

Protecting Environmental Sustainability by Use of Energy Materials

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Abstract. In the 21st century, ever increasing energy and environmental problems such as pollution, fossil fuel depletion and global warming are ringing the alarm bell to human society. Therefore, clean and renewable energy materials as well as their devices are urgently demanded. In this paper, we first give the definition of environmental sustainability, then the forms of energy sources and its sustainability and environmental impact are discussed. Finally, the main characteristics of hydrogen storage as well as carbon materials and solar energy materials are expounded.

Introduction

Since the beginning of the 21st century, our world has changed dramatically. Many of the most dire predictions about fuel supply and environmental impact forecasted a generation ago are beginning to come true much more quickly than we thought possible. Environment, energy and materials constitute a trinomial combination of special relevance for the sustainable development of our society. We cannot ignore the environmental effect derived from the use of fossil fuels, mainly from transport, energy production, and industry. In this context, materials and, especially, carbon materials play an important role in both the abatement of hazardous emissions from the use of fossil fuels and the development of new clean technologies for energy production [1].

Material and energy flows are closely intertwined in social metabolism. First of all, materials are important energy carriers. Materials form by far the largest fraction of all primary energy inputs: biomass in the form of food and feed is the primary energy source for human and animal work; wood, coal, oil, and natural gas are fueling combustion processes and uranium is used as fuel in nuclear power plants. Vice versa, this means that a significant fraction of all the materials extracted by humans is converted into energy. This changed with the industrial revolution and the new possibilities of energy conversion, which boosted not only the overall amount but also the variety of materials used in the economy. Meanwhile, more than half of all extracted materials (roughly 32 Gt) are not converted into energy but serve as the material basis for stocks of artifacts.

Moreover, using materials inevitably involves considerable quantities of energy: energy is needed for all activities involving materials. Energy has to be invested to extract raw materials, to transport them, and to mechanically work or chemically transform them. All technologies to transport, convert, and store energy and to provide the requested energy services involve materials and material artifacts. Hence, energy and materials simply are two sides of the same coin [2].

A Definition of Environmental Sustainability

First of all, it should be noted that *sustainability* is about *continuity* and *development* is about *change*. There are many things about life that we want to sustain and many that we want to change. So it makes sense to create the notion of 'sustainable development' that combines desired change and desired continuity. For example, we might change exploitation, unhappiness, poverty, destructiveness, etc. and sustain the rest of nature, trust, tolerance, honesty, happiness, health, etc. Treated in this way sustainable development doesn't have to be an oxymoron.

Use of the word "environmental" quite often tends to be associated with some kind of human

impact on natural systems. This context distinguishes it from the word “ecological,” which can be characterized as a concept of interdependence of elements within a system. Hence, it seems reasonable to view “environmental” as a subset of the broader concept of “ecological,” i.e., the intersection of human activities and ecological systems[3-5].

Then, environmental sustainability becomes a subset of ecological sustainability. Broadly speaking, this concept of “environmental sustainability” might be seen as adding depth to a portion of the meaning of the most common definition of sustainable development, i.e., “meeting the needs of the current generation without compromising the ability of future generations to meet their needs,” by taking on the general definition “meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them.” [6]

More specifically, environmental sustainability could be defined as a condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity.

Sustainability of an Energy System

It has been pointed out that an energy system is sustainable if it complies with the following criteria[7-8]: (a) the *Energy Ratio*, calculated as the energy source output divided by the energy source input, is higher than one; (b) the marginal increase in the energy source input produces proportional or more than proportional marginal increase in the energy output; (c) no negative externalities are incurred by the use of such energy source, or such externalities are more than sufficiently compensated.

The first criterion indicates that the quantity of the energy generated during the process is larger than the amount of energy invested. The second suggests that, when the input is augmented, the output is increased as well at least proportionally. Finally, this energy system should be socially acceptable without causing any negative environmental impact, such as air, soil and water pollutions, deforestation, the increase of the amount of acids in the ocean, etc. Any energy system that does not meet these criteria cannot be considered sustainable, will be highly inefficient and even cause damages to the environment and mankind.

Fortunately, many renewable energy sources are able to satisfy these prerequisites. However, they are also characterized by their volatile performance, meaning that the amount of energy yielded can vary significantly within a very short period of time. For instance, the intensity of solar radiation reaching the ground can change within a day, during a week or a month, depending on the time of the day, the solar elevation angle and the meteorological conditions. The wind and other renewable sources unfortunately share the same volatility. Therefore, an economy intended to rely on this type of sources should tackle this daily and seasonal unevenness and smooth the fluctuations of the energy supply in order to provide a more reliable and programmable energy production structure. The solution lies in efficiently storing the energy produced and managing its distribution to the grid and to the final user. There are many different methods of energy storage available and hydrogen is a highly-advantageous and competitive option[9].

Energy Sources and Environmental Impact

The Sun provides energy to the Earth in the form of electromagnetic radiation. Such energy interacts with the Earth’s ecosystem and is transformed into different forms, such as biochemical energy accumulated in the organic systems and the potential energy stored in the movements of air or water masses[1]. Solar energy is also at the origin of most of the renewable energies: hydroelectric, wind mills, solar cells, biomass, etc. Only nuclear plants can deliver large amount of energy not originating from sun. Other types of energy are available from the planet itself or from the gravitational interaction with the Moon (see Table 1).

Table 1 Origins of Types of Renewable Energy Available on Earth

Origin	Energy	Type
Sun	Electromagnetic	Radiation (thermal and photovoltaic) Potential(water cycles) Potential(wind, waves) Biochemical (biomasses)
Earth	Radioactivity	Thermal
Moon	Gravitational	Potential (tides)

From a thermodynamic point of view, the sources that produce minimum entropy per energy unit are gravitational forces, nuclear fusion and solar radiation. These energies are manifested on Earth in the forms of electromagnetic energy, wind and tidal movements, oceanic thermal exchanges, marine currents, water cycles, geothermal sources, biomass and nuclear fusion. All of them generate limited environmental impact and possess considerable potential which has not yet been fully exploited on a large scale.

Up until now the world has obtained most of its energy from the combustion of fossil fuels. Such combustion produces by-products which cause severe pollutions of air, soil and water sources. It also emits billion tons of CO₂ into the air per year, together with other harmful substances like nitrogen and sulphur oxides. CO₂, when freed in the atmosphere, prevents the heat accumulated on the Earth's surface from being released into the space and creates a harmful greenhouse effect. The Intergovernmental Panel on Climate Change has predicted that for the next 100 years the average temperature on the planet will rise by between 1.4% and 5.8%, specifying that the emission of climate-altering gas is the most probable cause for such increase[10].

One solution that prevents the CO₂ from being accumulated in the atmosphere is to capture the released gas with the sequestration technology[11]. However, there is still much room for improvements for this difficult and expensive procedure. First of all, the current emission of CO₂ has been confirmed to be around 6 Gt per year, while to stabilize the current climate condition this volume needs to be reduced to 2 Gt per year. The sequestration technology will need to become operationally mature enough to process such amount each year. Furthermore, on the economic side, casting aside the possibility of generating revenues, this technology entails rather high costs that no business would be willing to sustain if not supported by some governmental incentive policies. In order to find a more attractive and revenue-generating solution to the problem of CO₂ sequestration, it has been suggested to use carbon in a more productive way: instead of storing the carbon in an ever growing volume on a permanent basis, it can be used as a raw material for construction purposes, so that each energy production plant can be regarded as an open-air coal mine of its own.

A Hydrogen New Energy System

Hydrogen is the lightest and most abundant element in the universe. The overall amount of hydrogen on earth is around 0.74 wt%; it is mostly bound in water and carbon-based materials, like plants, natural gas or crude oil. Due to its high enthalpy of combustion (-286 kJ mol^{-1}) and the absence of any environmental hazardous gases released from combustion, hydrogen is an attractive alternative as a secondary energy carrier. Future challenges of a hydrogen-based energy economy include the production, distribution and safe storage of hydrogen[12]. Hydrogen can be produced from a number of different sources and by a variety of methods. These include electrolysis of water, steam processing using natural gas, water splitting with thermo-chemical processes utilizing concentrated solar power or the production of hydrogen using certain species of algal. Large-scale distribution of hydrogen can be achieved by putting hydrogen gas under pressure in pipelines and high-pressure gas tanks, or alternatively using hydrogen in liquid form in super-insulated tank systems. One of the most important aspects is the safe storage of hydrogen for use by consumers in electronic devices, automotive applications or for heating and burning processes.

Like electricity, hydrogen is an energy carrier capable of storing energy converted from the primary sources such as natural gas, oil, coal, nuclear reaction and other renewable energy sources.

It can be used directly to produce electricity and heat and has the ability to replace hydrocarbon fuels in a wide variety of applications. Also, compared to traditional fuels, hydrogen contains a higher energy density per weight unit, however it has a very low energy density per volume unit.

There are three types of energy sources applicable to hydrogen production: (a) fossil fuels; (b) nuclear energy; (c) renewable energies, i.e. hydroelectric and geothermal energies, biomass, wind energy, photovoltaic and solar thermal energies. The production of hydrogen must avoid using fossil fuels or traditional nuclear energy technology in order to fulfil the third Moriarty-Honnery criterion discussed above[7-8]. Therefore, the remaining third source is the only option with the potential to construct a truly sustainable energy system.

One crucial problem with the implementation of a hydrogen-based fuel cell for applications in cars is the on-board storage of hydrogen. In principle, hydrogen storage in solid-state materials (adsorption or absorption materials) offers an interesting and safe method for the storage of large quantities of hydrogen. However, after more than ten years of intensive research a ubiquitous solution for the on-board storage of hydrogen in the solid state has not been found.

A crucial point for automotive applications is the fast on-board regeneration of the storage material. Materials with very high amounts of hydrogen (for instance AlH_3 , NH_3BH_3) are non-reversible and must be regenerated outside of the tank system using energy consuming chemical methods. During the refilling of reversible hydrogen storage materials (for instance Ti-doped NaAlH_4), large amounts of heat must be compensated for in a short filling time of less than 5 min. For a material with an enthalpy of formation ΔH of about $20 \text{ MJ kg}^{-1} \text{ H}_2$ (typical for many hydrides) the overall amount of thermal load of 100–120 MJ ($5\text{--}6 \text{ kg H}_2$) is produced. This has to be compensated for using high power heat exchanger. Because of cost, volume and weight reasons, this does not seem to be a realistic solution for mobile applications. The drawbacks of using porous materials are their low volumetric density and the requirement of low temperatures (77 K) necessary to produce sufficient storage amounts. With all these drawbacks in mind, the car companies have chosen the 70 MPa high-pressure gas tank as a compromise solution for the first generation of fuel cell cars instead of a chemical solution for the storage of hydrogen. The implementation of a high-pressure infrastructure has a significant impact on the prospective chemical storage systems. Newly developed materials for hydrogen store should be manageable under these restrictive conditions[9,13].

Carbon materials and Solar Energy Materials

The carbon materials are classified into four families, diamond, graphite, fullerene and carbyne on the basis of hybridized sp^3 , flat sp^2 , curved sp^2 , and sp orbitals used, respectively. Each family has its own characteristic diversity in structure and also in the possibility of accepting foreign species[14]. Carbon materials have always played important roles for human beings, charcoal as heat source and adsorbent since prehistorical era, flaky natural graphite powder as pencil lead, soots in black ink for the development of communication techniques, graphite electrodes for steel production, carbon blacks for reinforcing the tires in order to develop motorization, membrane switches for making computers and control panels thinner and lighter, etc. In electrochemistry, electric conductive carbon rods and carbon blacks support the development of primary batteries; a compound of graphite with fluorine, graphite fluoride, improved the performance of primary batteries; and the reaction of lithium intercalation/deintercalation into the galleries of graphite was greatly promoting the development of lithium-ion rechargeable batteries. Carbon nanotubes and fullerenes developed recently are promoting the development of nanotechnology in various fields of science and engineering. Carbon materials are predominantly composed of carbon atoms, only one kind of element, but they have largely diverse structures and properties. Diamond has a three-dimensional structure and graphite has a two-dimensional nature, whereas carbon nanotubes are one-dimensional and buckminsterfullerene C_{60} is zero-dimensional. Fullerenes behave as molecules, although other carbon materials do not. Graphite is an electric conductor and its

conductivity is strongly enhanced by AsF_5 intercalation, becoming almost comparable to metallic copper, whereas diamond is completely insulating. Diamond which is the hardest material is used for cutting tools, and graphite is so soft that it can be used as a lubricant.

Solar cell technologies can be divided into three generations. The first is the established technology such as crystalline silicon. The second includes the emerging thin-film technologies that have just entered the market, while the third generation covers future technologies, which are not yet commercialized[15].

- **First Generation:Crystalline Silicon (c-Si)** The first generation includes established technologies. Silicon-based systems make up around 90% of the current PV market and most are manufactured in Europe and Asia. The raw materials (silicon wafers) are expensive, shortages have had a massive impact on price, and high purity is required, therefore over half the cost is that of the silicon wafers. Nonetheless the cost per watt has decreased exponentially over the last few decades, leading to module retail prices of around $\$4.45 \text{ W}^{-1}$ in the USA.

- **Second Generation:Thin-Film Technologies** Thin-film technologies are becoming a competitive class of PV, doubling production from 2006 to 2007. The majority is produced in the USA where investment in alternative thin-film technologies is highest, but China should soon overtake the USA in terms of production capacity. It is expected that the growth in these alternative technologies should exceed that of c-Si over the coming years. The advantages of thin-film solar cells include the ease of manufacture of large areas at lower cost, a wider range of applications including building integration, higher battery charging current, attractive appearance and a range of possible deposition techniques resulting in the ability to assemble devices using flexible substrates. Materials that are suitable for thin-film PVs must have direct band gaps (high extinction coefficients) and maintain good electronic properties in polycrystalline form.

- **Third Generation:Nanotechnology/Electrochemical PVs** Despite improvements in efficiency and the increase in demand for renewable sources of electricity, solar power currently supplies only 0.1% of the primary energy demand. This can be attributed to the high installation cost of PV systems, 50% of which is the cost of the module. Solar electricity tariffs cost around three to five times that of conventional residential electricity tariffs, yet grid-connected systems are the highest growing applications. To compete with c-Si in this market, the next generation of solar cells should perform close to maximum efficiency over a range of light conditions and temperatures, have good long-term stability and, in order to lower installation costs, need to be durable, flexible and attractive so that they can be applied to building integrated PVs e.g. on flexible steel and architectural glass. Photovoltaics is perhaps the fastest growing industry today, with an increase in solar cell production of around 50% in recent years. Silicon type solar cells dominate, holding a market share of about 90%. The so-called second generation, thin-film solar cells are, however, catching up and there are various production lines being set up all over the world.

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