Artificial Photosynthesis - An Odyssey to Sustainable development

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Abstract

Nuclear power seems one of the most promising future energy resource but is it really sustainable bearing in mind its hazardous byproducts? Fukushima nuclear disaster which is the largest nuclear disaster is more than enough to rationalize the side effect of Nuclear power. But Sun which is a tremendous source of energy is nothing else than a massive nuclear reactor and the best approach for clean and sustainable energy will be the Solar energy.

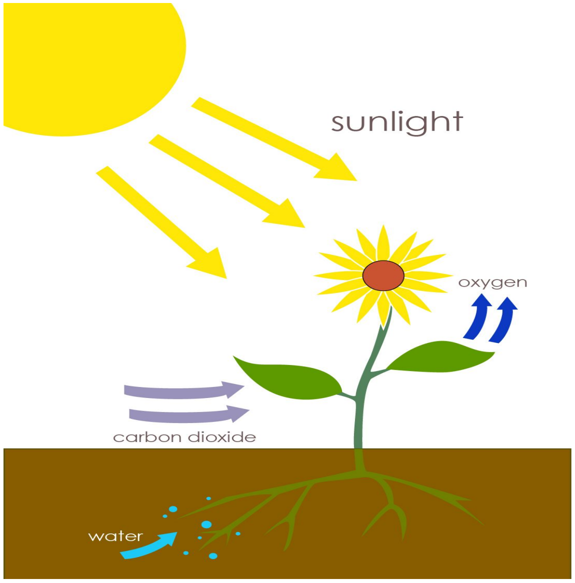
Solar energy which is one of the most prominent renewable energy resource can be harnessed using a range of technologies such as solar heating, photovoltaics, solar thermal energy, solar architecture and artificial photosynthesis. The most conventional and popular technology nowadays is Solar cell. A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity. All the solar cells are semiconductors devices made up of the one of the most abundant element, Silicon but which actually exists in its oxide form. The silicon used in the solar cell must be 99.9999% pure which makes silica inconvenient to use directly in the solar cell. Silicon is extracted by reduction of its silicates by coke at high temperature which is highly energy demanding and environment unfriendly. So it would be an excellent step to switch some other process which is not semiconductor based.

Nature is the most efficient system in this universe and photosynthesis is one of the best exemplars. Photosynthesis is a process used by plants and other organisms to convert light energy into chemical energy that can be later released to fuel the organisms activities. The idea of the paper is to replicate the photosynthesis process for the photoelectrolysis of the water which can give different products like carbohydrates, hydrogen and oxygen. Hydrogen and oxygen produced can be used for the fuel cell which makes the whole process clean, renewable, more efficient as compared to solar cells and it is easy to handle the hydrogen reaction.

Introduction

a) Natural Photo-synthesis

Photosynthesis is a process used by plants and other organisms to convert light energy, normally from the Sun, into chemical energy that can be later released to fuel the organisms' activities. This chemical energy is stored in carbohydrate molecules, such as sugars, which are synthesized from carbon dioxide and water – hence the name photosynthesis. In most cases, oxygen is also released as a waste product.



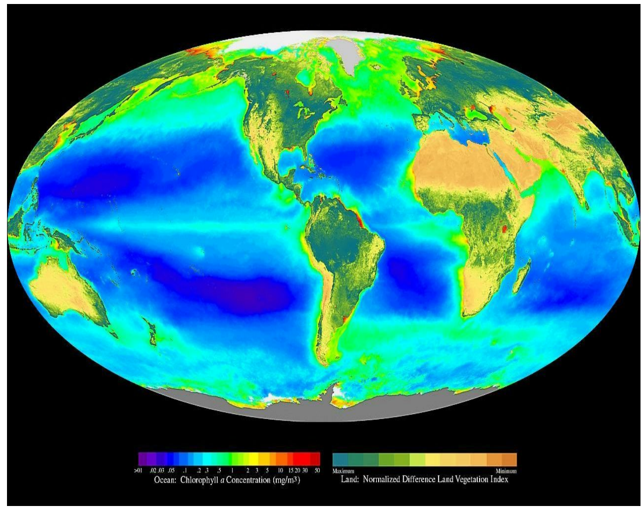


Figure T.1 : Schematic of photosynthesis in plants	Figure T.2 : Composite image showing the global distribution of photosynthesis, including both oceanic phytoplankton and terrestrial vegetation. Dark red and blue-green indicate regions of high photosynthetic activity in ocean and land respectively.

The equation for oxygenic photosynthesis process is:

$$nCO_2 + 2n\ H_2O + \text{photons} \rightarrow (CH_2O)_n + n\ O_2 + n\ H_2O$$

carbon dioxide + water + light energy → carbohydrate + oxygen + water

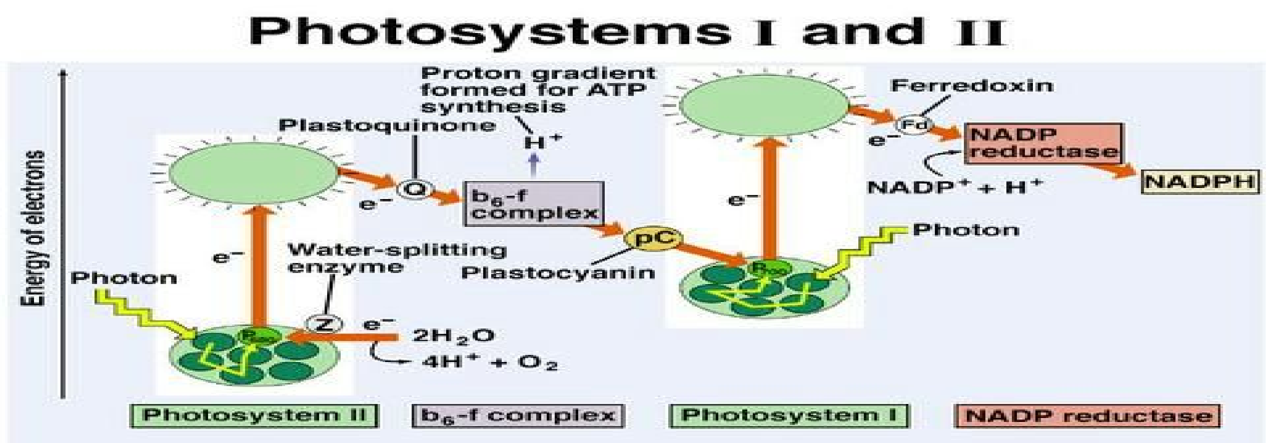


Figure T.3 : Schematic of photosynthesis process in plants

b) Artificial Photo-synthesis

Artificial photosynthesis is a chemical process that replicates the natural process of photosynthesis, a process that converts sunlight, water, and carbon dioxide into carbohydrates and oxygen. The term is commonly used to refer to any scheme for capturing and storing the energy from sunlight in the chemical bonds of a fuel (a solar fuel). Photocatalytic water splitting converts water into Hydrogen Ions and oxygen, and is the main research area in artificial photosynthesis. A Light-driven carbon dioxide reduction is another studied process, replicating natural carbon fixation.

The photosynthetic reaction can be divided into two half-reactions (oxidation and reduction), both of which are essential to producing fuel. In plant photosynthesis, water molecules are photo-oxidized to release oxygen and protons. The second stage of plant photosynthesis (also known as the Calvin-Benson cycle) is a light-independent reaction that converts carbon dioxide into glucose. Researchers of artificial photosynthesis are developing photocatalysts to perform both of these reactions separately. Furthermore, the protons resulting from water splitting can be used for hydrogen production. These catalysts must be able to react quickly and absorb a large percentage of solar photons.

Whereas photovoltaics can provide direct electric current from sunlight, the inefficiency of fuel production from photovoltaic electricity (indirect process) and the fact sunshine is not constant throughout time sets a limit to its use. Artificial photosynthesis aims then to produce a fuel from sunlight that can be stored and used when sunlight is not available, by using direct processes, that is, to produce a solar fuel. With the development of catalysts able to reproduce the key steps of photosynthesis, water and sunlight would ultimately be the only needed sources for clean energy production. The only byproduct would be oxygen, and production of a solar fuel has the potential to be cheaper than gasoline.

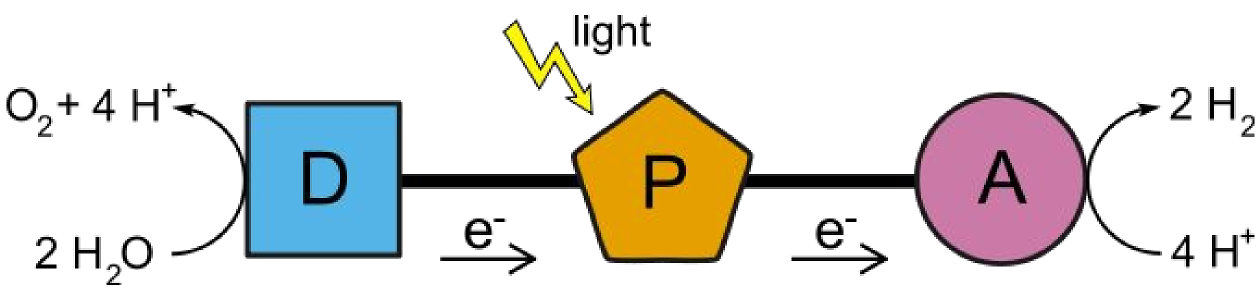


Figure T.4 : A triad assembly, with a photosensitizer (P) linked in tandem to a water oxidation catalyst (D) and a hydrogen evolving catalyst (A). Electrons flow from D to A when catalysis occurs.

c) Fuel Cell and Hydrogen Economy

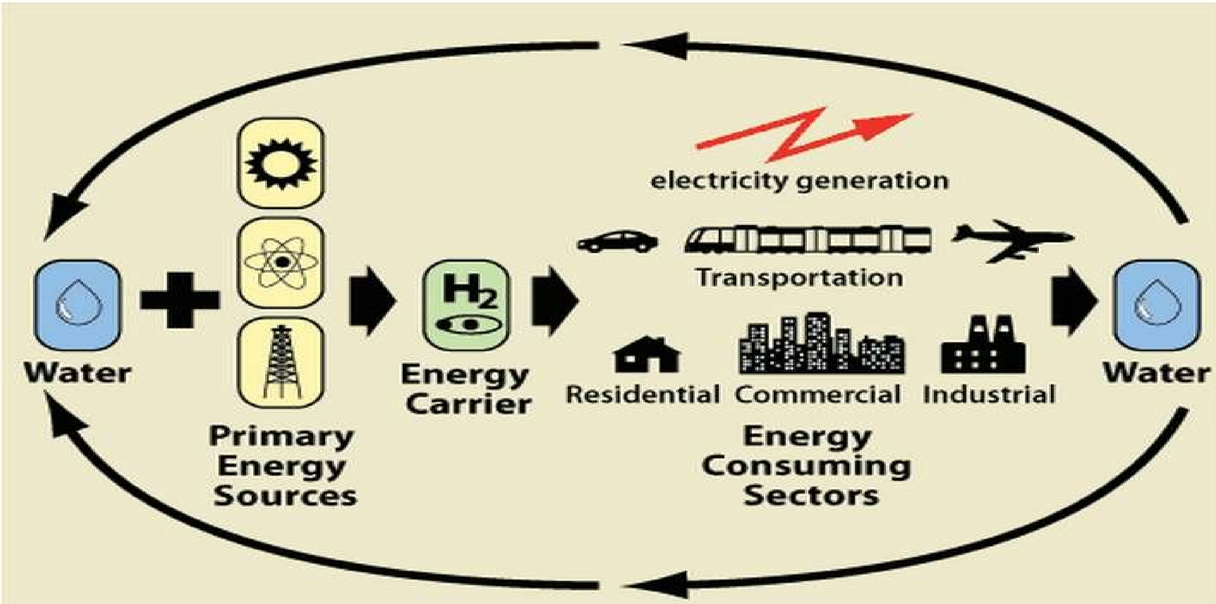


Figure T.5 : Hydrogen Economy Cycle

The hydrogen economy is a proposed system of delivering energy using hydrogen. The term "hydrogen economy" refers to the vision of using hydrogen as a low-carbon energy source. Hydrogen is attractive because whether it is burned to produce heat or reacted with air in a fuel cell to produce electricity, the only byproduct is water. One of the most potentially useful ways to use hydrogen is in electric cars or buses or households in conjunction with a fuel cell which converts the hydrogen into electricity.

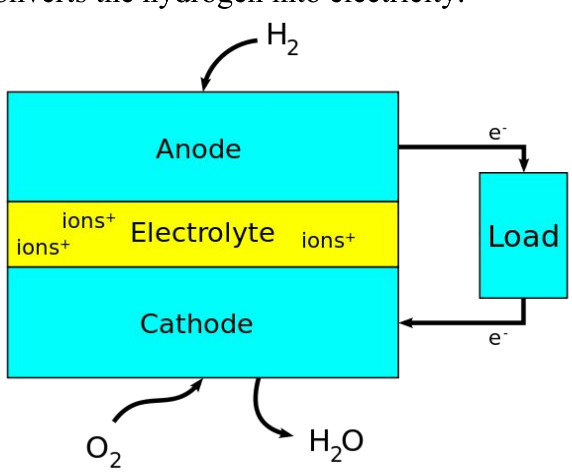


Figure T.6 : Hydrogen Fuel Cell

At the moment, hydrogen is most commonly produced from natural gas. The idea is to produce hydrogen from the artificial photosynthesis by photoelectrolysis of water which would be ultimately harnessing the solar power.

A **fuel cell** is a device that converts the chemical energy from a fuel into electricity through a chemical reaction of positively charged hydrogen ions with oxygen or another oxidizing agent. Stationary fuel cells are used for commercial, industrial and residential primary and backup power generation. Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, communications centers, rural locations including research stations, and in certain military applications. A fuel cell system running on hydrogen can be compact and lightweight, and have no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability.

d) PhotoVoltaics or Conventional Solar cells

Photovoltaics (PV) is the name of a method of converting solar energy into direct current electricity using semiconducting materials that exhibit the photovoltaic effect. The photovoltaic effect refers to photons of light exciting electrons into a higher state of energy, allowing them to act as charge carriers for an electric current.

Solar cell manufacturing requires several thermal processing steps. These processes include, diffusion, drying, firing annealing, deposition, and coating of the solar cell which demands a lot of energy. Solar cells are made up of semiconducting materials having certain characteristics in order to absorb sunlight. Solar cells can be classified into first, second and third generation cells.

The first generation cells—also called conventional, traditional or wafer-based cells—are made of crystalline silicon, the commercially predominant PV technology, that includes materials such as polysilicon and monocrystalline silicon. Second generation cells are thin film solar cells, that include amorphous silicon, CdTe and CIGS cells and are commercially significant in utility-scale photovoltaic power stations, building integrated photovoltaics or in small stand-alone power system. The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaics—most of them have not yet been commercially applied and are still in the research or development phase.

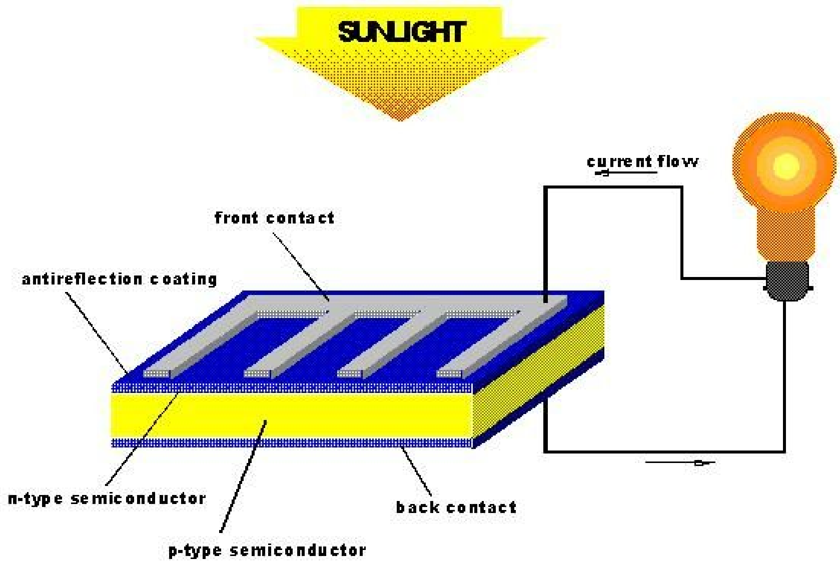


Figure T.7 : Solar cell

A thin-film solar cell which is most commonly used type is a second generation solar cell that is made by depositing one or more thin layers, or thin film (TF) of photovoltaic material on a substrate, such as glass, plastic or metal. The silicon required in solar cells must be 99.9999% producing them is a challenging task. An overview of some of the hazards posed by crystalline silicon (c-Si) PV production technologies - the most common technology found in the solar sector are:

1) Mining of Silicon - As with the production of silicon chips, production of Si wafers begins with the mining of silica, found in the environment as sand or quartz. Silica is refined at high temperatures to remove the oxygen and produce metallurgical grade silicon, which is approximately 99.6% pure. Higher purities are achieved through a chemical process that exposes metallurgical grade silicon to hydrochloric acid and copper to produce trichlorosilane gas. The trichlorosilane is then distilled to remove remaining impurities, which typically include chlorinated metals of aluminum, iron and carbon. It is finally heated or "reduced" with hydrogen to produce silane gas. The silane gas is heated again to make molten silicon, used to grow monocrystalline silicon crystals or used as an input for amorphous silicon.Higher purities are achieved through a chemical process that exposes metallurgical grade silicon to hydrochloric acid and copper to produce trichlorosilane gas. The trichlorosilane is then distilled to remove remaining impurities, which typically include chlorinated metals of aluminum, iron and carbon. It is finally heated or "reduced" with hydrogen to produce silane gas. The silane gas is heated again to make molten silicon, used to grow monocrystalline silicon crystals or used as an input for amorphous silicon.

2) To produce multicrystalline silicon, molten silicon is poured into crucibles and cooled into blocks or ingots. Both processes produce silicon crystals that are extremely pure (from 99.99999% to 99.9999999%),
3) In the silicon supply chain, the production of silane and trichlorosilane results in waste silicon tetrachloride, an extremely toxic substance that reacts violently with water, causes skin burns, and is a respiratory, skin and eye irritant.
4) The extremely potent greenhouse gas sulfur hexafluoride is used to clean the reactors used in silicon production. The Intergovernmental Panel of Climate Change considers sulfur hexafluoride to be the most potent greenhouse gas per molecule; one ton of sulfur hexafluoride has a greenhouse effect equivalent to that of 25,000 tons of CO2. It can react with silicon to make silicon tetrafluoride and sulfur difluoride, or be reduced to tetrafluorosilane and sulfur dioxide. Sulfur dioxide releases can cause acid rain, so scrubbers are required to limit air emissions in facilities that use it.
5) Other chemicals used in the production of crystalline silicon that require special handling and disposal procedures include the following: 1) Large quantities of sodium hydroxide are used to remove the sawing damage on the silicon wafer surfaces. In some cases, potassium hydroxide is used instead. These caustic chemicals are dangerous to the eyes, lungs and skin. 2) Corrosive chemicals like hydrochloric acid, sulfuric acid, nitric acid and hydrogen fluoride are used to remove impurities from and clean semiconductor materials. 3) Toxic phosphine or arsine gas is used in the doping of the semiconductor material. Though these are used in small quantities, inadequate containment or accidental release poses occupational risks. Other chemicals used or produced in the doping process include phosphorous oxychloride, phosphorous trichloride, boron bromide and boron trichloride. 4) Isopropyl alcohol is used to clean c-Si wafers. The surface of the wafer is oxidized to silicon dioxide to protect the solar cell. 5) Lead is often used in solar PV electronic circuits for wiring, solder-coated copper strips, and some lead-based printing pastes. 6) Small quantities of silver and aluminum are used to make the electrical contacts on the cell. 7) Chemicals released in fugitive air emissions by known manufacturing facilities include trichloroethane, acetone, ammonia and isopropyl alcohol.

World Energy Crisis, carbon emission and future energy sources

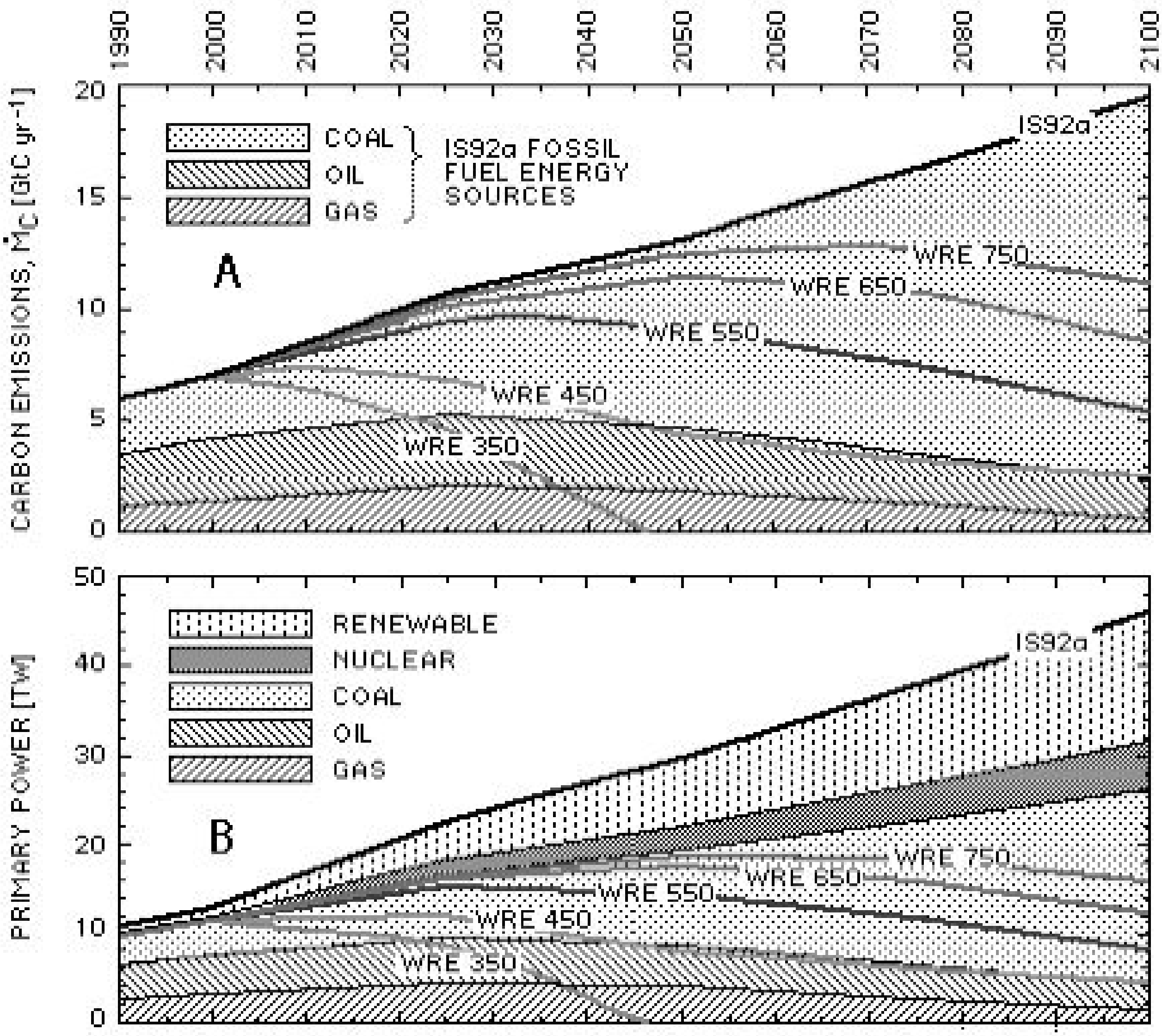
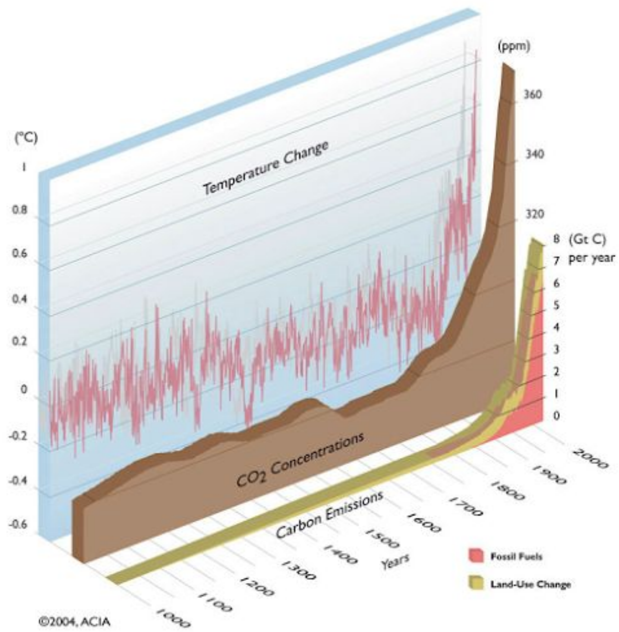


Figure T.8 : Carbon Emission and Primary Power trends



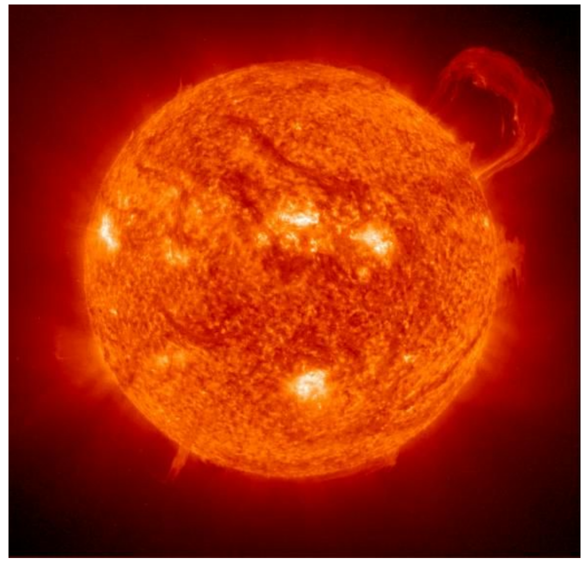


Figure T.9 : Global Temperature Change	Figure T.10 : Solar energy strike Earth per hour = Total human Consumption per year

The future energy requirements are massive and carbon emissions are alarming. The possible future energy sources are nuclear power, Solar power, Wind power, Tidal energy, etc. Nuclear power seems promising but its side effects are fatal. Fukushima nuclear disaster which is the largest nuclear disaster is more than enough to rationalize the side effect of Nuclear power. But Sun which is a tremendous source of energy is nothing else than a massive nuclear reactor and the best approach for clean and sustainable energy will be the Solar energy.

Solar energy which is one of the most prominent renewable energy resource can be harnessed using a range of technologies such as solar heating, photovoltaics, solar thermal energy, solar architecture and artificial photosynthesis.

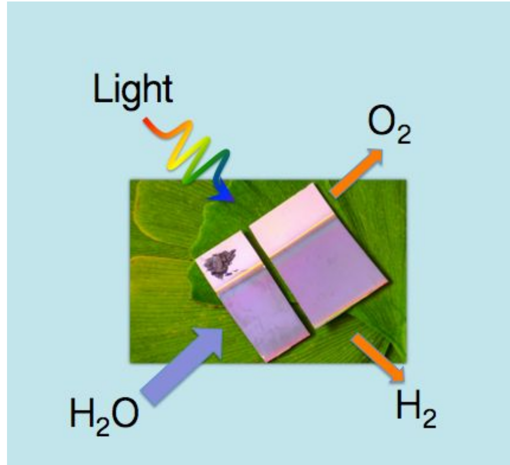


Figure T.11 : Fukushima Disaster	Figure T.12 : Artificial Photosynthesis

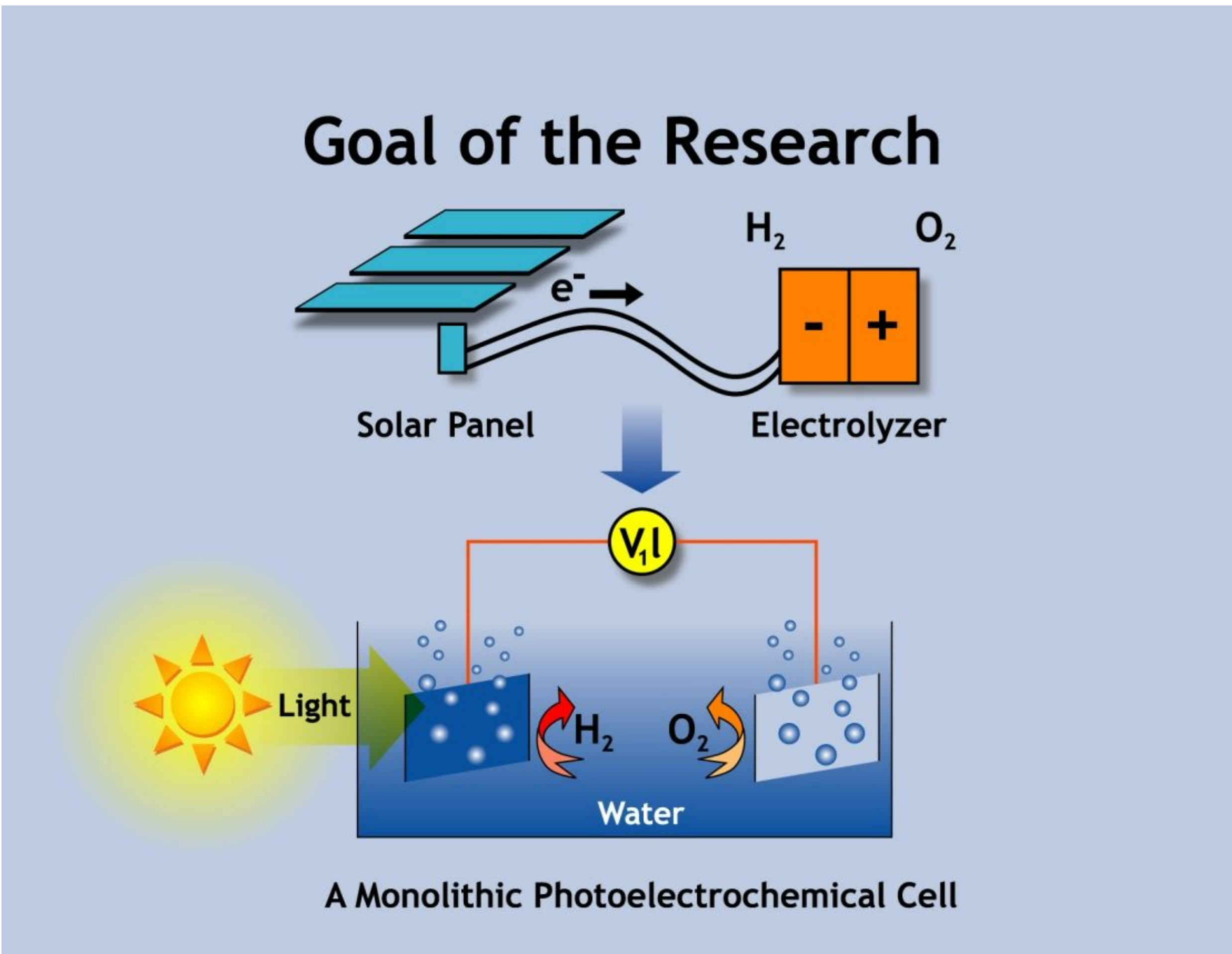


Figure T.13 : Photoelectrochemical-Based Direct Conversion Systems - Combines a photovoltaic system (light harvesting) and an electrolyzer (water splitting) into a single monolithic device.

Artificial Photosynthesis provides several opportunities for clean, renewable, and sustainable energy:

a. We are going someway to mimic nature's most effective process for creating energy rich products from simple input materials.
b. Producing a new fuel that can power vehicles from naturally occurring input materials, CO_2, water and Sunlight
c. It makes Carbon storage more economically viable as the CO_2 can be used to create a saleable product.
d. If we are able to tap into existing big producers of CO_2, such as power station exhaust we are able to use the CO_2 twice before it enters the atmosphere.
e. Energy produced can be stored in form of hydrogen gas rather than the batteries but again Hydrogen storage is not easy.
f. The byproducts of these reactions are environmentally friendly. Artificially photosynthesized fuel would be a carbon-neutral source of energy, which could be used for transportation or homes.

Disadvantages include:

- Materials used for artificial photosynthesis often corrode in water, so they may be less stable than photovoltaics over long periods of time. Most hydrogen catalysts are very sensitive to oxygen, being inactivated or degraded in its presence; also, photodamage may occur over time.
- The overall cost is not yet advantageous enough to compete with fossil fuels as a commercially viable source of energy

Conclusions

Future Prospects

While current artificial photosynthesis methods are far less efficient than the natural process, there has been continual progress in the field. One of the reasons that the technology is being pursued is that, compared to current solar panel technology, molecular nanoparticles are cheaper, lighter, and more environmentally sound. Aside from providing a renewable energy source and eliminating our reliance on rapidly diminishing fossil fuels, it has also been suggested that artificial photosynthesis on a large industrial scale could reverse global warming since the process consumes carbon dioxide and releases oxygen. With the potential of such beneficial impacts on the environment and our energy supply, continued research into combining nanotechnology and natural processes should remain a central goal.