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Sustainable Chemistry for Energizing the Planet**

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Energy policies have become major societal issues worldwide, and the urgent building of a new world without fossil fuels is imperative for the following reasons: 1) The supplies of these fuels are finite and one could make better use of them for chemicals production rather than burning them; 2) climatologists have placed the responsibility of climate change exclusively on the combustion of fossil fuels; 3) in the context of an economic crisis, the huge energy invoice requires both drastic energy savings and efforts to guarantee more energetic independence; 4) people identify with stronger environmental values that call for the use of cleaner and renewable sources of energy. As a result, today there is an unprecedented global consensus that an energetic transition, not to say a revolution, is urgently required. The transition can be defined as the process by which all fossil fuels (and nuclear energy) are replaced by renewable energies; primarily solar and wind energies but also hydropower, biomass, and geothermal energy. The main question is thus: how can we achieve this transition in the shortest time? There are two major obstacles, one political and the other scientific, for achieving such a quick change.

With regard to political challenges, while a global action would be most appropriate, international differences in economic systems, historical development, and social concerns have proven that a homogeneous answer is difficult, if not impossible, to find. This is reflected in the poor outcomes of the scheduled international climate summits (the next one will be held in Paris at the end of 2015) and in the increased consumption of fossil fuels, despite strong and repeated recommendations to the contrary. China has the obligation to provide heat and electricity at the cheapest price to more than one billion inhabitants; France has built its economy on cheap electricity based on nuclear energy; as the first producer of coal in Europe (and first for lignite in the world), Germany strongly relies on fossil fuels; and the United States is in the midst of recovering economic growth thanks to the exploitation of their own shale gas. At the same time, emerging countries are justifiably reluctant to compromise their economic growth and social progress through efforts that the developed countries mentioned above have not made.

The second obstacle to a quick transition is related to the huge complexity of the scientific and technological questions to be answered. Some individuals feel that this is not such a demanding challenge, and governments, under the pressure of ecological activists, pretend that the seven billion humans (soon to be nine billion) on Earth will live on renewable energies within the next 30 years. They incorrectly suggest that technologies are already available and only have to be scaled up, and that no funding for research and development is needed. The result might be both a huge waste of money and the great disappointment of many people.

As a chemist working with a group in the field of (bio)catalysis for new energy technologies, first at the Commisariat à l'Énergie Atomique et aux Énergies Alternatives (CEA; French Alternative Energies and Atomic Energy Commission) in Grenoble and now at the Collège de France in Paris, I have to tell that which I strongly believe is the truth. Firstly, the energy transition will take more time than expected. Secondly, it requires huge research efforts in many different challenging directions. Thirdly, no populist or even demagogic decisions should be taken by governments, including decisions with regards to the "old" technologies (fossil fuels, nuclear energy). Whilst a day will come when humanity will get rid of those technologies, paradoxically, they now contribute to the advent of the sustainable world, as they encourage cheaper energy prices and the competitiveness of the industry. This view is not pessimistic, it is just realistic.

At the same time, I also feel extremely enthusiastic, as do all my colleagues working in this field. The necessary energy revolution is opening fantastic perspectives and spectacular challenges to address. Converting dilute and intermittent renewable energies into electricity or fuels, storing these energy vectors with high yields, improving combustion efficiency, saving energy in buildings and factories, developing new technologies for the salvaging and recycling of materials and elements, as well as capture of carbon dioxide are not trivial issues. They provide scientists with a unique opportunity, if they are given enough time and money, to further

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increase our basic scientific knowledge areas such as material sciences, electrochemistry, photochemistry, catalysis, including biocatalysis. To begin to address these challenges, the primary focus should be made on the development of an integrated strategy based on: 1) tight collaboration between academic (universities, research agencies) and industrial research, on which innovation depends; 2) international collaboration avoiding unnecessary competition; 3) interdisciplinary pursuits with new research developments at the interface between chemistry, physics, engineering sciences, and biology. Currently, this integration is unfortunately limited but might be strengthened through both updated scientific training programs and major public investment at the national, continental, and global levels.

In this context, it is important to say that chemistry will play a major role in the success of this energy transition. Chemical innovations will provide the cheap and stable materials that allow the development of economically viable technological devices. New solid semiconductors, molecular photosensitizers, supercapacitors, high-temperature superconducting materials, homogeneous and heterogeneous catalysts, polymers, resins, plastics, and membranes with improved performances, coatings and lubricants, and nanostructured electrode surfaces are currently prepared in academic and industrial chemistry laboratories. These materials are essential for improving building insulation, minimizing energy transmission losses, reducing the weight of cars and wind turbine blades, converting agricultural and forest wastes into liquid or gaseous fuels in high yields, and achieving more efficient solar cells, fuel cells, and electrolyzers (energy conversion), as well as (rechargeable) batteries (energy storage). This is also reflected by the high proportion of papers in *Angewandte Chemie* with these terms in the title in 2013 and 2014 and the recent special issue on commemorating 150 years of BASF that contained several overview articles on these topics.

A nice illustration of the value of chemistry to the development of increasingly efficient materials might be found in the optimization of solar cell efficiencies and costs. Sunlight is an abundant energy source, and harvesting just a small fraction of solar energy and converting into a useful energy vector such as electricity would be enough to indefinitely satisfy the world's energy demand. Thus photovoltaics (PV) will undoubtedly constitute an important component of the world energetic sources. Recently, chemistry has provided new and very promising high-band-gap light-absorbing materials, so-called inorganic–organic metal-halide perovskites, which are poised to revolutionize the PV industry, as they might allow cheap solar cells, with an overall efficiency close to 30%, to appear soon.

The drawback of sunlight is the daily, seasonal, and regional variability of its intensity. If solar energy is ever to be used on the scale of fossil fuels, a method to store that energy is necessary. Nature provides a great example of solar energy storage by using sunlight to convert CO_2 into energy-dense organic compounds (biomass) by photosynthesis. Inspired by this, chemists have recently made fruitful efforts towards the development of artificial photosynthetic systems, thanks to the development of efficient, cost-effective, stable, and abundant synthetic materials, both for sunlight capture (semiconductors) and for catalysts. This strategy has been developed successfully in the form of hybrid PV–PEC (photoelectrochemical) water splitting devices, to store solar energy in the form of hydrogen, a high-energy-density fuel. The next step will be to build up similar devices in which the electrons photo-extracted from water will be used to reduce CO_2 into organic products, which represents "true" artificial photosynthesis.

Even though it is an old institution, established in 1530 by King Francis I, with primary missions of "teaching science in the making" and "Docet Omnia" (in English "teach everything"), the Collège de France in Paris has recently shown its ambition to contribute to the development of the future sustainable world through specific investments in chemistry. The three most recently recruited Professors of Chemistry, whose teams form the Institut de Chimie, all have significant and complementary research projects related to the development of new technologies of energy and were provided renovated and well-equipped laboratories. Clément Sanchez and his group push the frontiers of hybrid (nano)materials, which have applications in photovoltaics and photocatalysis; Jean-Marie Tarascon develops next-generation batteries for electricity storage and applications for electric vehicles and networks by the elaboration of original electrode materials and basic research on the mechanism of redox reactions; my own group, in collaboration with Vincent Artero in Grenoble, is now focusing on bioinspired molecular homogeneous and heterogeneous catalysts, including photocatalysts and biocatalysts, for CO_2 reduction, with the aim to invent novel chemistry that utilizes CO_2 as a feedstock for chemical synthesis of commercially useful chemicals and fuels. We believe that this effort of multidisciplinary integration within a dedicated institute is an appropriate strategy to make the much-needed energetic transition become reality.

Our task is not to foresee the future, but to enable it.
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