Application of Artificial photosynthesis in harnessing Solar Energy for production of sustainable and Reliable Energy in Nigeria

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Abstract: Securing environmentally sustainable energy supply is one of the key societal challenges which both developed and developing world has in its roadmap. This paper present "Application of Artificial Photosynthesis in Harnessing Solar Energy for production of Sustainable and Reliable Energy in Nigeria". This research will describe the photosynthesis-like process of Daniel Nocera's artificial leaf, which uses solar energy to split water into its components and produces solar fuel (Hydrogen H_2). The description will introduce the photosynthetic process, focusing on photosystem II, explain artificial photosynthesis as regards the artificial leaf's components, and elaborate on the working principle of hydrogen fuel cells. This technology also offer lower-costs over conventional silicon-based solar cells. Usually, solar cells generate current from photons, making electricity which can run things or are stored in batteries. This new and different approach, can store nearly five 5% of solar energy chemically as hydrogen. This artificial photosynthesis, splitting water into oxygen and hydrogen, allows solar energy to be stored in the form of hydrogen, which can then be used as a fuel either directly or in the form of methane, or it can generate electricity in a fuel cell. The research also adds a ray of solar-powered hope. The artificial leaf's photosynthesis procedure is similar to processes utilized by photosystem II in natural photosynthesis. Within photosystem II lies the oxygen evolving complex, which uses photons, or light energy, from the sun to decompose water into hydrogen and oxygen. This process supplies energy for use in later stages of natural photosynthesis. However, instead of storing energy in the leaves of a plant, artificial photosynthesis aims to store the energy produced to power other devices. This energy could then be available at night or on cloudy days

Key Words—*Artificial photosynthesis, Hydrogen fuel cell, Photosynthesis, Photosystem II, water splitting and Hydrogen production.*

Introduction

Climate issues are creating a growing demand for sustainable energy systems based on renewable energy sources with minimal environmental impact. Guaranteed supply is another important demand. The Earth receives a vast amount of solar energy at the rate of approximately 120,000 TW (1 TW = 1012 W) in a highly reliable and distributed fashion. The question is how this solar energy can be transformed simply and cost-effectively into useful forms of energy such as heat, electricity and fuel. Solar energy is unfortunately at a minimum during the winter, when the dark and cold mean of our energy needs are greatest. It is therefore necessary to store the solar energy in a suitable energy carrier. The ability to produce a clean fuel without generating any harmful by-products, like greenhouse gasses, makes artificial photosynthesis an ideal energy source for the environment. It wouldn't require mining, growing or drilling. And since neither water nor carbon dioxide is currently in short supply, it could also be a limitless source, potentially less expensive than other alternative energy type. This research paper aimed at making a detailed technical analysis of the artificial system and how it "[mimics] natural photosynthesis, directly converting solar energy to fuel" [9]. In summary, the artificial leaf accomplishes this through the use of an artificial oxygen evolving complex (OEC) created by Dr Nocera and his research team as presented at the 2011 national meeting of the American Chemical Society.

Hydrogen gas is one of several possible energy carriers. One of its advantages is that the use of hydrogen gas does not lead to the emission of any carbon dioxide. But the current methods for producing hydrogen are based on fossil fuels. An energy-efficient and emission-free way of producing hydrogen would make it one of several interesting energy carriers for a sustainable energy system. This innovation cannot be effectively described without a good understanding of photosynthesis in general.

Photosynthesis

Photosynthesis is the process by which plants, algae and some bacteria store energy from the sun in the form of carbohydrates. These carbohydrates act as fuels: they are either used by the plant, or eaten by plant-eating animals. Photosynthesis is thus the ultimate source of all fuel we use today. Photosynthesis uses water and carbon dioxide as raw materials and oxygen is released as a waste product. It is thus also thanks to photosynthesis that we have the oxygen that we breathe.

For photosynthesis to take place, four major steps are involved and these includes;

- Light harvesting
- Charge separation,
- Water splitting, and
- Fuel production.

Light harvesting is the absorption and 'concentration' of sunlight. The collected light energy is then funneled to the place where charge separation takes place (the so-called 'reaction center'). There, the energy from the sunlight is used to separate positive and negative charges from each other. The positive charges are used to split water into hydrogen and oxygen (step 3). The negative charges are used to produce the carbohydrate fuel from carbon dioxide (step 4).

Revisiting the Solar Energy generation In Nigeria

Indigenous researchers have looked into the availability of renewable energy resources in Nigeria with a view to establishing their viability in the country. Onyebuchi estimated the technical potential of solar energy in Nigeria with a 5% device conversion efficiency put at 15.0×10^{14} kJ of useful energy annually. This equates to about 258.62 million barrels of oil equivalent annually, which corresponds to the current national annual fossil fuel production in the country. This will also amount to about 4.2×10^{5} GW/h of electricity production annually, which is about 26 times the recent annual electricity production of 16,000 GW/h in the country. In their work, Chineke and Igwiro show that Nigeria receives abundant solar energy that can be usefully harnessed with an annual average daily solar radiation of about 5.25 kW h/m^2/day. This varies between 3.5 kW h/m^2/day at the coastal areas and 7 kW h/m^2/day at the northern boundary. The average amount of sunshine hours all over the country is estimated to be about 6.5 h. This gives an average annual solar energy intensity of 1,934.5 kW h/m^2/year; thus, over the course of a year, an average of 6,372,613 PJ/year (approximately 1,770 TW h/year) of solar energy falls on the entire land area of Nigeria This is about 120,000times the total annual average electrical energy generated by the Power Holding Company of Nigeria (PHCN). With a 10% conservative conversion efficiency, the available solar energy resource is about 23 times the Energy Commission of Nigeria's (ECN) projection of the total final energy demand for Nigeria in the year 2030. To enhance the developmental trend in the country, there is every need to support the existing unreliable energy sector with a sustainable source of power supply through solar energy.

How could Solar Energy be stored?

Photosynthesis uses sunlight to create carbohydrates through equation (1) below:

$6CO_2 + 12H_2O + light \rightarrow C_6H_{12}O_6 + 6O_2 + H_2O$ …... (1)

Considering the above reaction, in the presence of sun light, the reaction reduces carbon dioxide to sugar and splits water into its components, generating oxygen (O2) as one of the products. The sun's energy, in the form of ultraviolet light, is necessary to drive this reaction [12]. Nocera's team sought to mimic the first overall step of photosynthesis: the light-dependent reactions of photosystem II. Photosystem II includes reactions fuelled by photons. This photosystem is responsible for splitting water into electrons, electron deficient hydrogen, and oxygen gas [12]. Primarily, the two parts of this process Nocera aimed to reproduce in the lab include converting sunlight to useable energy and splitting water into its components. To understand how the artificial components resemble their natural counterparts, one must understand what goes into the light-dependent reactions that take place naturally inside plant cells.

Photosynthetic Energy conversion – step by step

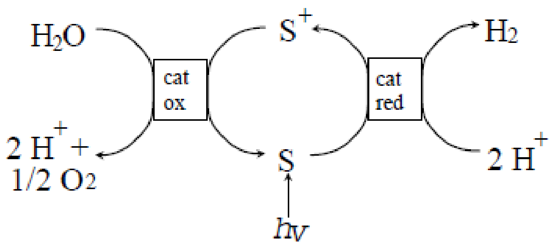
Light is captured by chlorophyll molecules (P). Electrons (e-) move from a manganese complex (Mn) to compounds that accept the electrons (Q). The electrons end their journey in the creation of carbohydrates, with carbon dioxide as a building block. Electrons are extracted from water (H2O),

Photosystem II

Considering the above equation, it works like this: Photosystem II contains chlorophyll molecules that absorb sunlight. When the chlorophyll (P) has been charged with extra energy from the light, it sends electron to electron carriers in the membrane (quinones, Q). The electron "hole" must be filled, and an electron is therefore moved to the chlorophyll from a complex made of manganese ions. The manganese complex (Mn) in its turn extracts electrons from water molecules (H2O) that become attached to the manganese complex. The water molecules are thus split, and oxygen is formed. Water-splitting takes place on one side of the membrane, and the extracted electrons are transported to the other side. The captured solar energy is secured by using the electrons to construct carbohydrates from atmospheric carbon dioxide (CO2). The electrons are the "glue" that holds the carbohydrate molecules together and these electrons are used to reduce protons, creating hydrogen in the form of NADPH, which is the resulting agent produced by the electron transport chain [15].

SPLITTING WATER

As previously stated in equation (1) above, the resulting oxygen is a product of the decomposition of water. The "oxygen-generating reaction" can be written as the following:



$$2H_2O \rightarrow 4H^+ + 4e^- + O_2 \quad (2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Water is stripped of its electrons, or oxidized, and broken up into protons, seen here as their equivalent hydrogen ions, and molecular oxygen, or O_2. This splitting of water is indirectly caused by P_{680}. As the energy previously accepted from the absorbed photon is passed in the reaction centre from P_{680} to the pheopythin molecule, P_{680} becomes oxidized. Oxidized P_{680} is very electronegative, meaning it strongly desires electrons, and can therefore strip them off of a water molecule [18]. This procedure is made possible by nature's Oxygen Evolving Complex (OEC). This complex is what Nocera used to model his artificial OEC and will be explained in detail in the upcoming section

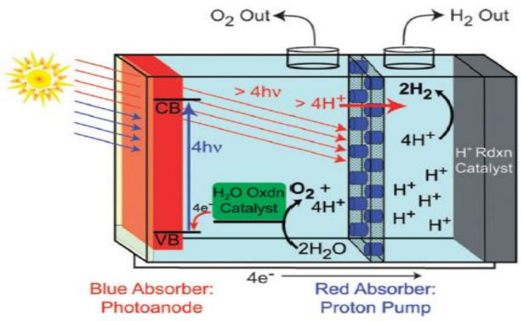


Fig 1.Model artificial photosynthetic water splitter

MIMICKING NATURAL PHOTOSYNTHESIS

In order to reproduce a similar result in the lab, the essential parts of the light-dependent reactions is requires, and these are, chlorophyll and the oxygen-evolving complex. The first step is to create a catalyst that can react with sunlight like chlorophyll does in order to create "oxygen and hydrogen evolving compounds that master water splitting," as in photosystem II [8]. The next step in constructing an artificial leaf is to add these compounds to a light-harvesting semi-conductor. Nocera does this through the creation of

Co-OEC, catalysts and a silicon-based semiconductor. To "stabilize silicon in water," Nocera coats "its surface…with a conducting metal oxide onto which the Co-OEC may be deposited" [8].

"For a synthetic material to realize the solar energy conversion" found in a natural leaf, Nocera states that the material must absorb a photon to "generate a wireless current that is harnessed by catalysts, which drive the four electron/hole fuel-forming water-splitting reaction under benign conditions" [8].

Silicon-Based Semiconductors

A semiconductor is a material whose "conductivity is in the range between that of metals and insulators and increases with temperature" [16]. In semiconductors, the electrons are limited to moving within two areas, the valence band and the conduction band. The valence band is of a lower energy and "is nearly completely filled with electrons," while the conduction band has a higher energy and "is nearly completely empty of electrons" [17]. As a result, the two energy bands are separated by a "band gap" where electrons cannot travel [17]. When there is sufficient energy present, electrons will move to the conduction band from the valence band, leaving holes behind which act as "fictitious…positively charged particle[s]," and travel opposite the electrons [16, 17]. The semiconductor "generates spatially separated electron-hole pairs" [15]. These pairs act as a wireless current, and are then "captured with two catalysts that drive the water-splitting reaction under near neutral pH conditions" [15]. These catalysts are the cobalt and nickel molybdenum zinc catalysts which were explained in the previous section.

In natural photosynthesis, a membrane is needed to separate oxidative and reductive species spatially, thus driving chemical reactions that can also produce electricity.

Photo-electrochemical cells (PECs) utilize this same principle of converting solar energy into electricity in solar cells [9]. In the artificial leaf, light activates the semiconductor, which then acts as a photo-catalyst, absorbing sunlight and exciting electrons, akin to the photons exciting electrons in chloroplasts. This excited electron travels to the conduction band of the semiconductor, leaving behind a positively charged hole in the valence band. The electron-hole pair generated by an electric charge goes to the surface of the anode, the negative end of the semiconductor adjacent to the

Co-OEC catalyst. With an electric field present, the holes and electrons are forced to move in opposite directions. The positive current produced by the holes deposits the oxygen at the anode side and the negative electron current carries the molecular hydrogen to the cathode side [17].

The processes that the semiconductor is responsible for are fundamental to the functioning of the cell. These include "light absorption, excited state electron transfer, separation of electron transfer-generated oxidative and reductive equivalents…electron transfer of activation of catalysts for

Mulit-electron, muli-proton solar fuel half reactions, and separation and collection of the products" [18]. It is also expected to do all of this without degradation or decomposition, limiting the selection of possible materials greatly [18]. One material that can perform the required tasks is silicon.

CONSTRUCYION OF ARTIFICIAL LEAVE USING SILICON

Silicon is an ideal construction material for the artificial leaf because it is earth-abundant and already popular in the electronics and photovoltaic industries [20]. The popularity coupled with the abundance of this material ensures that the cost associated with using it in the leaf will not rise drastically. Silicon also has a relatively small band gap, which enables it to absorb lower frequency, visible light, which accounts for more of the spectrum than the higher frequencies, such as ultraviolet light, absorbed by semiconductors with larger band gaps [20].

Another attractive feature of silicon is the fact that in its anamorphous state, it can be integrated with the water splitting catalysts mentioned previously with minimal engineering to allow direct conversion of solar energy to usable fuels based on water splitting [15].

The silicon semiconductor in the artificial leaf assumes the role of the photosynthetic membrane in natural photosynthesis by capturing solar energy and converting it into a wireless current [8]. Without it, the artificial leaf would be rendered useless.

Working Principle of Hydrogen Fuel Cells

There are many different kinds of fuel cells, though they share the same basic process of converting hydrogen and oxygen into electricity, heat, and water. The process begins with the hydrogen fuel. Hydrogen enters the cell at the anode, where it "reacts with a catalyst, creating a positively charged ion and a negatively charged electron" [16]. Next, the positively charged hydrogen ion, or proton, passes through an electrolyte as the electron produces an electric current as it travels through a circuit. Finally, "[w]hen the protons and electrons meet at the cathode, they join with oxygen to form water and heat, which are released as exhaust" [14]. If vehicles were to run solely on hydrogen fuel cells, the only waste product would be water vapour, instead of the current harmful greenhouse gas pollutants such as CO2. Using hydrogen fuel cells to convert hydrogen gas and oxygen to form water and heat is, in theory, the reverse process utilized by the artificial leaf. Both recycle hydrogen, oxygen, and water. The process is further demonstrated using the diagram in figure 3 below.

Furthermore, fuel cells vary depending on the form of hydrogen inputted, the electrolyte used, and the output. The electrolytes that are commonly used are a solid polymer membrane, potassium hydroxide solution in water, liquid phosphoric acid ceramic in a lithium aluminium oxide matrix, alkali carbonates retained in a ceramic matrix of LiHO2, and other solid ceramics [17]. Possible catalysts include platinum, and other, cheaper, non-platinum group catalysts. Most cell designs expel H2O, but one exception instead produces CO2 gas [17].

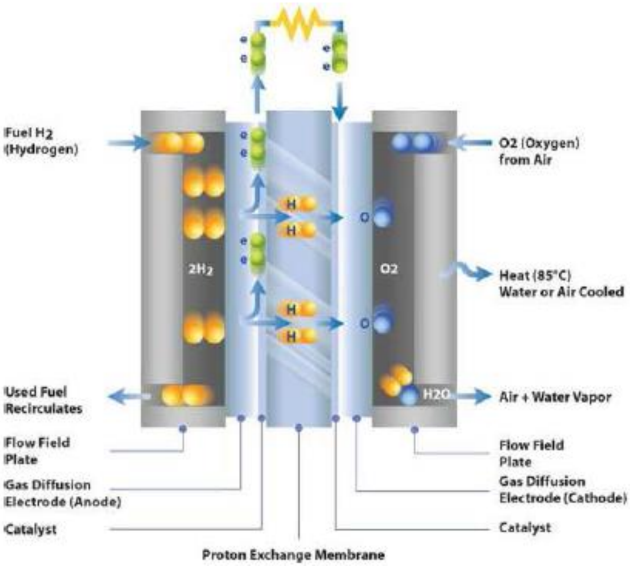


Fig 3. Operation of a hydrogen

OVERVIEW OF ARTIFICIAL PHOTOSYNTHESIS

WATER + SUN = FUEL

Solar fuels are storable fuels produced using solar energy. Solar energy can *indirectly* generate usable fuels through biomass. Alternatively, the *direct* conversion of solar energy into fuels through a fully integrated system is known as artificial photosynthesis. Artificial photosynthesis applies the principles that govern natural photosynthesis to develop a man-made technology. It strives to be a viable fuel source based on the consumption of abundant resources: solar energy, water, ... tosynthesis takes advantage of the efficient primary solar energy conversion steps of photosynthesis, but does not use energy to sustain life as does the natural process, nor does it necessarily require the land usage associated with biomass production.

Artificial photosynthesis produces fuel via two main pathways: carbon dioxide reduction to ultimately yield hydrocarbons and water oxidation to generate hydrogen. At pH = 0, water splitting can be described by the following overall equation:

$2H_2O \leftrightarrow 2H_2 + O_2 \quad E° = 1.23$ V vs. NHE ……... (2)

In (artificial) photosynthesis, sunlight provides the required energy (kinetic and thermodynamic) to drive the reaction in the forward direction and split water into hydrogen and oxygen.

Expansion of equation 1 demonstrates that it is the summation of two underlying half-reactions:

$2H_2O \leftrightarrow O_2 + 4H^+ + 4e^-$ $E_{ox} = 1.23$ V vs. NHE (3)

$2H^+ + 2e^- \leftrightarrow H_2$ $E_{red} = 0.00$ V vs. NHE ……….. (3)

These reactions show that converting water to hydrogen and oxygen is a multi-step, multi-electron process that not only needs energy to perform redox chemistry, but also requires different redox catalysts. These catalysts facilitate each of the above multi-electron half-reactions, where one catalyst evolves molecular oxygen by oxidizing water (equation 3) and a second catalyst generates hydrogen (equation 4) by reducing protons.

Similar to natural photosynthesis, artificial photosynthesis uses light absorbing molecules and/or materials to capture light and produce a charge separation. Then, through a series of inter-/intramolecular charge transfer reactions these charges are transported to catalytic sites to provide the requisite oxidizing/reducing energy to evolve oxygen or hydrogen. Depending on the architecture of the artificial photosynthetic device, the nature of the light capture, charge separation, charge transport and active catalytic sites vary greatly.

COMPARING PHOTOSYNTHETIC AND PHOTOVOLTAIC EFFICIENCIES

Efficiency is a concept that is deceptively simple yet can be elusive for comparisons between such different systems as living organisms and photovoltaic cells. The solar conversion efficiency of a PV device can be directly measured with high accuracy and is usually quoted by researchers and manufacturers in terms of power: electrical power out (W/cm2) divided by incident solar irradiance (W/cm2) measured over the entire solar spectrum. This instantaneous metric, measured at peak solar intensity, does not include energy storage and transmission.

A more direct comparison of PV and photosynthetic solar energy conversion efficiencies would consider a process in which PV also stores energy in chemical bonds. Application of PV-derived energy to electrolysis of water is a good choice for this purpose: Existing commercial electrolysers afford accurate efficiency benchmarks, and the free energy needed in order to split H_2O into H_2 and O_2 ($\Delta G° = 1.23$ eV) is essentially equal to the free energy change associated with photosynthesis [$\Delta G° = 1.24$ eV for

$CO_2 + H_2O$ to $(CH_2O) + O_2$, where (CH_2O) is shorthand for carbohydrate].

The power conversion efficiency of present commercial single-junction (single photosystem) silicon solar cell modules is typically 18 ± 2% (10).This value pertains to peak solar intensity (1 kW/m2), with an AM1.5 spectral distribution or solar zenith angle of 48.2° (sunlight passing through 1.5 atmospheres). The efficiency of a PV module changes during the day and throughout the year because of the changing solar zenith angle, and the PV efficiency averaged over a 1-year cycle is about 95% of the maximum

AM1.5 value. Modern commercial electrolysers have efficiencies as high as 80% [based on heat of combustion of H_2 to H_2O in liquid form at atmospheric pressure and 25°C, standard temperature and pressure (STP) conditions].

Thus, an annual averaged efficiency for solar water splitting by PV-driven electrolysis would be about (0.18) × (0.95) × (0.8) ~ 14% (11). This assumes that there is no mismatch between the photo-voltage generated by the PV array and the voltage required for electrolysis. Present Si

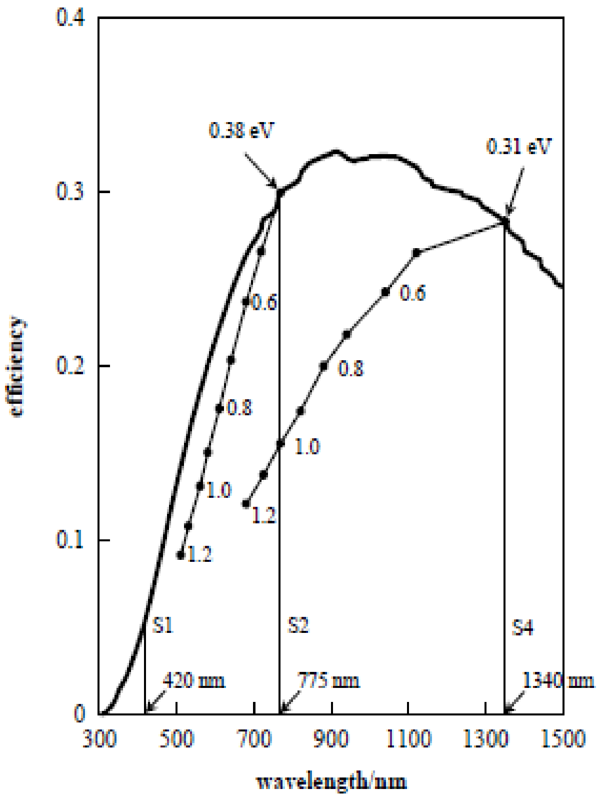
PV modules arranged in electrical series would suffer mismatch losses as high as 20 to 30%, bringing the overall H2O splitting efficiency down to ~10 to 11%. This constitutes the first benchmark to compare with the efficiency of photosynthetic fuel production. As discussed below, ongoing research is providing opportunities to construct PV devices with considerably higher efficiencies.

Several different measures of efficiency have been used in describing natural photosynthesis.

The quantum efficiency is the percentage of absorbed photons that give rise to stable photoproducts. Photosynthetic organisms typically can operate at nearly 100% quantum efficiency under optimum conditions (12). For comparison with PV electrolysis over an annual cycle, the energy efficiency of photosynthesis is a more useful parameter and is defined as the energy content (heat of combustion of glucose to CO2 and liquid H2O at STP) of the biomass that can be harvested annually divided by the annual solar irradiance over the same area. Using this definition, solar energy conversion efficiencies for crop plants in both temperate and tropical zones typically do not exceed 1% (7, 13), a value that falls far below the benchmark for PV-driven electrolysis. Higher 3%annual yields are reported for microalgae grown in bioreactors (14).

Short-term (rapid growth phase) efficiencies measured during the growing season are higher, reaching 3.5% for C3 and 4.3% for C4 plants (7), and perhaps 5 to 7% for microalgae in bubbled bioreactors (15). These efficiencies are measured in the absence of restrictions imposed by plant life-cycle regulation or by light and gas exchange limitations in the case of algae. Even so, these values fall below theoretical limits and ultimately limit the net annual productivity. Most natural photosynthetic systems store solar energy only during a growing season; efficiencies measured during that period must therefore be reduced accordingly to make valid comparisons on an annual basis, although the extent of reduction depends on the type of crop and the environmental conditions.

EFFICIENCY OF ENERGY CONVERSION IN



ARTIFICIAL LEAVES

Fig 4. Efficiencies for conversion of solar radiation into solar fuel

The full curve in fig 4 above shows η*p,* the ideal efficiency. The vertical lines at 420, 775 and 1340 nm show the maximum threshold wavelengths for the water photolysis reaction (reaction 7) carried out by S1, S2 and S4 schemes, respectively, under ideal conditions. The descending curves through the dots show the changes in efficiencies and band gap wavelengths for values of the actual energy loss *per molecule* in the overall conversion process *U*-loss greater than the optimum; the numbers at the dots are the respective values of *U*-loss in eV per photon at those points. [Taken from Bolton et al. (1985)].

CALCULATING THE EFFICIENCY OF THE PHOTOPRODUCTION OF HYDROGEN

We considered a suspension of algae irradiated with sunlight (irradiance 30 W m-2) where the area exposed to the sunlight is 10 cm2. Highly purified helium gas (saturated with water vapor) is passed through the suspension at a rate of 100 mL min-1 and analyzed for hydrogen and oxygen, which are found to be evolved in a 2:1 ratio with the hydrogen concentration at 100 ppmv. What is the solar photo-production efficiency?

100 mL min^{-1} corresponds to 6.81×10^{-5}mol s^{-1} of carrier gas; hence the rate of production of hydrogen is

$$R_{H2} = (1.0\ \times 10^{-4})(6.81 \times 10^{-5}) = 6.81 \times 10^{-9} s^{-1} mole$$

The hydrogen gas is produced at 10^{-1}atm; therefore, the ΔG^o must be replaced by

$$\Delta G = \Delta G^o - RTIn(P^O/P) = 237{,}200 - 8.3145 \times 298.15 In(1/10^{-4})$$

$$= 237{,}200 - 22{,}832 = 214{,}368KJ$$

The incident solar power ($E_S A$) is 30 ×0.0010 = 0.030 W. Thus from eq. 3

$$\eta_C = \frac{214{,}367 \times 6.81 \times 10^{-9}}{0.030} = 0.0487$$

$$or = 4.87\%$$

NIGERIA'S DEPENDENCE OF FOSSIL FUELS

Nigeria is increasingly dependent on fossil fuels which is far from sustainable. "The consumption of fossil fuels will continue to rise up to about 34 percent by 2030" [14]. The use of these fuels creates pollutants that are harmful to the environment. Therefore, we must find an alternative.

Hydrogen can act as that alternative. The artificial leaf brings hydrogen into a virtually unlimited supply, and it is the most prevalent element in the universe [21]. This allows for the nation's continuous increase in consumption, with plenty to spare. Additionally, there is no need to buy hydrogen from other countries, since it is readily and cheaply available.

IMPACT ON THE ENVIRONMENT

Since artificial leaf' have the ability to self-repair, its corrosion rate is low and the film lasts longer. This means that fewer supplies are required over a longer period of time. The current construction materials for the leaf are all earth abundant, so there is no danger of running out any time soon. The artificial leaf is fuelled by the sun, which will remain available to use for at least the next few thousand years, and by water, which does not even need to be pure. The leaf also does not require extra heat input to initiate nor maintain the reaction; it functions normally in room temperature water.

Also, because the "Co-OEC operates in neutral water…nonprecious metals may be used" [8]. In the 1970's, platinum was used in conjunction with TiO2 as a counter electrode to split water [12]. Because we can now use a NiMoZn alloy in its place, less money needs to be spent on the materials of the leaf, making it more economical for the public.

The artificial leaf is relatively simple. Nocera states that the leaf possesses "low-cost systems engineering and manufacturing that is required for inexpensive solar-to-fuel systems" [8]. It only uses materials that produce a minimal effect on the earth, while supplying energy in the form of hydrogen gas. This hydrogen gas can be used as an alternative to fossil fuels to power devices or run vehicles. If our vehicles ran on hydrogen rather than fossil fuels, the quality of life of those living in urban areas would substantially increase due to better air quality as a result of less pollution of the environment.

COSTS IMPLICATION

The artificial leaf has the potential to revolutionize the Nigeria's energy sector by introducing more commercializing this new technology. However, the leaf itself should not be regarded as super-efficient quite yet. As stated by Nocera in The Artificial Leaf, "overall solar-to-fuels efficiencies (SFE) were observed to be as high as 4.87% (for a 7.7% solar cell when Ohmic losses are minimized" [8]. 4.7% is the product of overall efficiency for water splitting and solar cell efficiency [8]. Although 4.87% may not appear entirely efficient, Nocera believes that "higher overall cell efficiencies (>10%) may be readily achieved through the use of more efficient PVs" [8]. More efficient need not be expensive, but as of today, the cheaper, more efficient PV remains undiscovered. The following sections will continue to address the practicality of its application.

COST OF SUPPLIES

With Nocera's leaf, most of the elements are earth abundant and relatively inexpensive. Each leaf would cost approximately N1, 105 to make, which is less expensive than the models that use platinum in the place of silicon [26]. However, the price of production should drop for the design to be invested in because, "the prices of solar cells are dropping all the time…" [26] Though silicon is, in fact, earth-abundant and relatively inexpensive, it is limited in its absorbance of sunlight [7]. Nocera claims that, "the device could eventually produce a kilogram of hydrogen for about N510 Naira" [26]. If this is true, then personal, affordable hydrogen gas production will be possible. With continued research and less expensive materials, the artificial leaf could become an integral part of the average Nigeria's daily life.

COST OF STORING HYDROGEN

Another obstacle in the way of a hydrogen economy is finding a reliable, cost effective way to store and distribute the hydrogen to consumers. Hydrogen has a very high energy density, but an extremely low physical density. This means that to have the appropriate amount of hydrogen gas to power a car requires enormous compression and expensive composite materials [7]. With the gaseous storage option, "the heat produced by the compression stage gradually reduces the gas density, limiting the positive impact of compression on energy density of the tank" [18].

The cryogenic liquid form of hydrogen requires a process that is quite expensive as previously mentioned. The hydrogen needs to be continually cooled, adding to the energy costs.

Also, the ideal shape of tank for liquid hydrogen is a sphere. Spheres are much more expensive to manufacture than cylinders, which are the most economical solution [18].

Though liquid and gaseous storage carry many drawbacks, the solid method has only a few limitations. For metal hydrides with low desorption temperatures, meaning that they require only a little heat to release hydrogen, the main fault lies in their low gravimetric energy density, which "does not reach the targets useful for road vehicle application…" [18] Nearly all of the other solids that have the potential to store hydrogen need more research done to determine their reliability and efficiency. These hurdles can be overcome in the future with more research into new materials and processes.

CONCLUSION

Photosynthesis-like process of Daniel Nocera's artificial leaf, which uses solar energy to split water into its components was discussed. Overall, Daniel Nocera's artificial leaf possesses many benefits. It relies on the sun and pure water, which are readily available and will not run out any time in the near future. The processes behind the artificial leaf are adapted from those naturally occurring in plants during photosynthesis. The materials used to make his leaf are nearly all earth-abundant and economical. It also produces hydrogen, which can be utilized in various ways, including hydrogen fuel cells which generate clean water as a product. One important way that hydrogen can be used to improve the environment is by allowing the Nigerians to have access to the amount of fuel required to introduce a hydrogen economy.

To do this, hydrogen fuel cells could possibly replace the standard gas tank in vehicles. If Nigeria's energy industry replaces fossil fuels with hydrogen, less harm will be caused due to greenhouse gases because the products of the latter reaction consist only of pure water and oxygen gas. The artificial leaf allows the human race to exploit the processes behind photosynthesis for the benefit of mankind.

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