Alternative Solar Cells and Their Implications

An Interactive Qualifying Project

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ABSTRACT

Alternative solar cells can have practical implications for renewable energy production. This study mainly focuses on electrolytic solar cells which can serve as an alternate to solid state solar panels. A thorough evaluation of the performance of existing solar cells (a-Si and c-Si) was conducted first, before designing a concurrent solar cell. As a next step, a custom electrolytic solar cell was built. Our custom electrolytic solar cell consisting of a cuprous oxide electrode produced a potential difference up to 80 mV and a steady current of 4 mA. Various factors such as light intensity, concentration of the electrolyte, surface area of the electrodes and the distance between the electrodes were tested.

Thus, by applying our experimental knowledge and engineering background, we are able to strongly support future economical and social implications of these type of cells. 72 % of Earth's surface area is composed of salt water and solar energy could be harnessed in a similar fashion using ocean water and electrodes. This would result in an extremely cheap production of solar power.

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1. INTRODUCTION

Since the latter half of the 20th century, the world's energy consumption has risen dramatically due to a variety of reasons including the increase in the world population and industrialization all over the globe. The total consumption of oil, which accounts for 35% of the world's energy consumption rose from 50 million barrels per day to 72 million barrels per day during the last decade. This has led to a price hike from $15/barrel in 1999 to about $70/barrel today[1]. The trend for the world's energy consumption over the last 50 years and a projected rise is shown in **Figure 1**.

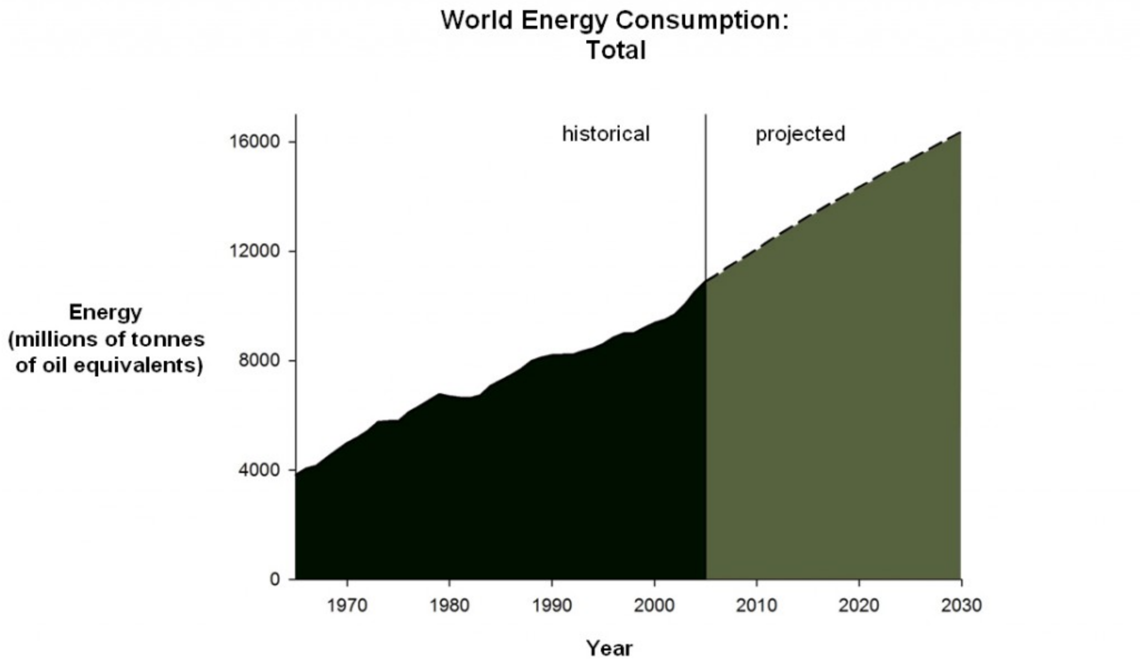

Figure 1: Yearly trend of world energy consumption[2]

Currently the supply of energy falls under two broad categories: energy produced by renewable sources and energy produced by non-renewable ones. Renewable energy is the energy produced

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[1] (DeGroat)
[2] (DeGroat)

by using resources that are naturally replenished, such as water, wind, sunlight, tides etc. On the other hand, non-renewable energy comes from using those resources that are finite in nature and will eventually diminish. This includes fossil fuels and nuclear energy. The world energy consumption from different resources can be seen in **Figure 2**.

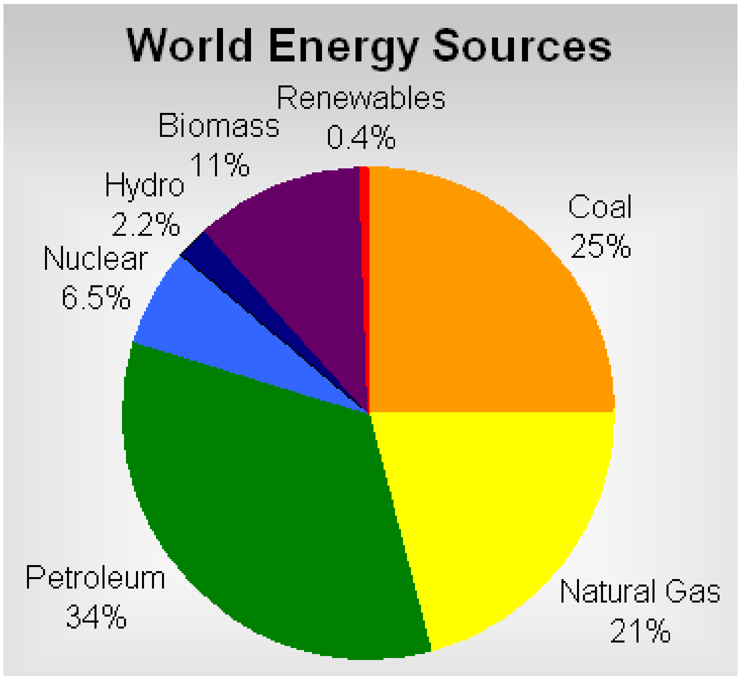

Figure 2: World energy resources[3]

The pie chart clearly shows that the world is relying very heavily on the non-renewable sources, which satisfy nearly 88% of the total world consumption. If this trend continues, there will be a grave energy crisis in the near future. This will be because we have a finite supply of fossil fuels such as oil and natural gas coupled with an ever-increasing human demand for these resources. According to the estimates, if fossil fuels are continued to be exploited at the present rate then they will run out in the near future.

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[3] (Energy Infrastrucutre Promotion & Development Division)

Scarcity is not the only problem associated with fossil fuels. Fossil fuels are primarily composed of carbon. When they are burnt in the presence of oxygen, Carbon dioxide (1) is produced which contributes towards the increase of CO_2 levels in the atmosphere.

$$C + O_2 \rightarrow CO_{2(g)} \qquad (1)$$

This increase in Carbon dioxide causes global warming by the greenhouse effect. **Figure 3** shows the increase in atmospheric CO_2 levels with increasing fossil fuel emissions.

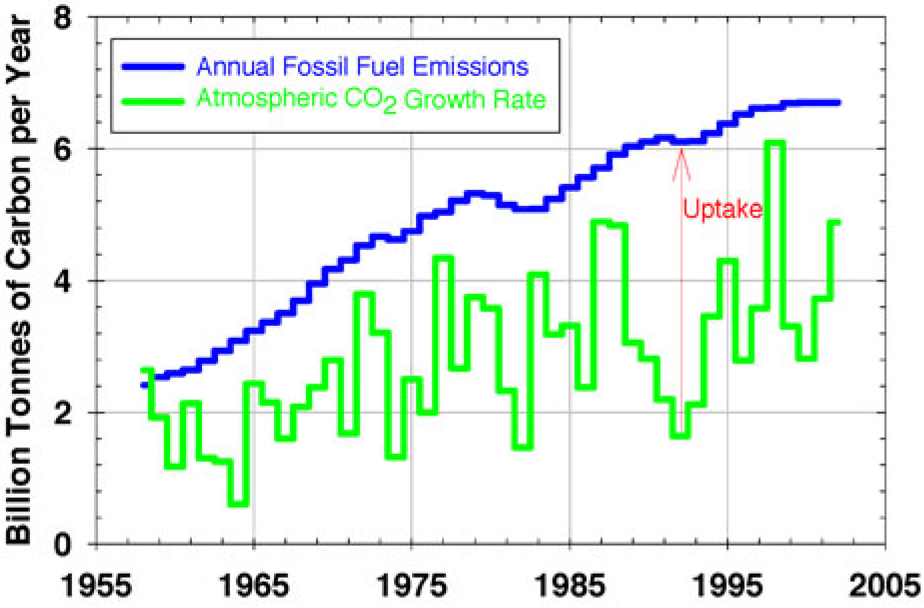

Figure 3: Fossil Fuel Emission - CO_2 Correlation[4]

Today, as the price of oil skyrockets and consciousness about its pollution increases, alternative solutions are being sought. Hence, it becomes essential that we gradually shift our reliance from fossil fuels to renewable forms of energy.

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[4] (CO2 Now Online: Greenhouse Gas Watchdog)

1.1 Renewable Energy

There are three popular green renewable energy sources that are currently being used and provide a total 2.5% of world’s energy requirements. They consist of

- Hydro - 2.2%
- Wind - 0.2%
- Solar - 0.1%

Hydro power sources use the power derived from water to generate electricity. It is the most commonly used green energy source and hydroelectric dams are found world over. However, hydropower sometimes comes with huge social, economic and environmental costs as vast amounts of land has to be inundated and thousands of homes have to be relocated to make way for the dam reservoir. Moreover, it may destroy forests and natural habitat for wildlife. As human population increases it would becomes economically non-viable to provide gigantic tracts of land for dam construction. Thus it makes hydropower less feasible to serve as the leading renewable energy source in future The remaining two sources namely wind and solar appear have far less social and environmental costs and look poised to become the major renewable energy sources of the future. However, this paper will focus solely on solar energy.

1.2 Solar Power

Solar power commonly refers to the generation of electricity using the energy directly delivered by sunlight. This power can either be generated using the photovoltaic effect or be concentrated to use as a heat source as in a conventional power plant.

The photovoltaic method, which is more widespread, involves using arrays of cells that convert the energy delivered by the photons in sunlight into direct current (DC) electric power. Solar power production using photovoltaic panels has doubled every two years since 2002, and is currently the fastest growing energy technology worldwide leading to the speculation that it is going to be the main source of power in the future. However, the current cost of production of solar panels has prevented it from becoming widespread especially among the public who could benefit greatly from its use. The current price per watt of solar power stands at $5/Watt for small capacity solar panels (1-10W) compared to grid electricity, which costs around 0.0115 Cents/watt.

This high cost can be attributed to the fact that presently, solar cells are made of expensive semiconductor crystalline and poly(multi)crystalline doped materials on the base of Silicon and Germanium.

Moreover, the efficiency of the solar cells used today is low. Efficiency of a solar cell (Photovoltaic Efficiency) is defined as the percentage of power converted to electrical energy versus total incident sun power, when a solar cell is connected to an electric circuit. At the time of writing this report, the highest efficiency ever achieved in a controlled laboratory setup has been 42.8%. This means that a larger surface area solar cell is required to produce the same amount of electricity, which can otherwise be produced, by a smaller and more efficient solar cell.

Therefore, to tackle the high cost problem associated with solar cell we can adapt two different approaches namely:

1. Increase the efficiency of solar cells (Photovoltaic Efficiency).
2. Use cheaper materials for the construction for solar cells.

The issue of increasing the photovoltaic efficiency has been of great interest since 1950s, both from the academic and economic points of view. Many papers have been published, claiming possibility of high efficiencies after conducting optical measurements under many hypothetical conditions.

However, none of this research has translated into any revolutionary increase in efficiency under real conditions. From 1950s to present, the efficiency has gradually increased from approximately 5% to about 13-14% for general-purpose solar panels currently on the market.

Therefore, for the purpose of this IQP, it was decided to take the secondary approach and proceed forward with researching and designing an alternative solar cell that would be made of cheaper materials that are more abundant.

2. BACKGROUND AND LITERATURE REVIEW

2.1 History of Solar Power

Mankind has been harnessing the energy of the sun since the seventh century B.C. The sun's rays shower the earth's surface and humans have been using them to meet their energy needs. Every hour of sunshine theoretically can contribute to meet the world energy demand every year. The ancient civilizations namely, Rome and Greece demonstrated their first documented use of sunlight by burning mirrors to light torches for religious purposes. Ancient architecture in Rome and Greece utilized passive solar design i.e. the use of sunlight to heat and light indoor spaces. This technique still remains today as one of the most economical ways to use solar power. This was taken a step further and mica was used to cover south facing buildings to trap the heat.

A jump in time to the 19th century shows great advancements in technology and different needs to tap sunlight to useful work. Auguste Mouchout invented a steam engine powered by the sun recognizing the inevitable depletion of fossil fuels during the Industrial Revolution[5]. This era also saw the discovery of the photovoltaic effect by a French scientist Antoine Edmund Becquerel in 1839. His theory then sparked the idea of using semiconductor material as a source to convert solar power in electrical energy. The 20th century witnessed the discovery of the photoelectric effect by Albert Einstein and others. This led to research in the field of materials whose chemical properties were desirable to convert solar into electrical energy. Modern day devices that most efficiently convert sunlight to electricity are known as (semiconductor) photovoltaic panels.

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[5] (The History of Solar Cell)

The history of solar power hence, demonstrates advancements in solar technologies corresponding to changes in human energy demand. The driving factor for research and development in the field has always been to achieve useful work in both mechanical and electrical forms. With environmental concerns and depletion, and cost of fossil fuels, today's world constantly strives for the best technically and economically feasible way to use definitely the greatest natural resource - the sun.

2.2 The Photovoltaic Effect

2.2.1 Initial Discovery

The most significant usage solar power has found has been in electrical energy generation. The previous century has witnessed a plethora of advancements in the processes of using solar energy in the form of electrical energy. The discovery of the phenomenon known as the photovoltaic effect enabled this conversion of the two forms of energy. It was first recorded by Alexandre-Edmund Becquerel in 1839. He observed that the application of light on platinum electrode coated with silver in an electrolyte produced electric current. This marked the first time in history when electricity was produced by the effect of light. His apparatus consisted of two electrodes of the same metal such as platinum, gold or brass - metals are chemically inactive in electrolyte consisting of dissociative ions. The electrolytes used were dilute acids and ionic solutions. This simple setup, albeit similar to a chemical galvanic cell functioned in the exact option. Electric current was produced not by electrolysis, but by a combination of the photovoltaic effect and ionic conductivity in the electrolyte. **Figure 4** below shows a simple setup of Becquerel's experiment, which will be further detailed in later sections of the report.

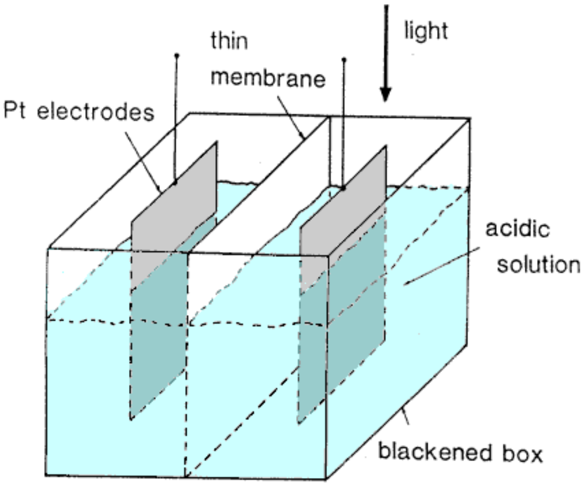

Figure 4: A.E. Becquerel's experimental setup. One of the electrodes is subject to sunlight[6]

After the advent of the photovoltaic effect, several experiments similar to the Becquerel setup were conducted and some of the ones pertaining to this project are detailed in later sections. Solid-state devices were also designed in the years following and Charles Fritts developed the first photovoltaic device in 1833. **Table 1** shows the major breakthroughs and significant points that led to the modern day photovoltaic panels.

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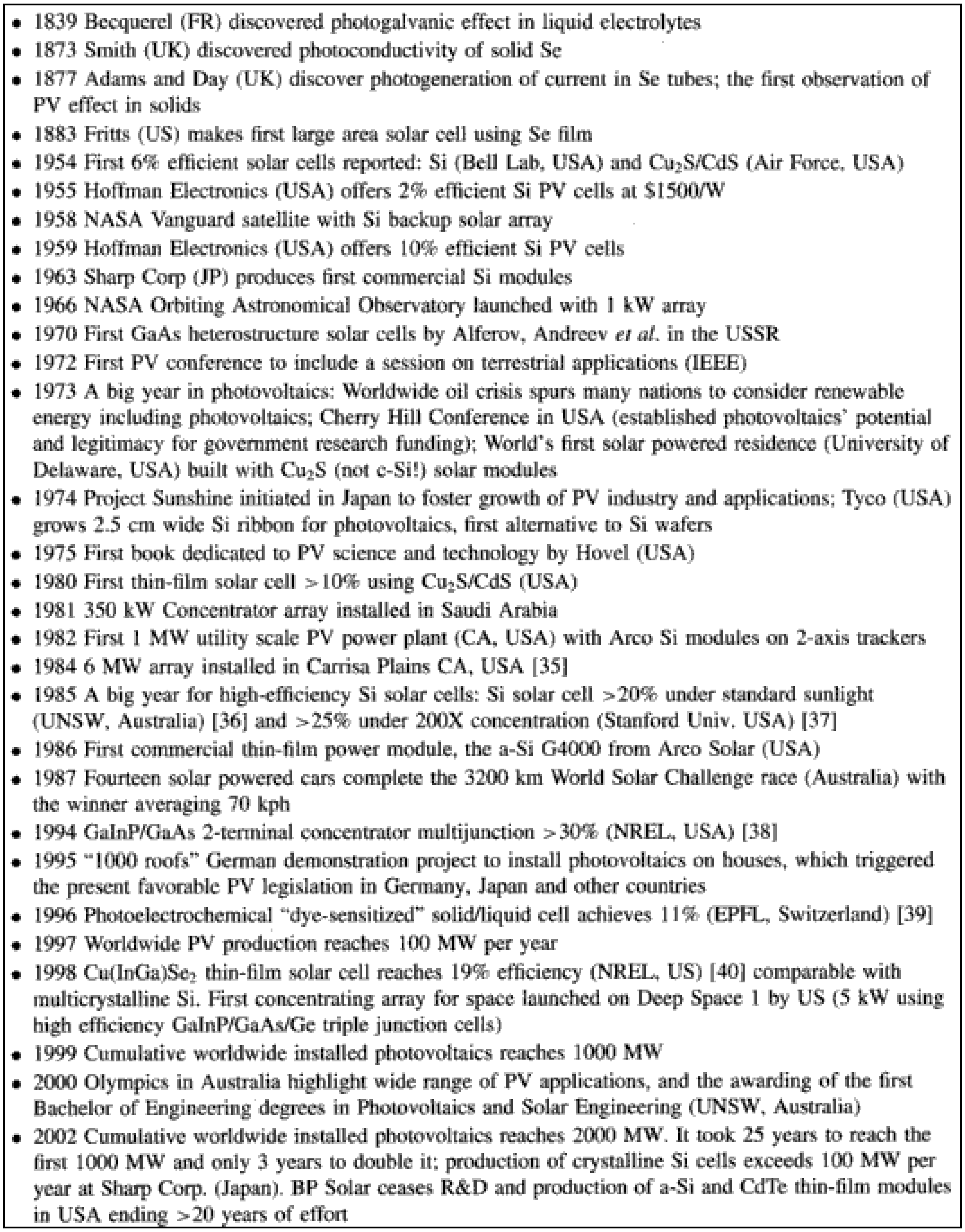
[6] (First Photovoltaic Devices)



- 1839 Becquerel (FR) discovered photogalvanic effect in liquid electrolytes
- 1873 Smith (UK) discovered photoconductivity of solid Se
- 1877 Adams and Day (UK) discover photogeneration of current in Se tubes; the first observation of PV effect in solids
- 1883 Fritts (US) makes first large area solar cell using Se film
- 1954 First 6% efficient solar cells reported: Si (Bell Lab, USA) and Cu_2S/CdS (Air Force, USA)
- 1955 Hoffman Electronics (USA) offers 2% efficient Si PV cells at $1500/W
- 1958 NASA Vanguard satellite with Si backup solar array
- 1959 Hoffman Electronics (USA) offers 10% efficient Si PV cells
- 1963 Sharp Corp (JP) produces first commercial Si modules
- 1966 NASA Orbiting Astronomical Observatory launched with 1 kW array
- 1970 First GaAs heterostructure solar cells by Alferov, Andreev *et al.* in the USSR
- 1972 First PV conference to include a session on terrestrial applications (IEEE)
- 1973 A big year in photovoltaics: Worldwide oil crisis spurs many nations to consider renewable energy including photovoltaics; Cherry Hill Conference in USA (established photovoltaics' potential and legitimacy for government research funding); World's first solar powered residence (University of Delaware, USA) built with Cu_2S (not c-Si!) solar modules
- 1974 Project Sunshine initiated in Japan to foster growth of PV industry and applications; Tyco (USA) grows 2.5 cm wide Si ribbon for photovoltaics, first alternative to Si wafers
- 1975 First book dedicated to PV science and technology by Hovel (USA)
- 1980 First thin-film solar cell >10% using Cu_2S/CdS (USA)
- 1981 350 kW Concentrator array installed in Saudi Arabia
- 1982 First 1 MW utility scale PV power plant (CA, USA) with Arco Si modules on 2-axis trackers
- 1984 6 MW array installed in Carrisa Plains CA, USA [35]
- 1985 A big year for high-efficiency Si solar cells: Si solar cell >20% under standard sunlight (UNSW, Australia) [36] and >25% under 200X concentration (Stanford Univ. USA) [37]
- 1986 First commercial thin-film power module, the a-Si G4000 from Arco Solar (USA)
- 1987 Fourteen solar powered cars complete the 3200 km World Solar Challenge race (Australia) with the winner averaging 70 kph
- 1994 GaInP/GaAs 2-terminal concentrator multijunction >30% (NREL, USA) [38]
- 1995 "1000 roofs" German demonstration project to install photovoltaics on houses, which triggered the present favorable PV legislation in Germany, Japan and other countries
- 1996 Photoelectrochemical "dye-sensitized" solid/liquid cell achieves 11% (EPFL, Switzerland) [39]
- 1997 Worldwide PV production reaches 100 MW per year
- 1998 $Cu(InGa)Se_2$ thin-film solar cell reaches 19% efficiency (NREL, US) [40] comparable with multicrystalline Si. First concentrating array for space launched on Deep Space 1 by US (5 kW using high efficiency GaInP/GaAs/Ge triple junction cells)
- 1999 Cumulative worldwide installed photovoltaics reaches 1000 MW
- 2000 Olympics in Australia highlight wide range of PV applications, and the awarding of the first Bachelor of Engineering degrees in Photovoltaics and Solar Engineering (UNSW, Australia)
- 2002 Cumulative worldwide installed photovoltaics reaches 2000 MW. It took 25 years to reach the first 1000 MW and only 3 years to double it; production of crystalline Si cells exceeds 100 MW per year at Sharp Corp. (Japan). BP Solar ceases R&D and production of a-Si and CdTe thin-film modules in USA ending >20 years of effort

Table 1: Significant events in photovoltaic history[7]

The 20th century saw development of new ideas and more discoveries. The discovery of the photoelectric effect by Albert Einstein in 1905 explained the physics behind the photovoltaic

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[7] (Luque and Hegedus)

effect. Towards the millennium mark, the world saw a great need for sources of renewable energy that do not contribute towards negative environmental impact and slow down the depletion of natural resources. Several key concepts that help explain the theory of the photovoltaic effect include the photoelectric effect and PN junction theory. A completely new area of study today focuses on solar power and photovoltaic (PV) technologies.

2.2.2 The Photoelectric Effect

Heinrich Hertz noticed in 1877 that electrodes illuminated by ultraviolet light emitted electric spark[8]. This marked that discovery of the photoelectric effect – the phenomenon in which electrons at the surface of any matter are emitted by absorbing energy from electromagnetic radiation such as visible light. Albert Einstein developed the theory behind the photoelectric effect 28 years later and defined light as photons. **Figure 5** below shows a physical description of the photoelectric effect. An incoming photon of light with sufficient energy can knock out an electron from the valence (outermost) shell of an atom. The same process could happen with a (transparent) volume – a semiconductor crystal.

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[8] (Chopra)

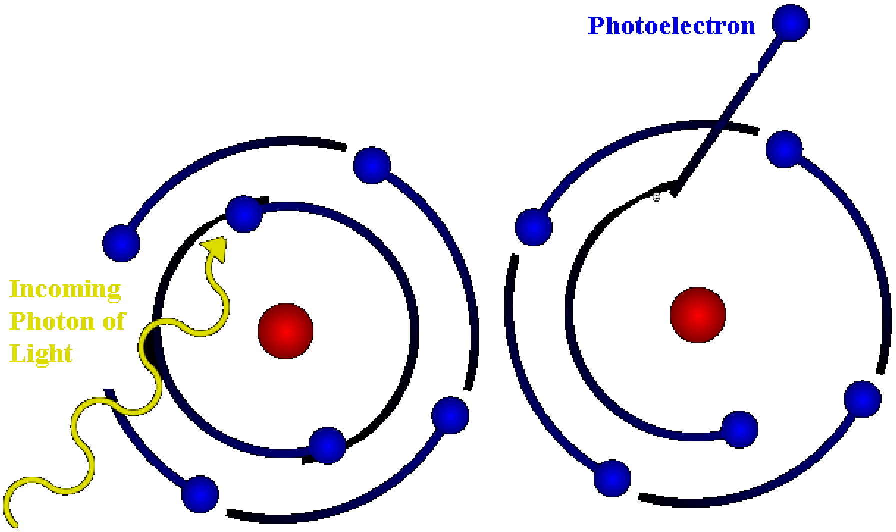

Figure 5: The Photoelectric Effect experienced by an atom[9]

The energy of each photon of light is the product of its frequency and a constant known as the Planck's constant. The work function is known as the binding energy of electron i.e. minimum energy required to remove an electron from a material. The emission of an electron occurs when the energy absorbed by it (energy of photon) is greater than the work function of the specific material. No electrons are emitted when the work function is greater than the energy of incoming photon. Increase in the light intensity increases the number of emitted electrons, but does not increase the energy of the photon and hence, the energy of the emitted electron. Following is a list of notable observations that add to theory of the photoelectric effect:

- Ejection rate of the electrons is directly proportional to incident light intensity for a constant frequency.
- Frequency of incident light increases intensity of photoelectric current for a particular work function.

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[9] (Huenniger)

- Threshold frequency is defined as the minimum frequency of the incident of photon below which no electrons can be emitted.

The work function of any given material is given by the formula,

$$W = hf_0 \tag{2}$$

where h – Planck's Constant = 6.626 x 10^{-34} m^2 kg/s, and f_0 – threshold frequency. The maximum kinetic energy of an ejected electron can be thus, be defined by the following formula,

$$KE_{max} = h(f - f_0) \tag{3}$$

The photoelectric theory is the underlying principle behind the solar cell i.e. PV cell. Sunlight which has in the visible spectrum of light with a wavelength of 400 – 750 nm (10^{-9} meters), illuminate the panels. The photons of sunlight can a) can pass straight through, b) can reflect off the surface or c) can be absorbed if the photon energy is higher than the band gap value of the material.

2.3 Semiconductors

A PV panel is known as a semiconductor device made up of semiconductor material. A semiconductor is defined as a material whose electrical conductivity is between an insulator and a conductor. Materials that semi-conduct are typically crystalline or amorphous solids. At a temperature close to absolute zero (0 Kelvin), solids act as insulators and do not have any free electrons. However, at room temperature a part of insulators, for bond energies between the valence electrons and nucleus in an atom is three to five electron Volts (eV), contains a number of free electrons. This fact results in electrical conductivity and materials that exhibit this change from absolute zero to room temperature are known as semiconductors.

Similar to any material that experiences the photoelectric effect under illumination, electrons in semiconductors leave their valence band. Instead of leaving the outer surface, the valence enter the conduction band. The resistance to this excitation and jump depends on the band gap value of the semiconductor materials[10]. A bandgap energy is referred to as the energy required to free the outermost electron shell of an atom from its orbit around the nucleus in order to create a mobile charge carrier. The band gap is a characteristic of insulators and semiconductor materials which do not contain any delocalized electrons available to carry charge (like in metals). **Table 2** below shows the bandgap energy values for different semiconductor materials.

Material	**Band Gap Value (eV)**
Silicon	1.11
Selenium	1.74
Germanium	0.67
Silicon carbide	2.86
Aluminum phosphide	2.45
Gallium arsenide	1.43
Indium phosphide	1.35
Zinc selenide	2.7
Cadmium telluride	1.49
Copper oxide	1.2

Table 2: List of band gap values for different materials[11]

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[10] (Berger)
[11] (Streetman and Banerjee)

Semiconductor (and semiconducting) materials that are most compatible with the energy of sunlight (the bandgap energy is less than the energy of a significant fraction of photons in the sun spectrum) are Silicon, Germanium, GaAs, and copper oxide. Extensive research has also been done in the field of photo - electrochemistry to determine whether semiconducting materials such as copper oxide can be used for solar power. These experiments will be detailed in Section 2.4 below.

The photovoltaic effect in solar panels occurs between junctions of two dissimilar materials. The photoelectric effect occurs in the materials themselves, but the ejected electrons need a transfer medium and, which is most important, a built-in electric field to generate current. Semiconductor materials are used to enable a flow of current upon illumination of the two dissimilar materials.

2.3.1 PN Junctions

A junction between two dissimilar materials known as P-type and N-type semiconductors, which are held in close contact, is known as a PN junction. A P-type semiconductor material has electron holes as *positive* charge carriers. It is obtained through a process known as doping where additional atoms of a different element are added to the parent semiconductor element to increase the number of electron holes. The doping atom accepts the outer electrons from the semiconductor and creates an abundance of electron holes. For example, Boron atoms doped into Silicon will accept the loosely bonded electrons in the Silicon lattice. A N-type semiconductor on the other hand has *negative* charge carriers and an abundance of electrons. It is obtained by doping a semiconductor material with atoms that can give away electrons. For instance, Silicon can be doped with Phosphorous and the resulting atom will have an additional electron. For N-type semiconductors, the extra electrons are very weakly bonded to the atom and can very easily be excited to the conduction band (become free electrons).

Upon close contact and with no external voltage applied to the junction, the N and P materials cause a non-conducting region between two doped semiconductors known as the depletion zone, with no free charge carriers. This area is predicted by an electrostatic theory; it might be also caused by the diffusion of electron holes and electrons from the P-type and N-type and vice versa for charge neutralization.

This theory forms the basis for the functionality of a simple rectification device such as a diode. A diode only conducts current in one direction (from P to N) and doesn't allow a reversal due to the nature of the PN-junction. Its most common purpose is to convert alternating current to direct current. It is characterized by the PN-junction built-in electric field that sets a forward bias voltage or a built-in electric field.

A bias voltage is a minimum voltage drop across the diode for it to pass current from P material to N material and to overcome the built-in voltage. For instance, a diode made of Silicon has a bias of 0.6 V to 0.7 V. Other semiconductor materials have different bias voltages. A PN-junction diode also follows a general I-V (Current-Voltage) curve as shown in **Figure 6** below.

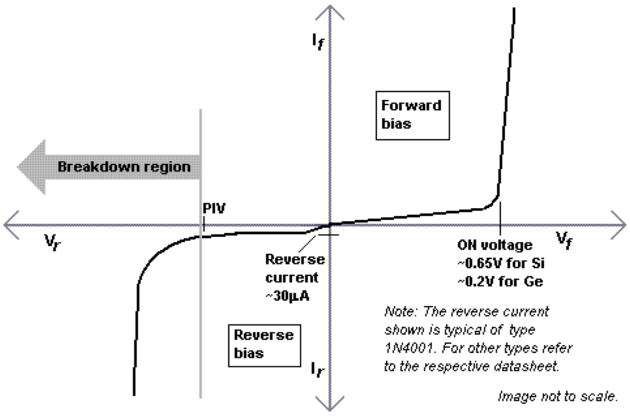

Figure 6: Current-Voltage Curve for Silicon (Si) and Germanium (Ge)[12]

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[12] (Rectifier VI Curve)

2.4 Electrolytic Solar Cells

By discovering the photovoltaic effect in 1839, A.E. Becquerel had also demonstrated the rudiments of a solar cell. As discussed earlier his experiment involved two metal electrodes separated by an electrolyte; a potential difference was generated upon the unsymmetrical illumination of the electrodes. Many similar experiments were conducted to enhance and understand the photovoltaic effect. The following section will discuss those that pertain to the experiments conducted in the project in brief detail with an explanation of their results.

2.4.1 Cells with two similar metal electrodes separated by an electrolytic solution[13]

The first type of cell which served as a prototype for the future cells was the one demonstrated by Becquerel. He used two electrodes of the same metal such as platinum, gold or brass, ones that were non-reactive with the electrolyte. The electrolytes tested were dilute acids and ionic solutions. He concluded that the current produced due to the illumination of one of the electrodes was not due to thermionic emission. He added that the illuminated electrode became positive i.e. the illuminated electrode was the photoanode.

The magnitude of the potential difference between electrodes (the strength of the photovoltaic source) also depends upon the treatment of the electrodes before the experiment. This includes the time they were held in the air, the duration held in the electrolyte and pre-illumination. These factors have a significant effect in the accumulation of static charges in the electrodes that can cause initial discrepancies in current or voltage readings. This conclusion has been supported by an experiment conducted by a scientist named Buisson, who noticed how the electric voltage varied when the metal was immersed in the electrolyte after undergoing illumination from UV rays.

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[13] (Copeland, Black and Garrett)

A Swedish scientist V. Sihvonen drew conclusions from a cell made of pure metal electrodes such as copper, platinum, silver, etc immersed in acids, bases and salts. He reported in 1926 that current was produced due to the occurrence of a photoelectric effect on the photoanode, films of gas at the electrodes and ions in the electrolyte. The photoelectric effect caused electrons to be emitted in the solution; discharge of cations by electrons under illumination of electrode with sunlight; formation of anions from gas films; photovoltaic discharge of anions; and formation of cations at the cathode. Following Sihvonen's experiments, R Audubert was able to produce a potential difference of 10^{-7} to 10^{-5} volts.

Doubts arose in the early 20th century about the light sensitivity of the electrolyte causing photolysis and photochemical reactions in the solution. Swensson reported in his findings that electrolytes such as cupric sulfate, nickelous sulfate, zinc sulfate and sulfuric acid are indeed light sensitive and vary the potential produced by the cell. The concentration of the electrolyte has an impact on this effect.

In summary, the photovoltaic effect seems evident in cells consisting of two metal electrodes and an electrolyte. It is enhanced by a combination of photoelectric effect at the electrode and photolysis in the solution. Cells that contain a light sensitive electrolyte will also alter the potential difference reading, but thermal radiation apparently has a negligible effect. According to the above studies, the current generation could be due to a wide variety of factors.

The Methodology section (Section 4) of the report will discuss our solar cell experiments that were a replication of the original Becquerel's setup using aqueous NaCl solution and two metal (Copper and other materials) electrodes.

The purpose of a replication was to discover possible implications for using ocean water (salt water) as an electrolyte with two metal electrodes to generate current using sunlight. Any other electrolytic solution wouldn't have practical as its production would not coincide with cheap and safe electricity production.

2.4.2.1 Cells with two similar metal electrodes, one of which is coated, separated by an electrolyte solution[14]

2.4.2.1.1 Metal electrodes coated with silver halide

Becquerel also tested cells in which silver electrodes were coated with silver halide and were immersed in dilute sulfuric acid. Current was generated upon the illumination of one of the electrodes. This effect was greater than that of plain metal electrodes as silver halides are light sensitive. They are used extensively in photography, radiography and to make corrective lenses. They are known to be "light absorbing" compounds, in which electrons are promoted to a conduction band due to photons.

Becquerel's experiment involved studying the effect in terms of light intensity and the visible light spectrum. For different halides such as silver bromide, silver iodide and silver chloride, he was able to determine the light intensity and spectrum that provided the greatest current.

Following Becquerel, H Luggin produced 0.42 volts using silver bromide coating on platinum electrode in potassium bromide solution. He noted that for continuous strong illumination, there was a gradual decrease in potential difference over time after a peak was reached.

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[14] (Copeland, Black and Garrett)

There have been several experiments that used light sensitive metal halides on inert metal electrodes that enhanced the photovoltaic effect in electrolytic solar cells. Research was also done to determine the light spectrum that provided the greatest effect.

2.4.2.1.2 Copper oxide coated on Copper electrodes

This topic is most closely related to the subject of our research. The initial discovery, which showed the light sensitivity of oxidized copper, was demonstrated by W Hankel in 1877. Gouy and Rigollot in 1888 reported that copper oxide on one of the two copper plates in a solution of a metal chloride was very sensitive (even at low light intensities). Particularly, they made a distinction between cuprous oxide (Cu_2O) and cupric oxide (CuO) noting that Cu_2O is more sensitive than CuO. By illuminating the copper-copper oxide electrode in a sodium chloride solution, they produced a potential of 0.1 volt. The maximum wavelength of light for this setup was determined to be 5000 angstroms. The electric current was also found to be proportional to the intensity of light but it approached a constant value upon very intense illumination for a relatively long time.

Following this research, another group of scientists, Goldmann and Brodsky, reported some important observations. Using oxidized copper electrodes in sodium chloride solution, they were able to show that the photoelectric effect and the magnitude of current was independent of the concentration of the solution. Furthermore, like Rigollot, they too noted that current either decreased or became constant upon prolonged and repeated intense illumination. They added that the ratio of current to light intensity decreased as intensity increase, but with stirring of the solution, this ratio was proportional. Increase in temperature also showed an increase in the current.

A British physicist T.W. Case used two copper plates (one coated with cupric oxide) immersed in sodium chloride solution. This setup produced a current of 0.5 milliampere and 0.1 volts when the coated electrode was illuminated.

Generally, the cuprous oxide was observed to be more sensitive and extensive research was done with cuprous oxide electrodes. Some of the significant results were summarized by A.D Garrison. A cuprous oxide electrode turns positive upon illumination, but can be made negative by increasing the density of cuprous oxide on copper. Current flows in the direction that will cancel the oxide film. The photovoltaic effect was described in terms of shifting of chemical equilibrium. Upon illumination, Cu_2O dissolves in the electrolyte and dissociates into 2 Cu^+ and O^{2-} and the illuminated electrode becomes positive (i.e. photoanode) when Cu^+ accepts an electron to become Cu. This establishes charge balance in the cell and produces current flow. Garisson's results explain the photovoltaic effect in copper-copper oxide cells as a result of red-ox reactions combined with the photoelectric effect.

Several scientists after Garrison have studied copper oxide cells in terms of barrier-layers. There is photoelectric effect in cuprous oxides and there is a rectification layer in those photovoltaic cells, similar to the diode depletion region discussed above. The rectification layer depends on the behavior of cuprous oxide with the electrolyte and the copper. The electrolyte in the cell acts dominantly as the conductor of charges (for the photoelectric current), but some chemical effects affect the current.

The focus of our research and experimentation relied on social and economic implications of this approach. The primary goal, as mentioned in earlier sections, was to show that an inexpensive solar cell made of cheap materials does exist. Becquerel's initial experiments and copper-cuprous oxide cells in salt solutions offer the fundamental for our cell. The field of photo-electrochemistry and the physics of basic semiconductor devices was used to support the theory of operation of a device that we were able to create and document.

3. METHODOLOGY

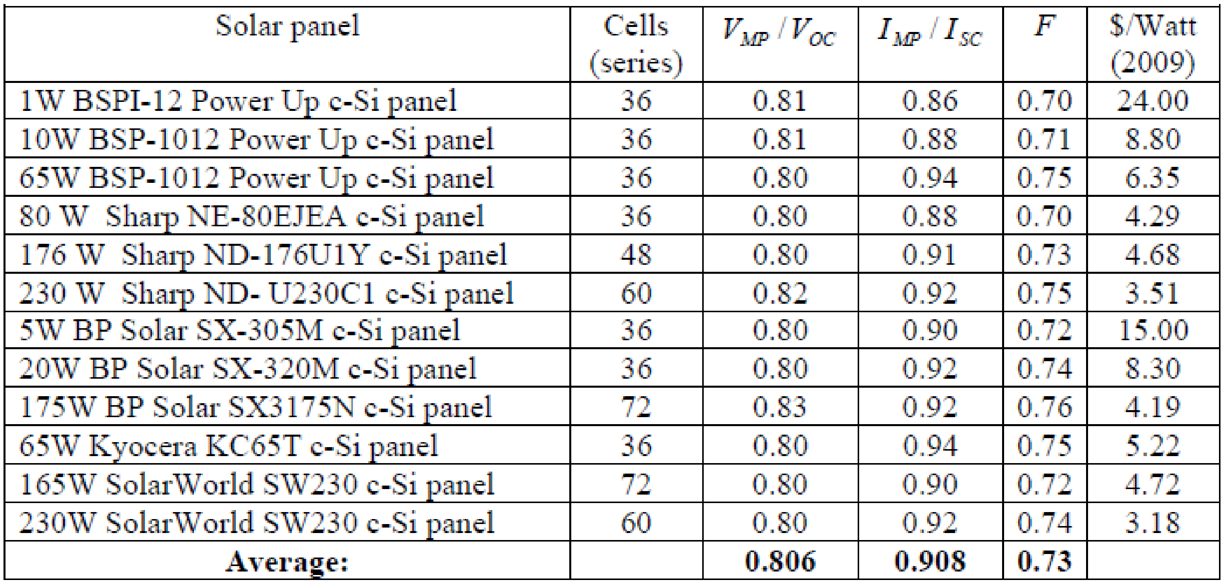
The following section will outline our experimental procedures and decision-making based on several parameters. The progress of our findings and experiments have been described thoroughly as well.

3.1 Design Goals

After observing the Photovoltaic effect demonstrated by A.E Becquerel in 1839, it was decided that our model was going to be based on the experimental setup used by Becquerel. The main goals of our setup were to:

- Design a solar cell that uses materials which are found abundantly in nature;
- Design a solar cell that would eliminate the need for expensive semiconductor materials (such as doped silicon and germanium crystals, etc.), and hence help us reduce the price/watt for our cell.

The solar cells present in market today are highly priced mostly because of the fact that they use expensive semiconductor materials (about 50% of the total cost is the semiconductor cost). Most of them use silicon (poly)crystalline, which presently costs about $400 per kilogram. After reading this figure, it would become pretty clear to any observer that how expensive it is to build a modern day solar cell. Therefore, if we are able to propose a solar cell design that doesn’t require silicon or any of the other solid-state semiconductors, then it’s very likely that our solar cell would cost much less than the ones present in market today. **Table 3** below shows the price per watt of c-Si solar cells from five different manufacturers who sell cells of different power outputs.



Solar panel	Cells (series)	V_{MP} / V_{OC}	I_{MP} / I_{SC}	F	$/Watt (2009)
1W BSPI-12 Power Up c-Si panel	36	0.81	0.86	0.70	24.00
10W BSP-1012 Power Up c-Si panel	36	0.81	0.88	0.71	8.80
65W BSP-1012 Power Up c-Si panel	36	0.80	0.94	0.75	6.35
80 W Sharp NE-80EJEA c-Si panel	36	0.80	0.88	0.70	4.29
176 W Sharp ND-176U1Y c-Si panel	48	0.80	0.91	0.73	4.68
230 W Sharp ND- U230C1 c-Si panel	60	0.82	0.92	0.75	3.51
5W BP Solar SX-305M c-Si panel	36	0.80	0.90	0.72	15.00
20W BP Solar SX-320M c-Si panel	36	0.80	0.92	0.74	8.30
175W BP Solar SX3175N c-Si panel	72	0.83	0.92	0.76	4.19
65W Kyocera KC65T c-Si panel	36	0.80	0.94	0.75	5.22
165W SolarWorld SW230 c-Si panel	72	0.80	0.90	0.72	4.72
230W SolarWorld SW230 c-Si panel	60	0.80	0.92	0.74	3.18
Average:		**0.806**	**0.908**	**0.73**	

Table 3: Price ($) per Watt of solar cells with different power ratings for 2009[15]

3.2 Design Iterations

Based on these major design goals, we went forward and designed, after several iterations, our liquid based (electrolytic) solar cell. As we followed the original Becquerel's model described above (**Figure 7**), our design also included two metal electrodes which were immersed in an electrolyte.

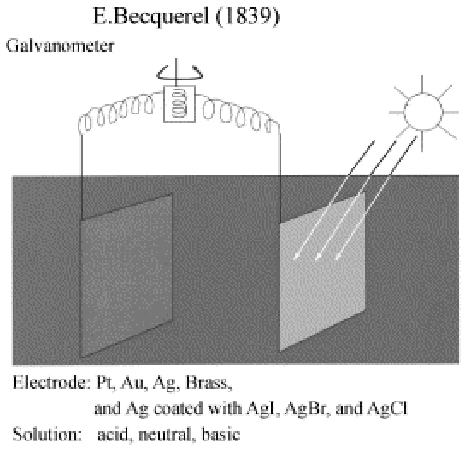


Figure 7: A.E Becquerel's cell apparatus[16]

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[15] (Makarov, Ludwig and Bitar)

For the cavity, we initially decided to use a glass tank as it is often used for electrolysis experiments. The glass tank appeared to be a suitable setup for our experiment at first sight. But after we conducted several experiments with the glass tank (as seen in **Figure 8**), it was observed that the results were not as prominent or substantial as we were expecting them to be.

So we looked up the properties of glass and found out that the glass was absorbing a large fraction of the ultraviolet (UV) light that the setup was being exposed to. That was the reason for our poor initial results, which meant that we needed a new container for our cell. Therefore, this time plastic was selected as the cavity material. Furthermore, the size of the plastic container that we selected was much smaller as compared to the previous glass tank that we used, so that more efficient photovoltaic effect could be observed.

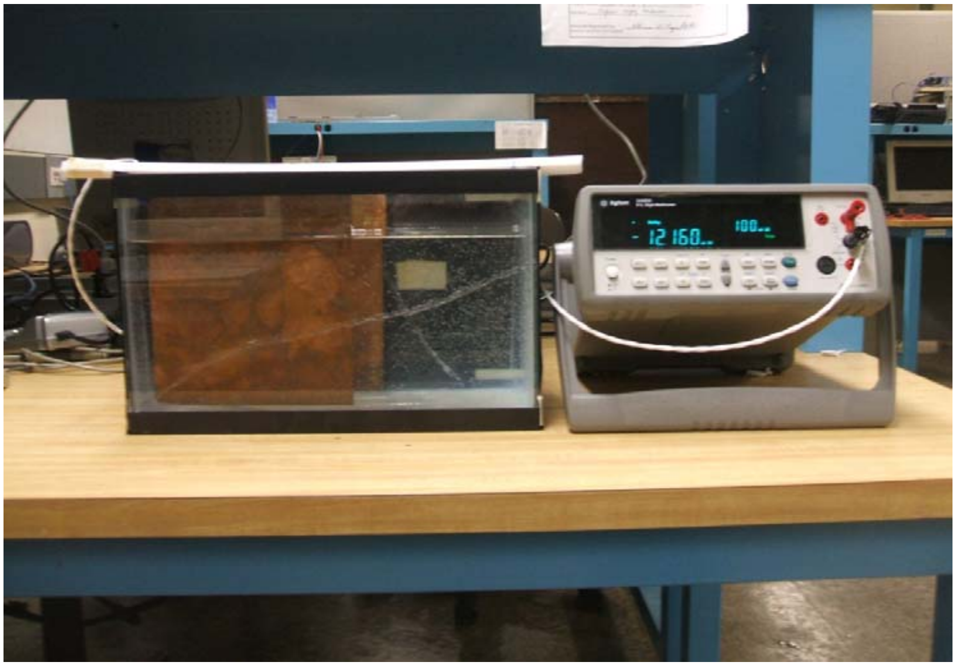

Figure 8: Our initial setup consisting of two copper plates immersed in NaCl solution inside a glass tank.

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[16] (Honda)

For the electrolyte, we had an option of using either one of the following: an acid, base, or a neutral salt solution. We decided to go with the salt solution because it the most readily available solution out of all of these; and it is also the least harmful one to be used in an experiment such as this. Last but not least, the salt water is the ocean water.

But before we could use it as the electrolyte, we needed to prove that it would yield us better results than a plain water solution. So we conducted our experimentation first with pure water and then with salt water, and then compared the results that were achieved with each one of them. Distilled water was used for this purpose, and then regular table salt (NaCl) was added to it to prepare the salt water solution. After comparing the results that were obtained by using each one of these as electrolytes, it was clear to us that salt water acted as a much better electrolyte. Hence, we used the aqueous Sodium Chloride (NaCl) solution as the salt water electrolyte for our cell. Varying concentrations of this solution were used and corresponding results were observed and recorded. These different concentrations of the solution were achieved by adding different amounts of table salt into the solution before conducting each experiment.

To decide what kind of electrodes we should use for our experimentation, we need to test different materials. This implies that we have to carry out the experimentation with different materials as electrodes. For this purpose, the experimentation was carried out with aluminum, steel, and copper plates separately, and their respective results were recorded. The best results (meaning the maximum potential difference and current values) were seen when we had the two copper plates as our electrodes. Hence, copper was selected as our material for the electrodes. An experimentation was also conducted to see whether the size of the electrodes had any effect on the produced potential difference or not. It was observed that the surface area of the electrodes was directly proportional to the electric power produced. Hence, in our final design we had to keep this factor in mind while selecting the size and shape of the electrode.

In Hankel's experiments (1877) it was suggested that one of our electrodes had to be made out of pure copper, while the other one needed to have a uniform coating of cuprous oxide on top of it. That is because the oxide layer, when coupled with the metal itself, helps in creating a P-N junction. This circumstance creates a rectifier effect in the design, and facilitated the flow of electrons through the electrolyte and between the two electrodes.

To create this oxide layer on the copper electrode, we applied a large amount of heat to the copper plate. For that purpose, this copper plate was heated in a furnace at a thermocouple temperature of about 700°C for almost an hour. The plate required oxygen from the air in order to get oxidized, and for this reason the furnace door wasn't closed completely while it was being heated. By the end of this heat treatment, a reddish-brown layer of cuprous oxide (Cu_2O), along with some black patches of cupric oxide (CuO), was clearly observed on the plate. This means that most of the copper on the surface had been oxidized to either one of the two copper oxides, and that this plate was now ready to be used as an electrode in our cell.

For the second electrode, which was supposed to be made out of pure copper electrode, we decided to use a pure copper mesh. The mesh was chosen to be the electrode instead of a regular plate in order to maximize the light-exposed surface area of the metal in the electrolyte. We had determined in our initial experimentation that a greater surface area for the electrodes leads to a greater output power, and this was the main reason why we used the copper mesh as the second electrode.

3.3 Final Design

After going through all of the design iterations and initial design experimentation described above, the final design for our setup was eventually determined. The main features for our liquid junction solar cell were as following:

- Electrolyte: Aqueous Sodium Chloride (NaCl) of varying concentrations.
- First electrode: Copper plate (4.85’’ x 3.70’’) coated with cuprous oxide layer
- Second electrode: uncoated Copper mesh (4’’ x 4’’).
- Cavity material: Plastic (7.38’’ x 5.31’’)

The CAD (Computer-Aided Design) layout for our cell can be seen in the following **Figure 9**:

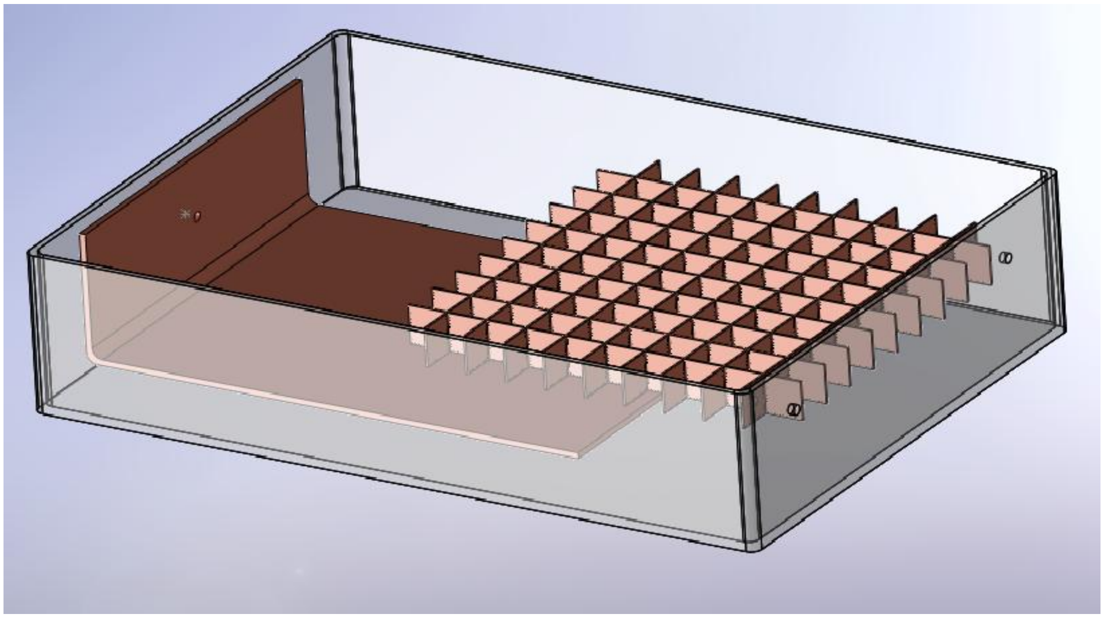

Figure 9: CAD model of our solar cell cavity

In this CAD layout of our design, we can clearly see the two electrodes placed inside the plastic cavity. The pure copper mesh can be seen on top of the second electrode in the figure. But these two electrodes were not in direct contact with each other. The cavity was filled with salt solution almost to the brim, until the point that both the electrodes were completely immersed in the electrolyte. Then, it was exposed to the external light source.

Figure 10 shows the mechanical diagram for our solar cell from different angles, which contains all the dimensions for the cavity, the oxidized copper plate, and the copper mesh. All measurements in the figure were made in inches.

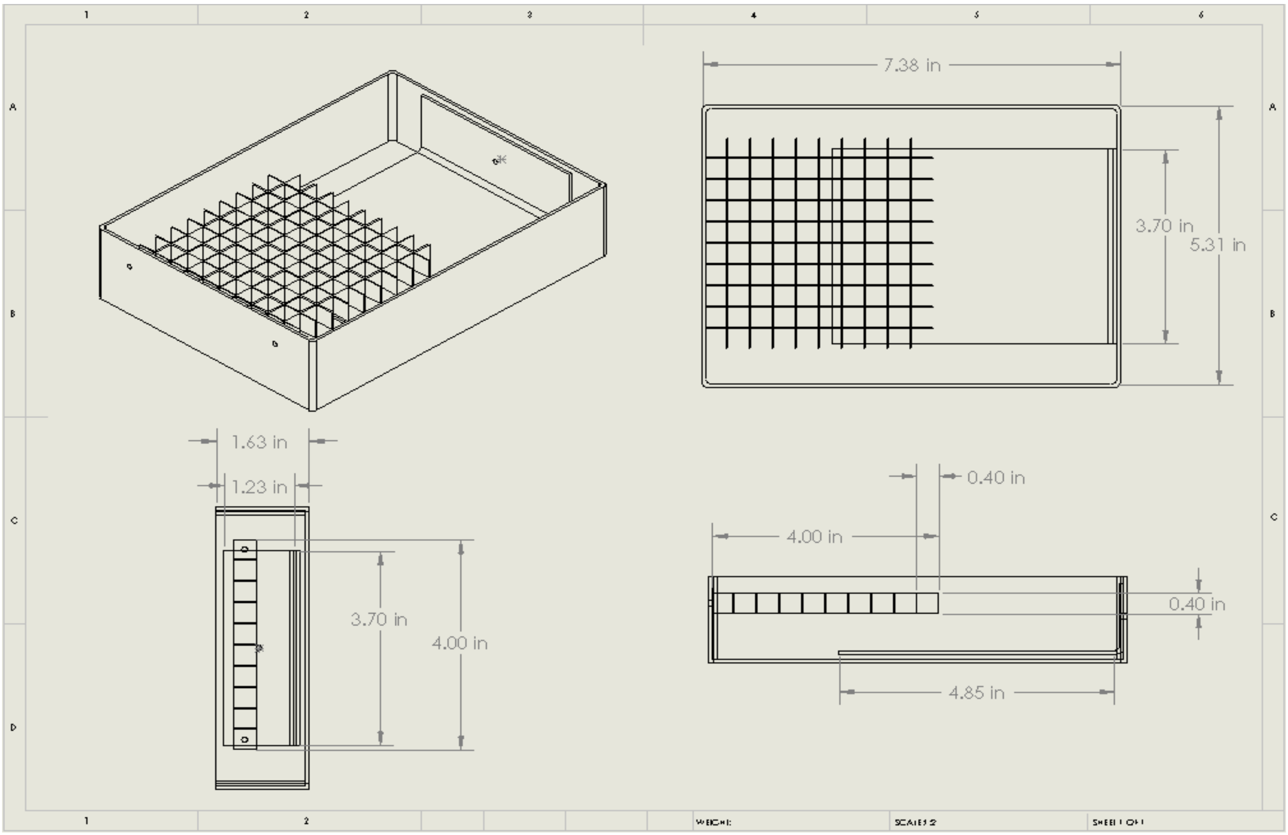

Figure 10: Mechanical diagram of our solar cell

The overall size of our solar cell was smaller as compared to the original glass container that we had. This can be seen in the diagram above, which shows that the dimensions for our plastic cavity were 7.38’’ by 5.38’’. This choice of container helped us in keeping our total cell size very small and compact. It was an easy setup to maintain, and also the results obtained were much closer to what we were initially expecting.

Throughout the experimentation, a 500W incandescent light bulb was used as the external light source, at a certain distance from the container. Its spectrum approximately approaches the spectrum of the sun light. The bulb was mounted on a tripod stand so that it was easier to shine it down on our solar cell. An Agilent 34405A digital multimeter (DMM) was used through out to measure voltage and/or current values that our cell was generating. Hence, two wires coming from the multimeter were connected to each one of the electrodes to make these measurements.

The solar cell, the digital multimeter (DMM), and the wire connections can be seen in the actual photograph of our design in **Figure 11**. The 500W light bulb illuminating the whole setup can also be seen.

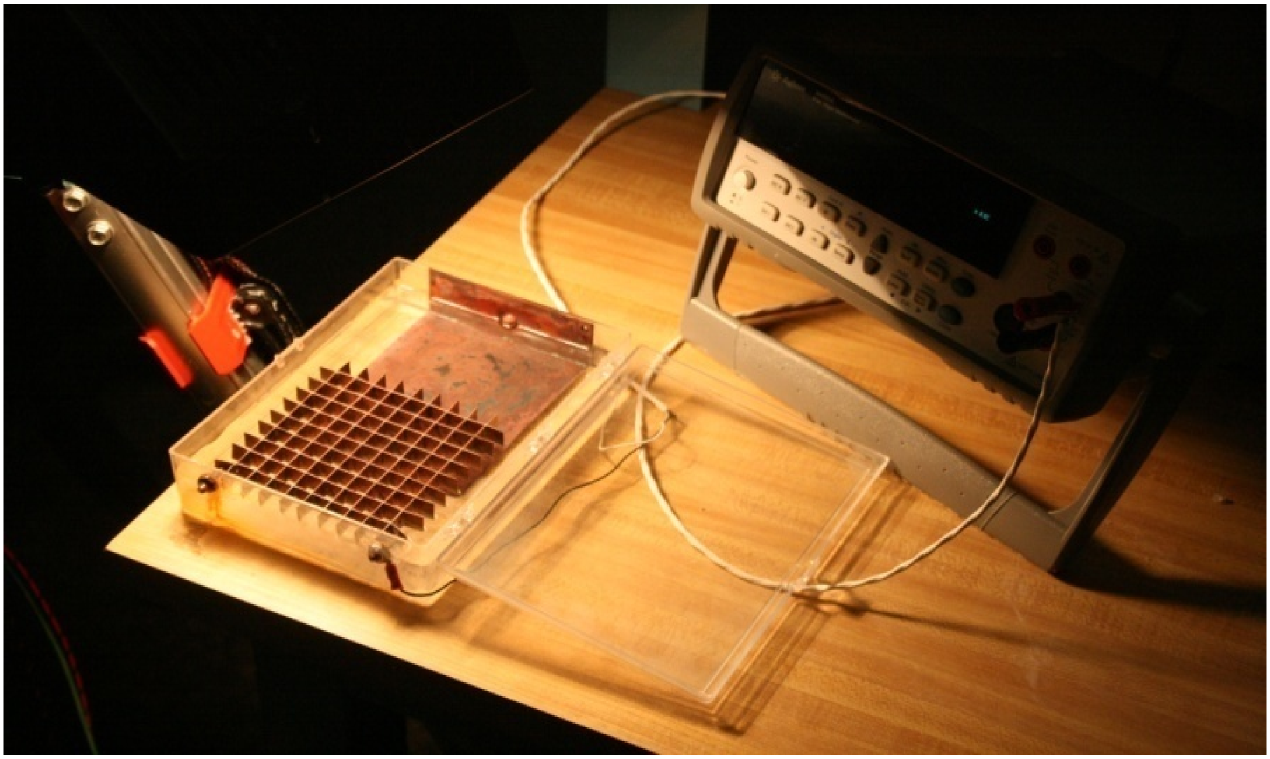

Figure 11: Photograph of apparatus

3.4 Experimentation

Having decided on our final setup, we proceeded forward and carried out experimentations that were necessary to prove that this solar cell was capable of producing the desired results. Therefore, we connected our DMM probes to the electrodes and filled up the container with the different electrolytes that we were going to use one by one.

However, the experimentation that is described in the following first subsection was still conducted in our initial glass tank setup, and hence its output values were quite different from the rest of experimentations, that were performed using the plastic cavity.

3.4.1 Glass Tank Experimentation

This part of the experimentation was performed when we were using the glass container as the cavity, and this setup can be seen in **Figure 12**. In this setup, we were using two copper plates as the electrodes, with one of them coated with the oxide layer. Later, we modified our design and used a plastic container for the cavity and a copper mesh as one of the electrodes for the cell.

Figure 12: Glass tank apparatus

Using plain water as the electrolyte:

As was described in the design iterations section, we first conducted our experiment using distilled water as the electrolyte for our system. When no light was applied to the setup, a **15mV** voltage was produced between the two electrodes. This was because the copper plates and the distilled water together formed a capacitor in which the electrodes were initially charged statically. When light was applied to one of the electrodes from our 500W light bulb, the voltage reading on the DMM changed to **-30mv**. This meant that a total potential difference of **45mV** was being produced when we had the distilled water as our electrolyte.

Using Aqueous Sodium Chloride (NaCl) as the electrolyte:

For this part, we added a few table spoons of table salt to prepare a 3% aq. NaCl solution. With that as our electrolyte, we observed some difference in our results. The potential difference produced this time was about **60mV**, when we switched on the high-power light bulb on top of the setup. However, this voltage was not being produced because of the capacitor effect that was seen with distilled water. It was being produced because of the ions that were now present in the solution (aq. Na^+ and aq. Cl^- ions). These facilitated the movement of the electrons in the solution and thus caused a photo-voltaic effect to be observed on the DMM.

3.4.2 Plastic Container Experimentation

As we were not getting the desired results with our initial setup, we had to revise it accordingly. Our new setup consisted of a plastic container, a pure copper mesh and a copper plate coated with cuprous oxide. Once we had it setup, we conducted our experimentation in a slightly different manner.

In our new setup, the light from the source could be introduced from the top of the setup and not necessarily from the side, as was supposed to be done with the glass-tank setup. And with our new setup, we felt a need for a more accurate and reliable technique of measuring the voltage and current values. And hence, we installed the software "LabVIEW Signal Express" from National Instruments on the computer on our bench, and connected our DMM to this computer, so that the voltage/current values could be recorded and displayed in a more proper manner using this software. It allowed us to record voltage/current over a certain period of time, store the data in a spreadsheet, and finally display it in the form of a graph.

After we had all our hardware and software setup, we went forth and performed the experimentations using the different concentrations of salt solution. To vary the solution concentrations, different amounts of table salt were added to the distilled water every time to make sure that the correct solution concentration was achieved. We conducted our experimentation for three different concentrations of the salt solution:

- 3.5% aq. NaCl solution;
- 35% aq. NaCl solution;
- 60% aq. NaCl solution.

For each concentration, we recorded the voltage/current values using the same DMM and "LabVIEW" software. This gave us a large number of output values over a certain period of time, which we selected accordingly.

The light intensity of the external source was kept constant at **500lux** (kilo-Lux) throughout the experimentation. This was produced by the 500W bulb that we had mounted on a tripod, and it was measured using a light intensity meter. It gave us the 500lux value when the bulb was kept at a certain distance from the solar cell, and we made sure that the same distance from the setup was maintained throughout, while we performed our experimentation with different salt concentrations.

At the end, we also performed a set of experimentations where we wanted to observe the effect of light intensity on our output voltage and current values. For that, we kept the concentration of the salt solution constant and repeated the experiment several times with the light source placed at different distances from the setup. The light intensity at the electrolyte surface was measured every time with the light intensity meter and the corresponding current values were recorded. Each time when the light source was switched on, the corresponding rise in the current value was recorded. Finally, all the results were compiled together and compared to each other for evaluation purposes.

4. RESULTS

4.1 Experimental Parameters

The electricity produced by our setup described in the methodology section depends on important parameters. These include:

-The concentration (salinity) of the ionic salt solution

-The intensity of light

The following section will describe the effects of each of these variables on the current and voltage generated.

4.2 3.5% NaCl Solution

The concentration of the salt in our electrolyte was first changed keeping all the other factors constant. A light intensity meter was used to keep our 500W bulb at a distance that resulted in 500lux of intensity. This is the average light intensity that reaches the Earth's surface every day. National Instruments' LabVIEW SignalExpress was used as the program for signal acquisition and calibration of our solar cell. **Figure 13** below shows the graph of voltage versus time when the 500W light bulb was switched on and the solution was not stirred. When the light was off, a constant voltage of approximately 14 mV (milli-Volts) resulted. The spike in voltage to about 92 mV was observed when the light was turned on. It was also noticed that shortly after reaching the peak, the voltage decreased gradually to reach a constant value of 80 mV. The current versus time graph is shown in **Figure 14**. When the light was off, a constant current of 100 µA (micro-amperes) was observed using LabView SignalExpress. The light caused a spike in current of 3.8 mA (mili-amperes) and as it stayed on, the current gradually stabilized following an exponential law.

The current and voltage generated prior to the light were due to a few reasons. The positive and negative ions in the salt solution acted as charge carriers to conduct charge between the negative and positive copper surfaces. The water also acts as a capacitance dielectric and separates charges that are accumulated on the two separate plates. This explains the voltage observed while the bulb was off. Furthermore, the concentration of 3.5% matches the approximate 3.5% salinity of ocean water. This concentration was chosen to meet our goal to simulate copper electrodes in ocean water for the generation of power.

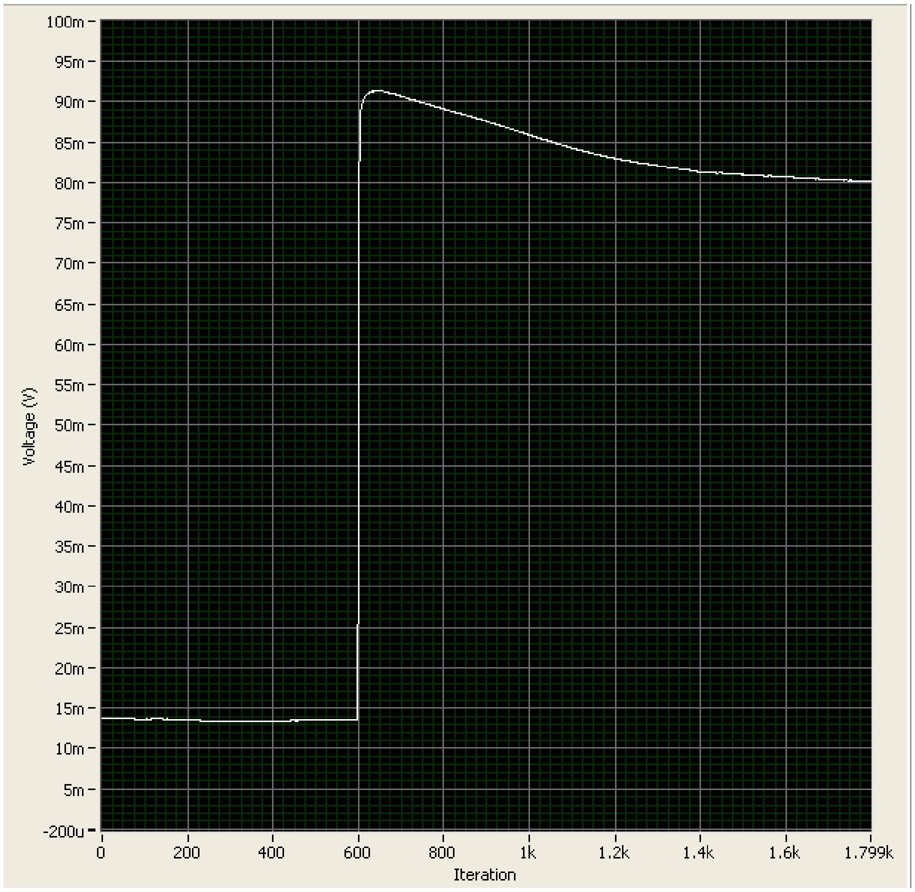

Figure 13: Graph of Voltage (V) vs Time (milliseconds; 1.4k=1.4seconds) with 3.5 % solution

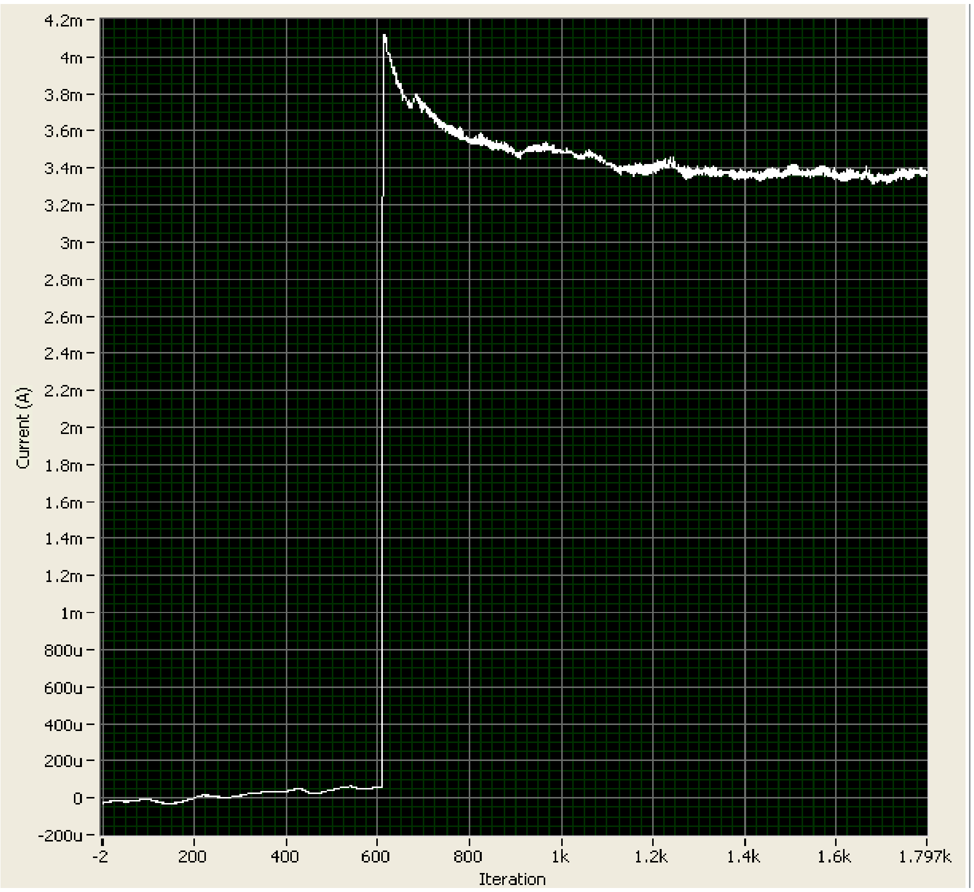

Figure 14: Graph of Current (A) vs Time (milliseconds; 1.4k=1.4seconds) with 3.5 % solution

4.3 35% NaCl Solution

The concentration of the solution was changed to 35% by mass of NaCl. The solution was stirred well to allow the salt to dissolve and not saturate the solution. The same procedure was conducted to measure the voltage and current generated. The two graphs of voltage and current versus time can be seen in **Figure 16** and **Figure 16** below, respectively. The voltage jump was from 162 mV to 210 mV. Note that even if the change is only 48 mV, the overall magnitude of the voltage has been more than doubled with an increased concentration and can be harnessed. Also, the initial peak current of 3.7 mA increased to 7.5 mA. This increase of 3.8 mA was observed and was close to the increase in the 3.5 % solution. The major differences can be seen in the profile of the curves. The voltage was increasing linearly when the light was off. There was a vertical spike and then a gradual increase (instead of a decrease as was the case with the 3.5% solution) The current profiles are also different. The 35 % solution creates a constant current before and after the spike, unlike the results for the 3.5 % solution.

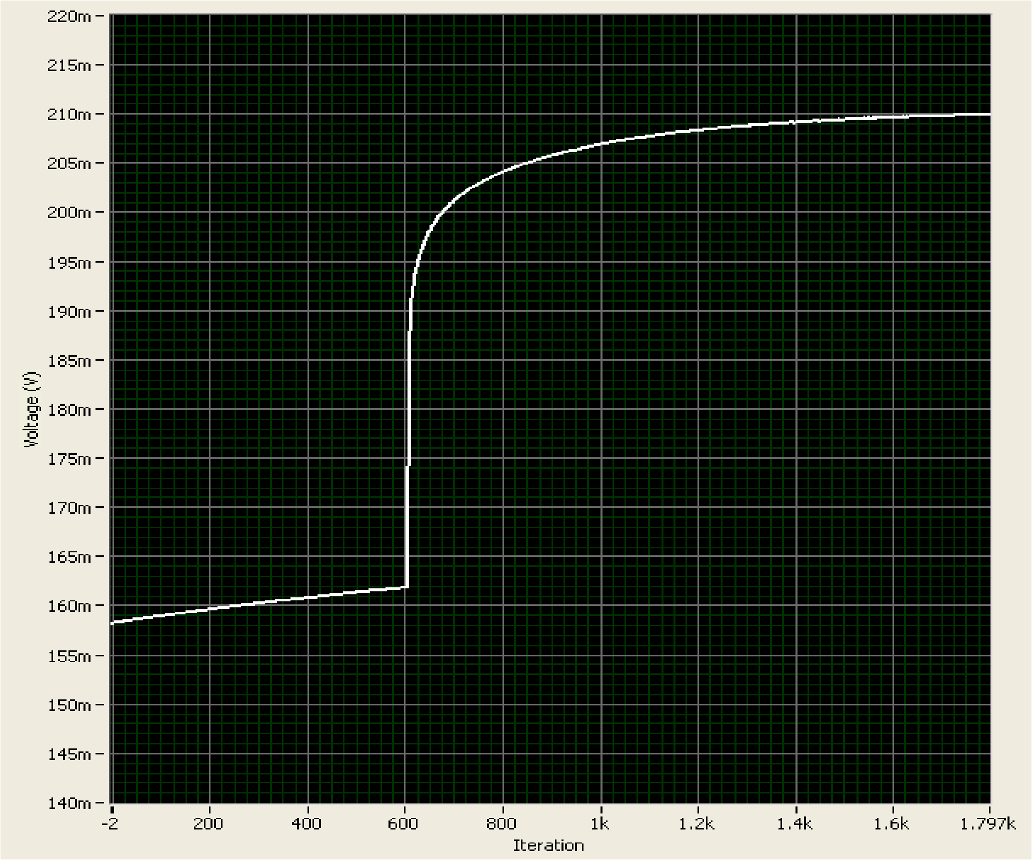

Figure 15: Graph of Voltage (V) vs Time (milliseconds; 1.4k=1.4seconds) with 35 % solution

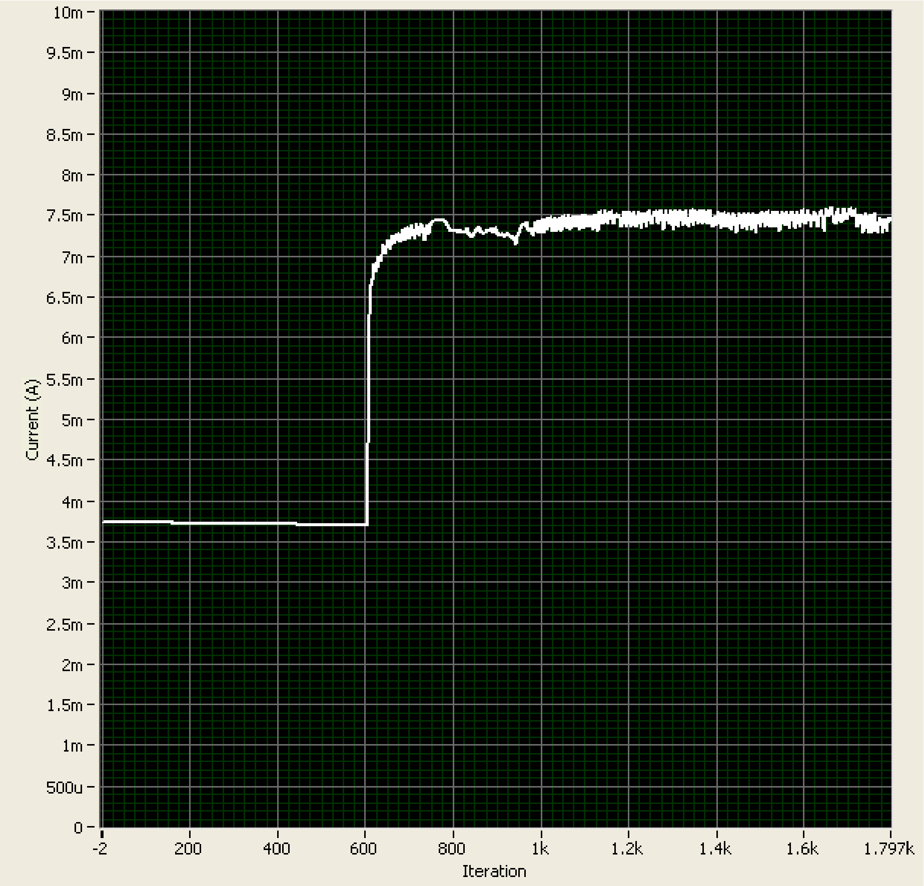

Figure 16: Graph of Current (A) vs Time (milliseconds; 1.4k=1.4seconds) with 35 % solution

Error! Reference source not found. below summarizes the results shown in the graphs above.

Table 4: SUMMARY OF OUR EXPERIMENTAL RESULTS

Solution Concentration	Current Analysis			Voltage Analysis		
-	Initial Current(mA)	Final Current(mA)	Current Rise(mA)	Initial Voltage(mV)	Final Voltage(mV)	Voltage Rise(mV)
3.50%	0	4.1	4.1	14	92	78
35%	3.7	7.5	3.8	162	210	48

4.4 Current Versus Light Intensity

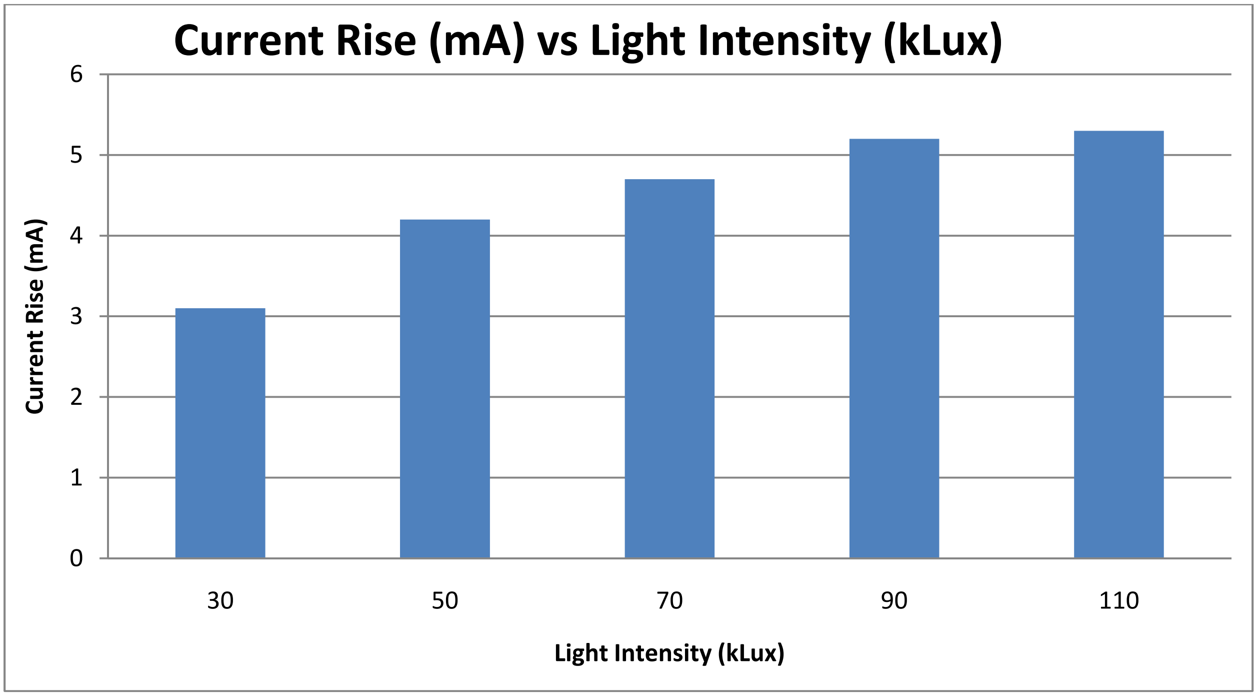

Figure 17: Current rise (mA) vs Light Intensity (kLux)

The effect of light intensity on the current was tested using a Lux meter to measure the light intensity of the 500 W light bulb. The light sensor was placed at the surface of our solar cell and the light bulb was moved towards or away to obtain the desired intensity in klux (kilo-lux). **Figure 17** above shows a bar chart of current in milli-amperes for different light intensities. The concentration of the solution was also set at a constant 3.5 % NaCl for varying intensities. Intensities in increments of 20 klux were tested and the current increased until it reached 90 klux. Further increasing the intensity i.e. moving the light bulb very close to the solar cell did not entice a raise in current. The current stayed constant instead. Hence, the 90 klux flux acts as a threshold intensity for the 3.5 % salt solution.

5. DISCUSSION

5.1 How does our solar cell work?

Cuprous oxide(Cu_2O) was used in our solar cell because it was the first reported substance to be used in liquid junction solar cells and in electronic diode rectification devices. **Figure 18** below shows a simple electric diode that used Cu_2O.

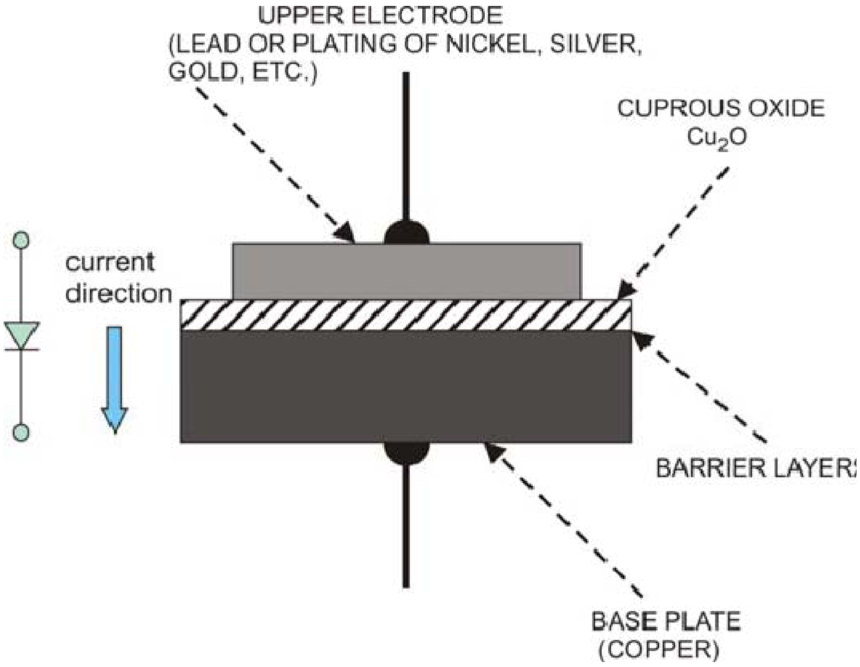

Figure 18: Cuprous oxide diode with metal-semiconductor junction[17]

The diode consisted of a Cu_2O which was formed on the copper baseplate using heat treatment as explained earlier. The upper electrode is a different metal such as Lead which was plated with a transition metal. Cu_2O also exists in nature as a naturally p-doped semiconductor. The junction between the copper metal and the oxide layer acts differently than that between two unlikely doped semiconductor materials (such as an n-type and a p-type). The junction is instead a metal-semiconductor junction and behaves more like a Schottky diode. A Schottky diode however, has a low rectification effect than a regular semiconductor diode made of Si or Ge.

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[17] (Stansel)

A typical solar cell’s p-n junction experiences charge separation when it is illuminated by light. **Figure 19** below shows a typical charge separation curve between p-type and n-type. When quanta of light (photons) hit the surface of a contacted p and n type material, the energy is absorbed based on the material’s work function. This energy enables electrons that are present in high energy states (quantum levels of an atom) to be knocked-off. In a p-type material, this results in electron holes to be created. In a n-type, it results in a more mobile electrons.

In **Figure 19**, a detailed explanation of how the charge separation occurs is provided. Any PN-junction (junction of two materials with opposite carrier types) has a built-in potential that causes a charge separation to take place resulting in an electric power generation.

In comparison to our solar cell, the above diode in **Figure 18** is a solid-state device; it has a low effect towards the current. According to our results, the more dominant junction appears between the p doped Cu_2O and the salt solution. **Figure 20** below suggests our explanation: the separation caused by the built in potential of the Cu_2O. Since the salt solution is neutral; it consists of an equal of amount of positive and negative ions, it acts as our intrinsic materials with no built-in potential.

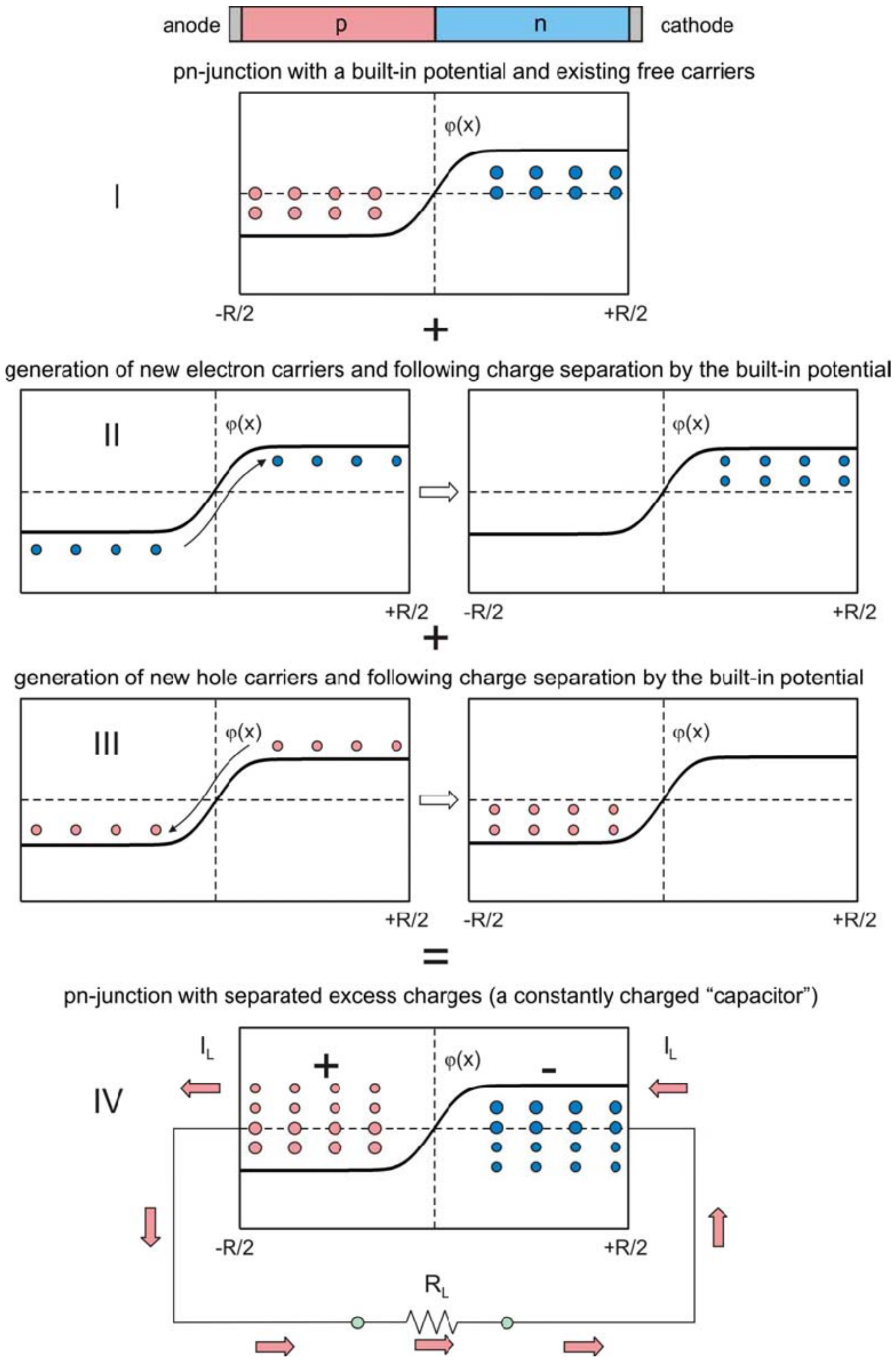

Figure 19: Charge separation caused by built-in potential[18]

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[18] (Makarov, Ludwig and Bitar)

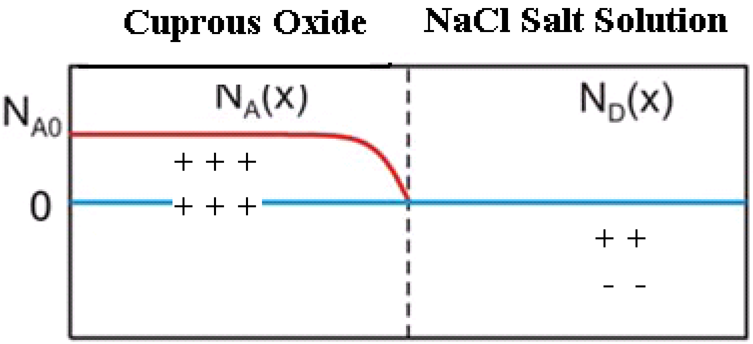

Figure 20: Charge separation in our solar cell[19]

Cu_2O has an abundance of holes while the salt solution is neutral and acts as an intrinsic material. This still causes enough charge separation to overcome the built-in voltage present between the copper metal and the cuprous oxide. The complete circuit that may describe our cell operation is shown in **Figure 21** below. A Schottky diode might exist between the Cu_2O and the copper metal but its voltage is negligible.

Thus, the ionic solution acts as a charge carrier as it has dissociative positive sodium ions and negative chloride ions. Furthermore, we know that the Schottky diode is not working in our cell because when the current flow and voltage were noted as positive values when we connected the terminals in the orientation of **Figure 21**. This can also be seen in our graphs in **Figures 14 to 16**.

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[19] (Makarov, Ludwig and Bitar)

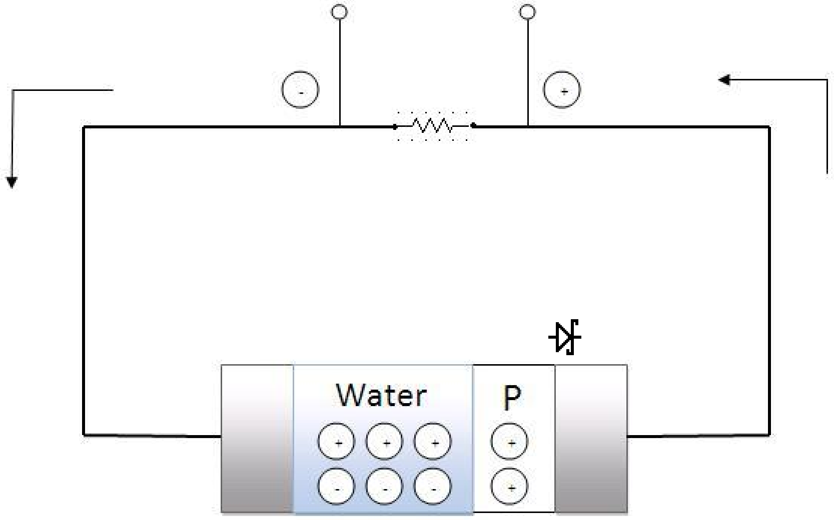

Figure 21: Circuit schematic of our solar cell with a negligible Schottky diode effect between cuprous oxide and copper

5.2 Light Intensity

The electric power generated by the solar cell upon illumination is measured in Watts and depends on the incident light intensity. The light intensity also only effects the current density and does not alter the voltage. A solar cell can be compared to be a regular battery with a specified output voltage (e.m.f). **Figure 22** below shows the two basic circuits of a solar cell and a battery. In the solar cell circuit, there is no theoretically no current flow during darkness., but current is generated when there is sunlight due to charge separation. This current is known as a short circuit current and the voltage an open circuit voltage. Hence, power is generated when there is any kind of resistance load present in the circuit. Similarly, a battery develops e.m.f due to the electrochemical reactions within it.

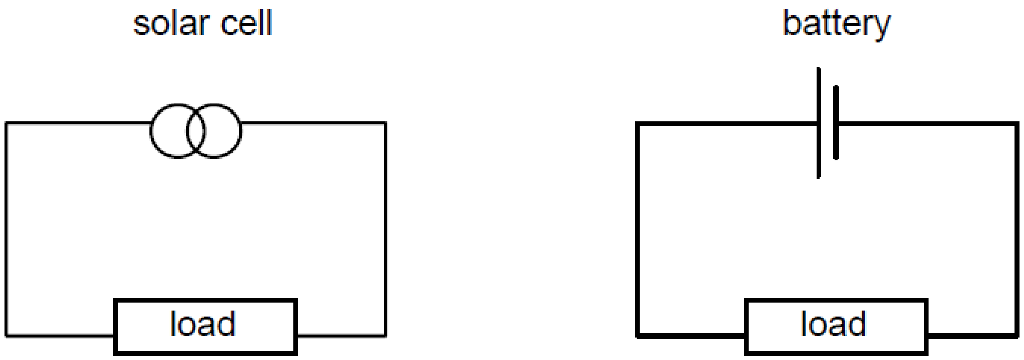

Figure 22: Basic circuits of a battery (left) and solar cell (right) where the solar cell is an ideal current source and the battery is an e.m.f generator[20]

The current density is directly proportional to the light intensity which leaves the voltage unaffected. The power generated is following the gain in current caused by the gain in light intensity of the solar cell as seen in our experimental results.

In our experiment, we increased the light intensity by moving the light bulb closer to the apparatus and simultaneously measuring the light intensity. The largest intensity was created with the bulb almost at the surface of the solar cell, but the current approached a constant value due to the limitations of charge carriers in the ionic solution. In a solid state solar cell containing a PN-junction, an increased intensity would proportionally increase current thereby increasing power output.

Since power is a function of current, an increased current resulted in greater power generation and improved the efficiency of our solar cell.

5.3 Ionic Concentration of the electrolyte

The ionic concentration of the electrolyte increased the magnitude of the current and voltage produced by our solar cell. Note that the change in current and voltage decreased. The presence

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[20] (Nelson)

of a greater number of ions in the solution introduced more charge carriers. It is due this reason that the peak voltage did not drop right after reaching the peak, but reached a steady value. Since more electrons were emitted on the surface of the copper, a greater number of charge carriers kept the flow and reduction-oxidation reactions alive. The electro potential produced by a regular electrochemical solution is given by the Nernst equations.

$$E_{cell} = E_{cell} - \frac{RT}{nF}\ln(Q) \quad (3)$$

In the above equation,

E_{cell} is the potential produced by the cell;

R is the universal gas constant;

T is the temperature;

n is the number of moles of electrons present in the solution;

Q is the reaction quotient;

As can be seen, the increase in ions and electrons in the solution enhances the electro potential produced. Note that a greater concentration resulted in a smaller change in voltage and current when the light was switched on. A greater solution means more charge carriers which results in an overall greater current. This increased the efficiency of our solar cell too.

6. CONCLUSION & RECOMMENDATIONS

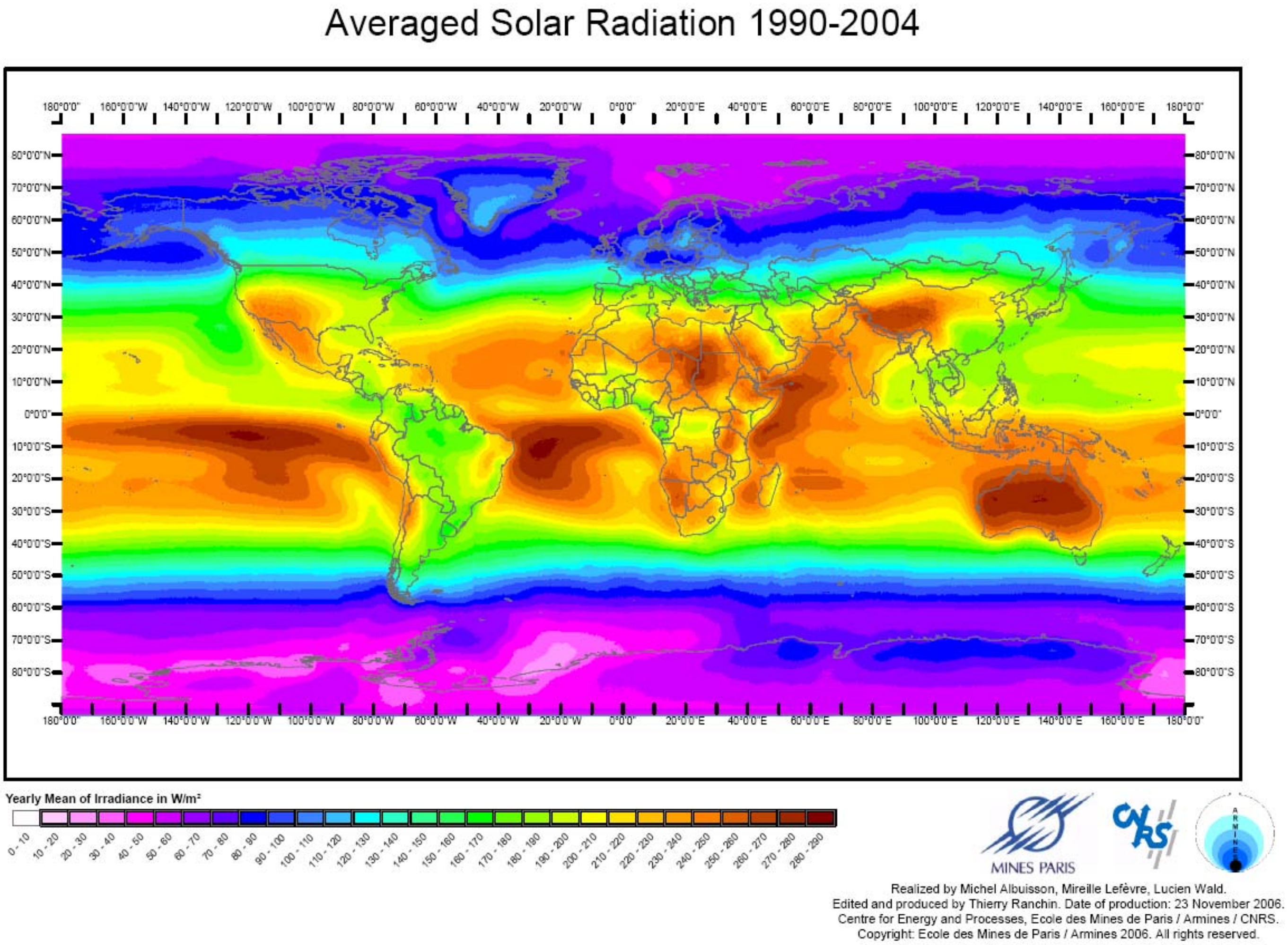
Our experimental proved to yield results that were higher than other experiments achieved. The copper-cuprous experiments conducted b Guoy and Riggollot (as mentioned earlier in the report) generated 0.1 Volts. In other experiments, the current generated was 50 microamperes at 0.25 Volts. In comparison, we were able to generate .21 Volts at 35% NaCl concentration and 4.1 milliamperes at 3.5% NaCl concentration. Our light intensities represented the average solar intensity that the Earth’s surface receives every day.

The goal of this IQP was to lower the price/Watt of solar power by proposing alternate solar cells made of cheap materials. Based on our research of existing solar cells and by designing and testing alternative ionic solar cells we have proposed a model for a new solar cell. It consists of a PN junction made of Copper and Copper (II) Oxide along with Ionic Salt water (NaCl) solution.

One major place where our proposed model of a solar cell can be implemented is in the large salt water bodies of the earth. Earth surface has nearly 60% salt water, in the form of seas and oceans. With our experiment, we were also able to propose a system using the ocean water and copper.

Theoretically, all these water bodies are potential solar cells because if we immerse copper and cuprous oxide electrodes in them. Then because of the photovoltaic effect as displayed in our model we would be able to harness a huge amount of solar energy and convert it into electrical energy.

Figure 23 shows the distribution of average daily solar radiation in different areas of the world. The darker sections of the map indicate the areas that would be most suitable for our proposed cell mode.



Realized by Michel Albuisson, Mireille Lefèvre, Lucien Wald.
Edited and produced by Thierry Ranchin. Date of production: 23 November 2006.
Centre for Energy and Processes, Ecole des Mines de Paris / Armines / CNRS.
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Figure 23: Average solar radiation received by the surface of the Earth[21]

Therefore our model does provide a certain ray of hope of lowering the price per watt. This is because of the fact that price per kilogram of copper currently stands at $6 per kilogram whereas, the cost of crystalline silicon stands at almost $400 per kilogram. This substantial difference in the costs of the materials can outweigh any differences in efficiency which exist between copper and silicon.

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[21] (Ranchin)

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8. APPENDICES

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