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Introduction

During a conference, in May 2003, the Nobel laureate Richard Smalley proposed a list of humanity's top 10 problems for the next 50 years. The list was (i) energy, (ii) water, (iii) food, (iv) environment, (v) poverty, (vi) terrorism and war, (vii) disease, (viii) education, (ix) democracy, and (x) population. This is a quite reasonable list, easy to agree with. The most striking point is that there is essentially one and only one problem, because each issue in the list is tightly correlated to all the others. Take anyone of the problems, and try to find connections to the others. For instance, let us take no. (iii) "food." Energy is needed to produce and distribute food; quality and quantity of water is also related to food production (both for agriculture and farming); environment dictates the quality of food (pollution) and is affected by food production techniques; poverty has much to do with lack of food; terrorism and war brings poverty and famine, and vice versa; diseases might be a consequence of food shortage or food deterioration (food conservation requires energy and education); education affects the way citizens choose and dispose of food; democracy has to do with wealth distribution, including food; and population growth poses an ever rising demand for food. There is one single problem; we can name it *sustainable development*.

In 1990, the world's total energy consumption (as primary power) was about 12 TW, with 5.3 billion people (US Census Bureau, International Database). In 2050, it is expected to be 28 TW, with a population of 8–10 billion people. Although these numbers are subject to large fluctuations, they point out a solid truth: energy demand will keep growing.

Another well-founded evidence is that fossil fuels, oil, natural gas, and coal are doomed to end. In particular, many share the view that the end of the oil era is approaching. The end itself can hardly be questioned, but when it will happen is a matter of debate. The fuel consumption curve is called *Hubbert plot*. Hubbert was a geophysicist working for Shell Oil Company back in the 1960s. His plot describes production of oil (or any other fossil fuel) versus time. It is obtained as a derivative of the logistic curve, $Q(t) = \frac{Q_\infty}{1+e^{A(\tau m - t)}}$, which describes self-limiting growth (for instance, population growth when resources are proportionally reduced). The Hubbert plot $P_\mathrm{H}(t) = \frac{\mathrm{d}Q}{\mathrm{d}t} = AQ_\infty \frac{e^{A(\tau m - t)}}{[1+e^{A(\tau m - t)}]^2}$ is very similar to a Gaussian plot. The rising slope is when new oil wells are localized. The slope slows down when

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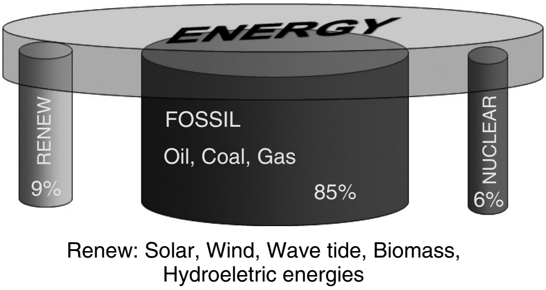

Figure 1.1 The breakdown in energy sources of the world energy supply (2005 data).

discovering new resources gets difficult and the extraction cost increases, to reach the peak. The peak is when half of the available reserves have been used. Decay is expected at the same rate of increase, giving rise to the characteristic symmetric bell shape. In real world, there is no reason for a symmetric shape, because many economic variables might change it, usually giving a slower decay tail. Fitting with true data, the increasing side allows ‘‘predictions’’ on peak and decay, which in 1970 for US oil turned out quite accurate. The peak is when half of the total reserve has been extracted. In 2011, most predictions place the world oil peak around 2040. This is particularly dramatic since oil itself takes about 30% of the energy balance, and including other fossil fuels (gas and coal), the figure approaches 90% (Figure 1.1).

The question of alternatives to oil is thus a hot one for this century. Nuclear energy might be an alternative, provided that hard environmental threats such as the storage of waste, the supply of raw material, and delicate political issues linked to military applications can be kept under control. The discussion among experts about which energy source can be cheaper is unfortunately never a scientific one, but most of the time it is a battle of religion. Each side struggles to support its own business (that could provide jobs, money, and power to the proponents). Having an objective opinion is difficult. While nuclear energy can be a choice for some of the countries with proper geopolitical conditions, it is not a universal solution and most certainly not the stable solution, because it is not renewable. Coal is another intermediate alternative, with its own problems. Coal is available in huge stocks, yet limited, but its use poses a considerable environmental challenge: burning coal produces large amount of carbon dioxide and other green house gases. It is curious to note that the negative effect on the environment of burning coal is seen as a social problem since long time ago. In 1273, King Edward I so spoke to his parliament: *Be it known to all within the sound of my voice, whosoever shall be found guilty of the burning of coal (in London) shall suffer the loss of his head*. This is sometime considered the first antipollution law and, needless to say, it was a very unsuccessful law.

The green house effect is seen as one of the worst challenge to planet stability, so carbon capture and sequestration (CCS) is an issue to be solved if coal has to be used. There is a ‘‘low carbon roadmap,’’ considering the connection between gross domestic product (GDP) and carbon emission, stated in the equation

$GDP = C \times (E/C) \times (GDP/E)$, which regards the increase in economic productivity (GDP) without increasing carbon emission (C). The second term, E/C, concerns the amount of energy produced per carbon emitted, while the third term GDP/E regards wealth over energy consumption. Both should be enhanced, and we need a research and development program aimed at increasing GDP in a carbon-constrained world. The G7 is moderately energy efficient, with about $30 GDP per capita and an energy efficiency of $160 of GDP per billion joule. The United States and Canada are the less efficient in the group. As an example, Russia, Saudi Arabia, and Iran are rather inefficient and low productive (with GDP per capita below $15 000), while in Asia, Philippines and Bangladesh are highly energy efficient but with the lowest productivity and GDP per capita within the top 40 economy (for GDP), with GDP per capita below or well below $5000. The case of the United States is indeed instructive. This rough trend tells us that where large energy stocks are available there is little care for efficiency, in spite of technology and wealth. Nations of the world have a long way ahead to reach sustainable efficiency. Meanwhile, the oil age is near its end. There are skeptics, who do not believe this, because they remind the burst in 1970 that led to nothing. At that time, we had an oil price crisis due to the prediction of extinguishing oil reserves at around 2000. Indeed, nothing happened because new resources were found and extraction technology improved. It is very hard, however, that the same could happen again, for many reasons. The extraction technologies might still improve, yet at exponential growth in the cost. New reserves, based on the present scanning and searching technology that allows looking at the planet as a transparent sphere, simply do not exist.

In summary, three reasons for rethinking our energy strategy are shortage, environment, and demand.

Scientists have an important role in the process of innovating energy strategy. First, break through in basic science is needed. We need new principles for energy harvesting and conversion, new materials, and new concept for devices. Nanoscience and bioscience stay on the forefront and offer the best chance for this innovation. Among the many possible solutions, the more extended use of solar energy plays a big role.

Solar radiation is a huge source of energy, about 170 PW. The average radiation intensity is $1000\,\mathrm{Wm^{-2}}$, which reduces to 10 in cloudy and polluted town atmosphere. Yet, it is estimated that covering 0.16% of the earth's land with 10% efficient solar panels would be enough to produce 20 TW, the expected planet demand around 2050. Solar radiation is the only known, safe, and reliable energy source from a nuclear fusion reactor, the sun. It is a clean energy source with low environmental impact, and it is renewable. Even if shortage of other sources is not an imminent threat, solar energy has many other appealing features to deserve attention from scientist and engineers. As writer Ian McEwan puts it, in his enjoyable novel "Solar," *the stone age didn't end because of a shortage of stones.*

Solar energy can be converted into thermal energy (solar thermodynamic), heating up high thermal capacity materials; it can be used to produce hydrogen and store it away; or it can be directly transformed into electrical energy. Solar thermodynamics is better suited for large plants; hydrogen production may be the future solution but it is still quite immature and difficult to be implemented. Solar photovoltaics are suited for portable energy sources and for local use in domestic or small, remote areas. This is expected to be the next revolution in energy use.

The beginning of photovoltaics is attributed to Alexandre Edmond Becquerel, who discovered a physical phenomenon allowing light–electricity conversion. Willoughby Smith discovered the photovoltaic effect in selenium in 1873. In 1876, with his student R. E. Day, William G. Adams discovered that illuminating a junction between selenium and platinum also has a photovoltaic effect. These two discoveries were the foundation for the first selenium solar cell construction, which was built in 1877. Photovoltaics remained a curiosity till silicon came into play. Early silicon solar cells date back to 1940, but the breakthrough occurred at Bell labs, when Gerald Pearson, a physicist, built, apparently involuntarily, a silicon solar cell with efficiency much higher than that of selenium cells. Improved by two other scientists at Bell – Darryl Chapin and Calvin Fuller – the Bell silicon solar cells could work with 6% efficiency on a sunny day.

This immediately attracted the interest of engineers of the most powerful armies of the time, the United States and Soviet Union, which well understood that such photovoltaic cells were best fitted for powering satellites in the cold war of space race. Curious enough, the first good customer for photovoltaic energy is the oil extraction industry. Photovoltaic cells were used on oil-drilling rigs in the Mexican Gulf for powering safety lights. Perhaps the more intriguing use is, however, in remote areas where grid power will never arrive. As an example, when a great drought hit the region of Sahel, in Africa, in the 1970s, father Bernard Verspieren started a program of photovoltaic water pumping to draw on water from the water-bearing stratum. In 1977, he installed the first of such devices. This is now a worldwide renowned model that became extremely popular. At that time only 10 photovoltaic water pumps were operating. Now there are tens of thousands.

Photovoltaic conversion and solar photoinduced water splitting to produce hydrogen bears a common ground in physics, and this book deals with such a scientific background. By and large, photovoltaic conversion regards seven processes (Figure 1.2), and considering particularly third-generation cells, we can name them as (0) light harvesting, (1) light absorption,(2) excited state thermalization, (3) energy diffusion, (4) charge separation, (5) charge transport, and (6) charge collection.

Each of these steps needs to be deeply understood and can be optimized, engineered, or innovated. Point (0) regards photonics, (1) regards radiation matter interaction, (2–5) concern material science and solid state physics, and (6) mainly regards interfaces. This book mainly focuses on points (1–5).

What is a book, and why in the time of Wikipedia? Of course, detailed derivations and list of notions are surpassed and obsolete. Perhaps, a simple compendium in which many different concepts and ideas are together, linked by a common purpose, is still useful. For this reason, topics here are discussed in a qualitative way, filtered by personal view. The goal is to provide a simple description, like a back-of-the-envelope description, and one can have that kind of discussion without using formal theory. Suppose a student asks you to explain a phenomenon, or

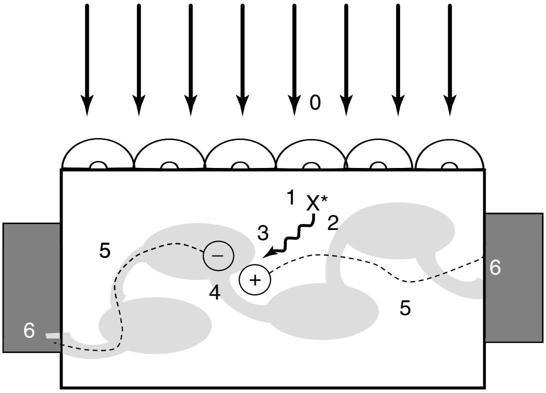

Figure 1.2 The seven processes into which photovoltaic conversion can be split, referring to a polymer bulk heterojunction cell. (0) Light harvesting, (1) light absorption, (2) excited state thermalization, (3) energy diffusion, (4) charge separation, (5) charge transport, and (6) charge collection.

you are in the laboratory and need to grasp the concept of the experiment you are doing. There is no time or space for a full theoretical derivation, yet it might be important to grasp the fundamental concept and evaluate orders of magnitude of the involved quantities. For instance, during a pump probe experiment you see triplet–triplet absorption, and knowing the triplet absorption cross section and the singlet bleaching you can estimate the formation rate and thus conjecture on the spin-flip mechanism. Reading this book should provide tools for assignment and evaluation of phenomena and an insight into the fundamental phenomena that are taking place.