparity in energy distribution among rich and poor one might propose to stop the growth in affluent countries while raising energy supply to poor countries. This is certainly more realistic than imposing a decrease of energy consumption among rich. Unfortunately, however, this strategy is inadequate because there are not enough resources on the planet for 6.5 billion energy voracious people. Any action to restore equity has thus to focus on lowering the standard of life of the rich while attempting to raise that of the poor.

What we can do as scientists is help developing countries to build their own research capacity for generating appropriate solutions to their specific problems involving energy resources, public health, agriculture, ecology, and basic education. Providing modern energy services is crucial for the eradication of extreme poverty as called for in the UN Millennium Development Goals.[62]

Conclusion

> *"If our black and nervous civilization, based on coal, shall be followed by a quieter civilization based on the utilization of solar energy that will not be harmful to progress and to human happiness"*
>
> Giacomo Ciamician

Prompt global action to solve the energy crisis is needed. Such an action should be incorporated in a more general strategy based on the consciousness that the Earth's resources are limited. The first step of this strategy is to drastically reduce consumption of fossil fuels. This is a task that mainly concerns the affluent countries, where a wrong model of life ignores any limit, dissipates enormous amounts of resources, produces huge quantities of waste, and causes an intolerable increase in disparity among the world's nations. The second step is to launch, without any further delay, a massive and concerted plan for research and development of renewable energies. This is again a task of developed countries where most of scientific research is currently performed.[63] The various forms of renewable energy should be carefully considered on the local scale. As technology improves, it will become easier for each community and each country to exploit the renewable energies available in its territory and to have a more and more diversified energy portfolio.

Political leaders of all nations should put energy as the number one priority in the agenda. The way out of the fossil-fueled civilization is indeed a global problem, bristling with difficulties. Since it will take a long time, any further delay will increase our responsibility towards future generations.

Scientists have to provide the technological advancements to make energy transition a reality, but not only that. They have the moral duty to inform the general public of the urgency and complexity of the energy problem and they must speak up with politicians on a key issue: the energy conundrum must be framed on a longer temporal perspective than that of political careers. Scientists, who are well aware of the consequences of the Second Principle of Thermodynamics, should also convince economists and politicians that sustainability requires that we reject the notion of endless economic expansion.[64]

> ***"Scientists have the moral duty to inform the general public of the urgency and complexity of the energy problem."***

Let us not forget that there is no renewable power source on Earth that can beat our wastefulness and ignorance. Each nation, community, and even every single citizen should identify thresholds of real needs. Consuming resources above such a threshold is not a necessary condition for a successful society and prevents the construction of a peaceful world. Indeed, the ultimate strategy to cope with the future is learning to say "enough". Initially it may be difficult, but living on the Earth believing that there is no need for the concept of "enough" is already quite risky and will clearly become impossible in a few decades. Perhaps most people, including politicians, will understand this "enough" if explained by responsible scientists.

The energy crisis is a challenge, but, indeed, also an opportunity. It offers a precious chance to become more concerned about the world in which we live and the society that we have constructed. It is actually an opportunity for scientists to take an active role in protecting the Earth and helping to change what is wrong in our social and political organization, beginning with the huge disparity between the rich and the poor. We are well aware that the stability of human society decreases with increasing disparities. Ronald Reagan's trickle-down approach to the world problems does not work and, if things do not change, sooner or later the poor will rise up against the rich. We try to set aside the problem of disparity, but in the long run it cannot be eluded. The fragile spaceship Earth is in our hands. Are we wise enough to develop, beside science and technology, a civilization capable of reducing disparity and creating a more peaceful world? Besides wise politicians, we need concerned scientists capable of knowing whether where we are going is the right place for us to go.

> ***"The Earth is in our hands. Are we capable of reducing disparity and creating a more peaceful world?"***

Of course, new energy sources may be found in the next decades, since science and technology will continue to advance. Nuclear fusion, if successfully exploited, could solve the energy problem at the root. Unfortunately, however, we cannot rely on what is presently unknown. Reducing energy consumption and using renewable energies are options already available. Someone may find the expansion of solar technologies unrealistic. In this regard, it is nice to recall that horse traders laughed at the first automobiles, shortly before going out of business. "Mainstream forever", namely new gas and oil explorations, seems to be the most audacious recipe of many analysts for the energy crisis. They sound like dinosaurs in a world under continuous evolution and are reminiscent of the 1970s information technology gurus, who did not even imagine the personal computer era.

We would like to close this Essay with a few comments on the role of our continent, Europe. The EU regions enjoy the highest quality of life but are the poorest as far as conventional energy reserves are concerned.[56] Oil production in the North Sea peaked in late 1990s and is now inexorably declining. Norway and Britain the greatest European oil producers, possess a mere 1.2 % of the world's proven oil reserves. The

"If a prompt action to energy transition is needed for the world, it is simply imperative for Europe."

combined gas reserves of Norway and the Netherlands, account for just 2.1 % of the total. The situation is not better with coal, with Germany and Poland holding 2.3 % of the world's recoverable amount. It might sound distasteful to some nuclear energy supporters, who talk about "energy independence", that not a single European region is listed among uranium and thorium reserve holders. If a prompt action to energy transition is needed for the world, it is simply imperative for Europe.

Given the scarcity of conventional energy resources, energy conservation is mandatory for Europe: we must make use of our limited energy resources in a smarter way. Just an example: to get one unit of light service by using a traditional tungsten lamp, we feed a power station with 100 units of primary energy, simply wasting 99 units as heat in the electricity production/transmission and in the bulb itself. We can perform better by using combined heat and power facilities (CHP)[65] and shifting progressively to solid-state lighting.[66]

Renewable energies are fairly well distributed all over the world, including Europe. As an average, solar power is only 1.5-times higher in Italy than in Germany (Figure 10). Europe must strengthen its role as world leader in renewable energies. Today we need to buy energy resources from other continents, tomorrow we must be able to share and sell our energy know-how to the rest of the world. Our European institutions give us the hope that this can be done in the framework of fairer international relationships than those established during the present oil era. Europe must lead the way for a real, albeit gradual, *structural economic reform*: passing from the intensive use of non-renewable energy resources (fossil fuels) to the use of the abundant, inexhaustible, less harmful primary energy source provided by the Sun. Our continent has the intellectual, cultural, and economic resources to lead this crucial endeavor.

European universities have a most important role in creating a new generation of conscious and responsible citizens who feel active members of society,[67] according to the strategic objective of the Council of Europe meeting in Lisbon (2000): "*to become the world's most dynamic and competitive knowledge-based economy capable of achieving a sustainable economic growth with new and better jobs and a greater social cohesion*".[8] Values such as consciousness, compassion and care have to be the roots of such a knowledge-based economy. And if the diluted nature of solar energy will force us to substantially modify our way of living, this will not necessarily mean that our lives will be less enjoyable in a more peaceful world. Certainly the existence of billions now underprivileged will be better than right now.

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[64] A reviewer has criticized this essay stating that "It does illustrate the idea that scientists should not be allowed to write about economics or public policy: they know a few of the words, but none of the music". We wonder which words and music the economists and politicians know who insist on the need to increase the gross domestic product (GDP) of developed countries when it is known that this does not make people happier (see, for example, D. Kahneman et al., *Science* **2006**, *312*, 1908–1910) and without considering that increasing GDP means increasing the consumption of resources, mostly taken form poorer countries, and accumulation of waste that is immediately distributed to the whole world (e.g. carbon dioxide) or later directed to poor countries (e.g. electronic waste). The mounting concern about the massive environmental degradation and related social unrest of the so-called world's factory, China, should prompt deep reflections in this regard.
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