Solar Power

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Abstract

The notion of using sunlight to create power has been around for a long time. With the discovery of semi-conductors and the advances of material processing in the 1960s, it became possible to convert the sunlight into usable electrical power on a larger scale then previously possible. The average irradiance that the sun delivers to the earth is approximately 1,000 W/m^2, so if it becomes possible to efficiently convert this irradiance into electricity, or other useful energy applications, solar power will become a vital resource to help fuel an ever growing population. Early theoretical investigations into the efficiency of single junction solar cells predicted a maximum efficiency of 31%. Advances in the theoretical understanding of solid state matter, and new technological innovations in material processing, has dramatically increased the maximum possible theoretical efficiency of solar cells to around 66%. This paper contains a brief historical overview of solar power, followed by a review of the physics involved in studying photovoltaic material. The review covers the process of oxygenetic photosynthesis and several types of photovoltaic cells. These being: the single junction solar cell, the multi-junction solar cell, hot carrier solar cells, hot impact ionization solar cells, and excitonic solar cells. A cost analysis of different methods of generating electricity and the pollution created by the power source is discussed. The paper concludes with a discussion of the future prospects for the solar power market.

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1. History

In 1839 Edmund Becqueral, a nineteen year old researcher, was the first person to observe and make account of the fact that light from the sun could be used to create electrical current. It would take 66 years before Albert Einstein would be able to quantitatively describe the cause of the electrical current in terms of the photoelectric effect.

This field of solar power is known as photovoltaics, where the sun's energy is converted directly into electricity. Another important field of solar power is the conversion of the sun's heat into mechanical work. Thermal solar power plants exemplify this. In a thermal plant large parabolic concentrators focus the light of the sun onto pipes filled with water in the focal lines of the collectors. The temperature achieved can be 400^{o} C. This boils the water and creates the steam used to turn a turbine, and create electricity. This historical review covers both aspects of solar power

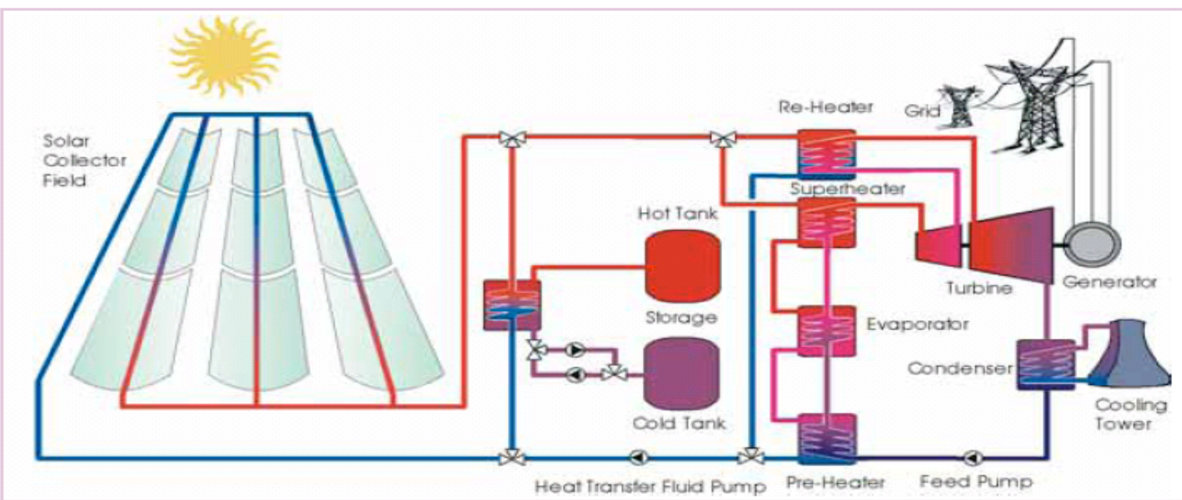


Figure 1. Steam cycle power plant. [1]

simultaneously. An example of a thermal solar power plant can be seen in figure 1.

By 1861, Auguste Mouchout was granted a patent for a motor that ran on solar power. The basic idea of the motor was to use concentrated sunlight in order to boil water and create steam to turn a turbine. Mouchout was successful in getting financial support from Emperor Napoleon III in Paris to construct an industrial solar powered motor. As a demonstration of the usefulness of this new device he connected it to a steam engine that powered a water pump. On a hot day, he showed the machine could produce one-half horsepower. When Mouchout reported his findings back to the French Academy of Science, he was met with a very positive response. The Academy decided the best way to use this new technology would be to utilize the geographical location of the French protectorate of Algeria which was close to the equator, and heavily dependent on coal which was difficult to obtain.

In photovoltaics, thirty seven years after Dr. Becqueral's discovery in 1873 a scientist by the name of Willouby Smith observed that the element selenium is sensitive to light. This was one of the first findings showing that solid state material could be used to convert the suns light into electricity.

Returning to Auguste Mouchout, after redesigning his invention in Algeria, he brought his device to the Paris Exposition in 1878. He hooked it up to a refrigeration device and "The steam from the solar motor, after being routed through a condenser, rapidly cooled the inside of a separate insulated compartment." {1} He was awarded a medal for his ingenuity in finding it was possible to create ice from the power of the sun. After this, in 1881, the French Ministry of Public Works appropriated money for two of its commissioners to ascertain the viability of solar power. Unfortunately for the nascent discipline of solar energy, the commissioners decided that solar power was not a viable option for the large scale production of power. France, at this time, was a consumer of coal and had just signed an agreement with England for the supply of large amounts of the product. Fossil fuels at this time, primarily coal, were taking the position of the dominant supplier of power, which it still has to this day. A timeline of the introduction of various forms power production is shown in figure 2.

By 1883 an inventor Charles Fritz created a solar cell with an efficiency of 1-2%.

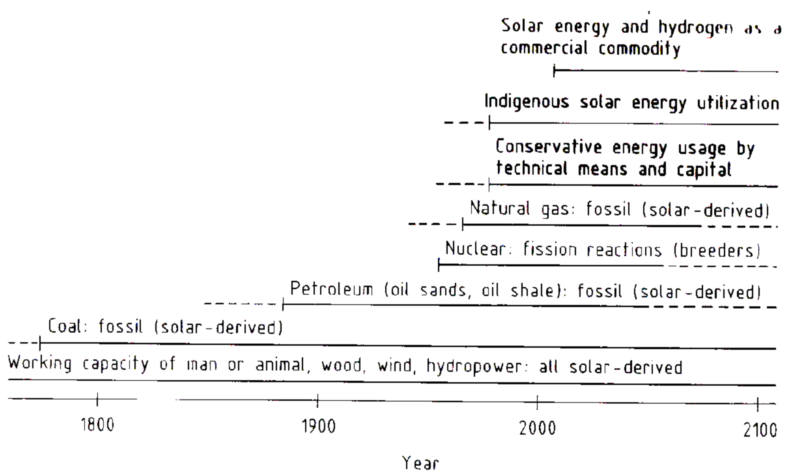


Figure 2. History of world energy. [2]

An Englishman by the name of William Adams, living in Bombay, India, was influenced by Auguste Mouchout's work and redesigned Augusts solar motor. With this motor he obtained a power output of 2.5 horsepower in 1878.

The next prominent figure in solar power is Charles Tellier, who is more prominently known for his work in refrigeration. In 1885 he redesigned the solar collectors to use ammonia instead of water as a working substance. "Tellier chose ammonia as a working fluid because of its significantly lower boiling point. After solar exposure, the containers emitted enough pressurized ammonia gas to power a water pump he placed in his well at the rate of some 300 gallons per hour during daylight." {1} So, while very slow progress was being made in the theory of photovoltaics (i.e. using solid state material to convert sunlight into electricity), a great deal of progress was being made in using concentrated solar light to power steam engines.

The focus of solar power development then turned to the United States in 1886 with Swedish born engineer John Ericsson. He was the first person to incorporate into the solar design the parabolic trough. The parabolic trough focuses the incoming light into a line and greatly increases its efficiency. In fact this design has withstood the test of time

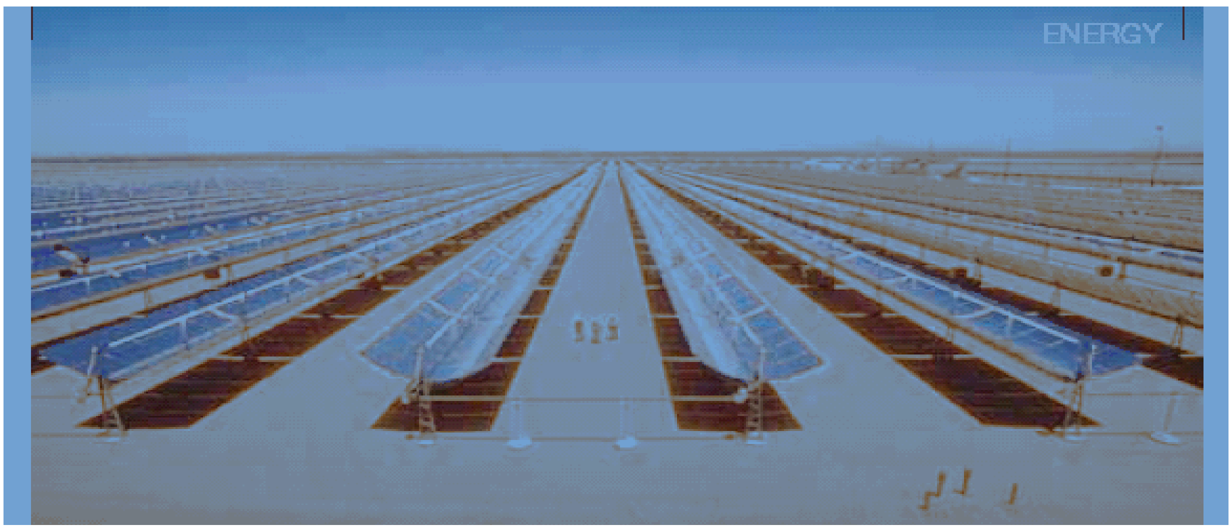


Figure 3. Parabolic trough concentrating solar collectors. [3]

and is used today at a number of large solar power plants. The parabolic mirrors of a modern plant are shown in figure 3.

In 1898, Thomas Edison obtained a patent for the incandescent light bulb. As a result of this invention and other new inventions, the demand for cheap and reliable electricity began to grow.

The first solar power company, The Solar Motor Company, was created in 1900 by American Aubrey Eneas. To demonstrate the usefulness of his solar motor he took his machine to sunny Pasadena California and successfully pumped water out of the ground at a rate of 1,400 gallons per minute. Unfortunately, the design of the system was susceptible to changes in the weather, and his machines were destroyed shortly after installation. This was due to the fact that the concentrating apparatus was over 30 feet in diameter. Because of Eneas' inability to create a reliable product The Solar Motor Company soon went bankrupt.

Next, Henry E Willsie picked up the torch of solar progress. He was the first person to realize that solar power plants could operate on a continuous cycle. Willsie used large insulating containers to store hundreds of gallons of water, which would be heated by the sun during the day. At night he would "submerge a series of tubes, or vaporizing pipes, inside the basin to serve as boilers. When the acting medium in this case sulfur dioxide passed through the pipes, it transformed into a high-pressure vapor, which passed to the engine, operated it, and exhausted into a condensing tube, where it cooled, returned to liquid state, and was reused." {1} With this technology, Willsie was able to construct two separate solar energy plants, one in St. Louis, MO that generated 6 horsepower, and the other in Needles, CA that generated 15 horsepower. Even though Willsie showed that the operation was economically viable over the long term, nobody was interested in investing in a unit. Eventually, his company also went bankrupt.

The person that was closest to making solar energy a viable power source was Frank Shuman. Who, in 1911, built a solar power plant that intercepted over ten thousand square feet of solar irradiance. He then asked engineer E.P. Haines to help optimize the assembly. When Shuman and Haines were complete the solar power station generated 33 horsepower and could pump 3,000 gallons of water per minute from the ground. According to Shuman, his power plant operated at a cost of $200 per horsepower. At this time coal was around $80 per horsepower. Frank Shuman ultimately wanted to export his technology to Africa where there was a plentiful supply of sunlight. In order to do this, it was necessary for him to get investors to finance the business venture. He successfully found investors in England. But, these investments came with the requirement that physicist C.V. Boys would be able to study the design and suggest improvements. When the redesigned model was finally constructed in Cairo, Egypt in 1912, it was found to generate 55 horsepower. A rendition of the plant is shown in figure 4. This system was capable of pumping 2,000 m^3/hr for irrigation.

Figure 4. First parabolic plant in Egypt. [4]

The possibilities seemed limitless as this point. With the ability to pump thousands of gallons per minute from the ground in these arid regions, it would be possible to irrigate large areas of land, and sustain the population with food. But in a cruel twist of fate, shortly after the Cairo plant had been completed, the Archduke Ferdinand was assassinated; World War One had begun. The conflict soon engulfed the entire region, and the plant in Cairo was destroyed, never to be rebuilt. The war also saw increasing dependence on fossil fuels, primarily petroleum, as a power source. It should be noted that during this development people realized that there was only a finite amount of fossil fuel that could be extracted from the ground. They also noted the importance of developing sustainable energy sources. Auguste Mouchout wrote in 1860, "Eventually industry will no longer find in Europe the resources to satisfy its prodigious expansion. Coal will undoubtedly be used up. What will industry do then?" {1} Also, John Ericsson wrote in 1886, "A couple thousand years dropped in the ocean of time will completely exhaust the coal fields of Europe, unless, in the meantime, the heat of the sun be employed." {1}

In 1941, the first monocrystalline silicon solar cell was constructed. This was made possible by the pioneering work of the Polish scientist Jan Czochralski who discovered a method of creating monocrystalline silicon in 1918. The next major event for photovoltaic solar power occurred in 1954 when a group of scientists working at Bell Laboratories discovered that silicon when doped with certain impurities became very sensitive to light. The result of this discovery was the first solar module with an efficiency of approximately 6%. There was initial excitement about the possible applications of solar power in space exploration, but widespread use of solar panels for terrestrial electricity generation was still a rather foreign concept to most people.

An important impetus for the development of solar power and other renewable energy sources was the oil embargo of the 1970s. This occurred when several countries in the Middle East, with Iran being the most prominent, decided to stop selling petroleum to the United States. This caused huge price increases to the consumer and led to vast supply shortages across the country. Briefly, the idea of energy independence entered into the public debate. Unfortunately, when the embargo was over and the price of oil fell back to within an acceptable range, the program of energy independence soon was of secondary importance. In 1970 the first applications of photovoltaic technologies emerged on the Earth, with the cost of a silicon solar cell of $30 dollars per Watt. By 1977, the worldwide production of photovoltaic modules exceeded 500 kW, and the United States government was actively funding the research of photovoltaic material.

The 1980s was a period of growth for the photovoltaic industry with new companies like BP (British Petroleum) coming into the industry. In 1980, Arco Solar constructed a 105.6 kW solar power plant in Utah. Three years later they build a 6 MW solar plant in California. By 1983, worldwide production of photovoltaics reached 21.3 MW and the Solar Trek vehicle was introduced. This vehicle operated on a 1 kW photovoltaic system and drove a distance of 4,000 km over a period of twenty days reaching max speeds of 72 km/hr. The most important contributions from the 1980s were the amorphous silicon cell and thin film technologies.

By 1991, a Los Angeles, California based company named Luz, which generated 95% of the world's solar based electricity had completed an 80 MW solar energy plant and was planning to build a 300 MW plant. What happened next? An example of what can occur if the government interferes in the marketplace. In the words of then Luz chairman of the board Newton Becker, "The failure of the world's largest solar electric company was not due to technological or business judgment failure but rather to failure of government regulatory bodies to recognize the economic and environmental benefits of solar thermal generating plants." {1} With the United States government subsidizing American oil companies, in the form of tax breaks and other incentives, it made it difficult for other energy sources to compete in the marketplace. The 1990s also saw a consolidation in the photovoltaic industry with foreign companies like Siemens buying

Arco Solar, and ASE Gmbh purchasing Mobil Solar Energy Corporation. The governments in Germany and Japan invested large resources into solar power facilities and have taken the role as the leaders in photovoltaic power production. The largest solar electric power plant is the Gut Erlasse plant in Germany and it produces about 12,000 megawatt hours annually. To put that number into perspective, it is roughly the power necessary to meet the energy demands of a town of 9,000 residents.

2. Single Junction Solar Cell

The single junction silicon cell is by far the most widely distributed photovoltaic cell in the world today. At room temperature the element silicon, which belongs to group IV on the periodic table of the elements, is an insulator with its four valence electrons forming covalent bonds with neighboring silicon atoms. When the silicon material is doped with different elements, it is possible to create steady state electric fields within the material. An example of this technique is the p-n junction, wherein silicon is doped with a group V element, like phosphorous, which has five valence electrons. When these two elements are brought into contact, four of the valence electrons of the phosphorous form covalent bonds with the electrons of the silicon atoms. The fifth electron of the phosphorous atoms is promoted into the conduction band of the material. This type of semi-conducting material is known as n-doped with the majority carrier being the free electrons and the minority carrier being holes (as described below). When silicon is doped with a group three element, like boron, which has three valence electrons, the situation is similar to the previous case but with some important differences. The three valence electrons of the boron atoms form covalent bonds with three of the electrons of the silicon atoms, but now the fourth electron of the silicon atom cannot form a covalent bond. This missing electron is what was previously referred to as a hole, and can be thought of as the absence of an electron. This type of semi-conducting material is known as p-doped with the majority carriers being holes and the minority carriers being free electrons.

When an n-doped region and a p-doped region are brought into contact there exists a condition of chemical potential energy. This is because there is a concentration gradient between the n-doped side which has many more free electrons then the p–doped side which is a majority hole carrier. At the same time, there is a concentration gradient between the p-doped side with its many holes and the n-doped side with its lack of holes. The chemical potential energy initiates diffusion of the electrons and the holes within a small region. Initially electrons on the n-doped side of the region diffuse to the p-doped side of the region and combine with the available holes to create a negative ion. At the same time, holes from the p-doped side of the region diffuse to the n-doped side to combine with electrons and create positive ions. As time goes on, the diffusion of the electrons and holes slows down and eventually stops. This is because the electrons that are diffusing from the n-doped side eventually fill all the available holes on the p-doped side, creating negative ions in the process. While this is happening, the holes that are diffusing from the p-doped side combine with the available electrons on the n-doped side creating positive ions. The average electric field created by adding together all of the individual ions eventually becomes strong enough to completely stop the diffusion within the material. The small region where there are only ions and no mobile charge carriers is called the depletion region. Within this region, a steady state electric field is created. "Eventually, the flow of electrons and holes ceases when the chemical forces of diffusion are exactly offset by the electrostatic forces of the created electric field." {2} The strength of this electric field is a crucial parameter in describing photovoltaic cells. It is commonly referred to as the band gap energy of the semiconductor.

The radiated energy that the earth receives from the sun consists of a spectrum that extends from the UV (ultraviolet), through the visible, and into the IR (infrared). The visible spectrum can be observed by using a prism to decompose white light into its spectral components. Each of these various components has its own unique energy. This energy can be expressed as $E = h\nu$, where h is equal to Planks constant, $h = 6.6262 \times 10^{-34}$ J-s $= 4.1357 \times 10^{-15}$ eV-s, and ν which is the frequency of the incoming electro-magnetic radiation. When the band-gap energy of the semi-conductor matches the energy of the incoming radiation, it is possible to create usable electricity. One can think of the electromagnetic radiation coming from the sun in terms of its exchange particle, the photon. When a photon with the necessary energy strikes either side of the p-n junction an electron-hole pair can be created. If the photon impacts an electron and imparts enough energy to propel the electron into the conduction band, an empty space will be created (a hole) where other electrons can transition to. The electron on the p-doped side that is knocked into the conduction band diffuses to the depletion region. The electric field accelerates the electron into the n-doped region. A hole created in the n-doped region diffuses into the depletion region where the electric field accelerates the holes to the p-doped region. It is possible to hook up each side of this circuit to a load and create usable electricity as is shown in figure 5. One of the major drawbacks of using single junction silicon cells is that a band-gap energy of 1.1 eV can only capture a small portion of the spectrum of the sun. Single junction silicon cells have maximum efficiencies of roughly 20% under

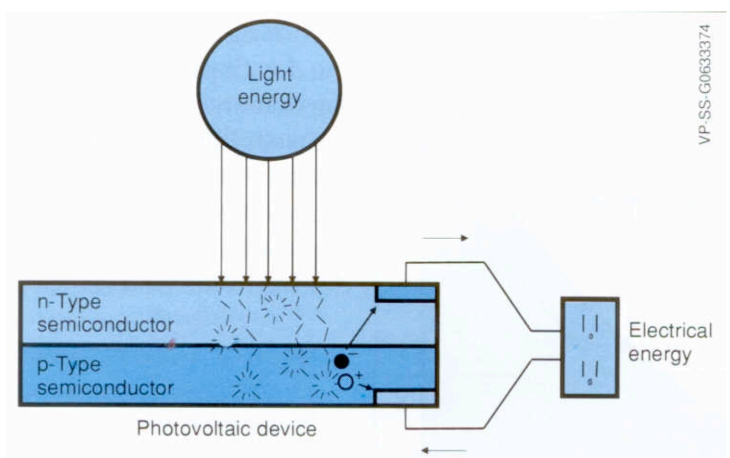


Figure 5. Creating electricity with a photovoltaic cell. [5]

ideal conditions. On the other hand the production cost of single junction silicon cells is much lower than the production cost of multi-junction solar cells.

The process of using sunlight to do useful work is not unique to humans, as photosynthetic plants have been doing this for many millennia it is worthwhile to study this process in a bit more detail.

3. Photosynthesis

It is insightful to describe the process of photosynthesis by which nature converts the energy from the sun into usable energy. In this case, the energy of the sun is used in the synthesis of organic compounds. "In plants, algae and certain types of bacteria, the photosynthetic process results in the release of molecular oxygen and the removal of carbon dioxide from the atmosphere that is used to synthesize carbohydrates (oxygenic photosynthesis)." {3} This section focuses on oxygenic photosynthesis as opposed to anoxygenic photosynthesis - a process used by some bacteria in which no oxygen is produced. The process of oxygenic photosynthesis plays a vital role in the Earth's overall carbon levels with more than 10% of the carbon in the atmosphere being turned into carbohydrates by photosynthetic organisms each year. While the photosynthetic organisms are absorbing the carbon they are also releasing oxygen, a molecule that is crucial for any organism that uses it in their life cycle. It was realized by the middle of the nineteenth century that plants could use the energy from the sun to make carbohydrates from carbon dioxide (CO_2) and water (H_2O). The equation that represents this is $CO_2 + 2\ H_2O + \text{Photon} = \{C\ H_2O\} + O_2 + H_2O$. Where $\{CH_2O\}$ is the carbohydrate glucose, a six-carbon sugar. In order to reduce one mole of CO_2 into glucose requires +486 kJ/mol of energy from the sun. The O_2 on the right hand side of the equation comes from the oxidation of the water molecule.

A complete quantitative description of all the steps in the photosynthetic process is still not established. However, there has been great progress in the understanding of the process. Around 1954, L.N.M Duysens showed that in photosynthesis the primary photochemical reaction occurs in the reaction center, a protein complex. The reaction center is where the energy of the photons is deposited. As the photons from the sun are intercepted by "an antenna system consisting of hundreds of pigment molecules (mainly chlorophyll or bacterio-chlorophyll and carotenoids) that are anchored to proteins within the photosynthetic membrane and serve a specialized protein complex known as the reaction center. The electronic excited state is transferred over the antenna molecule as an exciton" {3} A graph of the light absorbance of chlorophyll and carotenoid species as a function of the wave-length of the incoming light is shown in figure 6.

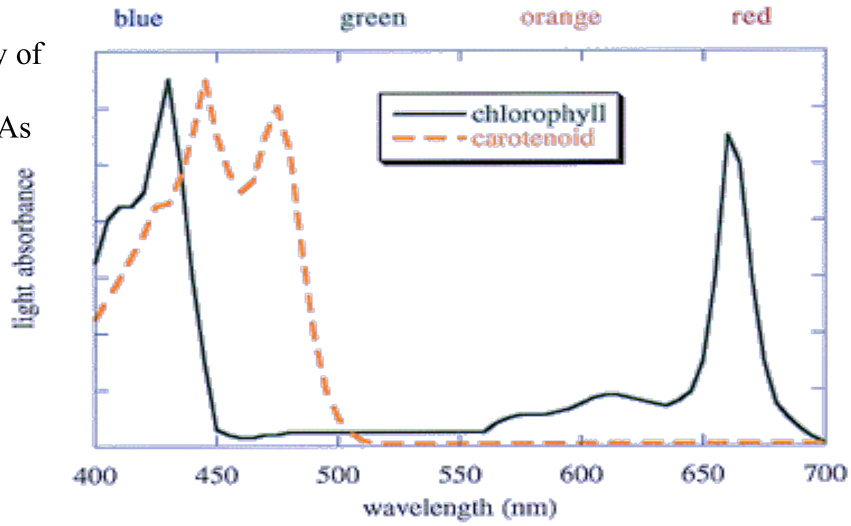


Figure 6. Light absorbance as a function of wavelength. The color is indicated above the graph. [6]

An exciton is defined to be a mobile excited state that is the product of a tightly bound electron-hole pair. While studying the inorganic semi-conductor silicon, it is found that when a photon strikes the p-n junction an electron-hole pair is created. The electron and the hole quickly separate spatially as a result of the electric field. In a light sensitive organic material the result of absorbing a photon leads to the production of an exciton instead of a free electron-hole pair. There are two separate reasons this happens "1) The dielectric constant of the organic phase is usually low compared to inorganic semiconductors, so the attractive Coulomb potential well around the incipient electon-hole pair extends over a greater volume than it does in inorganic semiconductors, and 2)

The non-covalent electronic interactions between organic molecules are weak (resulting in a narrow bandwidth) compared to the strong inter-atomic electronic interactions of covalently bonded inorganic semiconductor materials like silicon. Therefore, the electrons wavefunction is spatially restricted (small Bohr radius), allowing it to be localized in the potential well of its conjugate hole (and vice versa)." {4} The result of this spatial restriction is the creation of a tightly bound electron hole pair, which is mobile, and to the first degree of approximation unaffected by electric fields.

As the excitons are being carried on the antenna one of three things can happen. First, some of the excitons can be converted back into photons and are emitted as fluorescence. Second, some of the excitons are converted to heat. Third, and most probable, is that the exciton will be transported to the reaction center. At the reaction center, these excitons provide the energy for the primary photochemical reaction, the transfer of an electron from a donor molecule to an acceptor molecule.

There are two separate reaction centers in oxygenic photosynthetic organisms. These are known as photosystem I (PS1) and photosystem II (PS2). Photosystem II supplies electrons to photosystem I during the day. The process of the electron transport is complicated and involves many different molecules. A picture of the various photosynthetic processes is shown in figure 7. When the electrons from PSII, which are created by the oxidation of a water molecule, reach PSI they are combined with a complex molecule known as NADP+ (nicotinamide adenine dinucleotide phosphate). This reaction creates the reduced form of the molecule NADPH. Light energy is now stored as chemical free energy. This is commonly referred to as the redox free energy. The energy is ultimately used in the reduction of carbon. At the same time that the

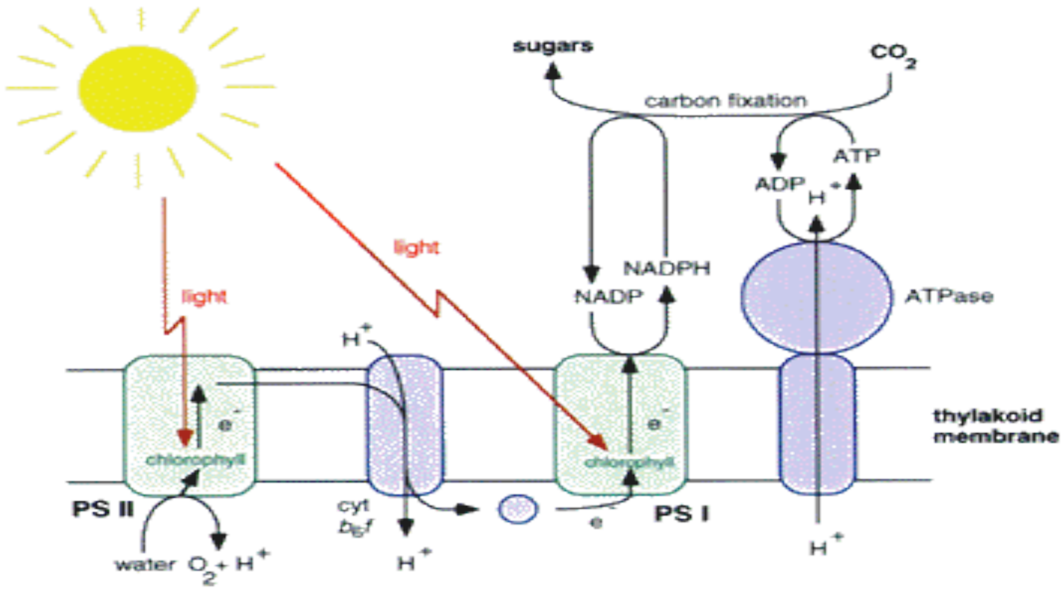


Figure 7. Overview of photosynthetic processes as they occur in plants, algae, and cyanobacteria. [7]

electrons are being transferred from PSII to PSI, there is a concentration of protons being created inside the membrane vesicle. This concentration of protons creates an electric field that acts across the photosynthetic membrane. The electrochemical potential of the protons is used by protein complex adenosine triphosphate-synthase (ATP-Synthase) to form adenosine triphosphate (ATP), where the energy is stored as phosphate group transfer potential. "The net effect of the light reactions is to convert radiant energy into redox free energy in the form of NADPH and phosphate group-transfer energy in the form of ATP." {3} The final use of the molecules is the reduction of CO_2 into carbohydrates.

IV. Multi-Junction Solar Cells

The function of multi-junction solar cells is to absorb as much of the suns spectrum as possible. This is accomplished by combining different elements in order to

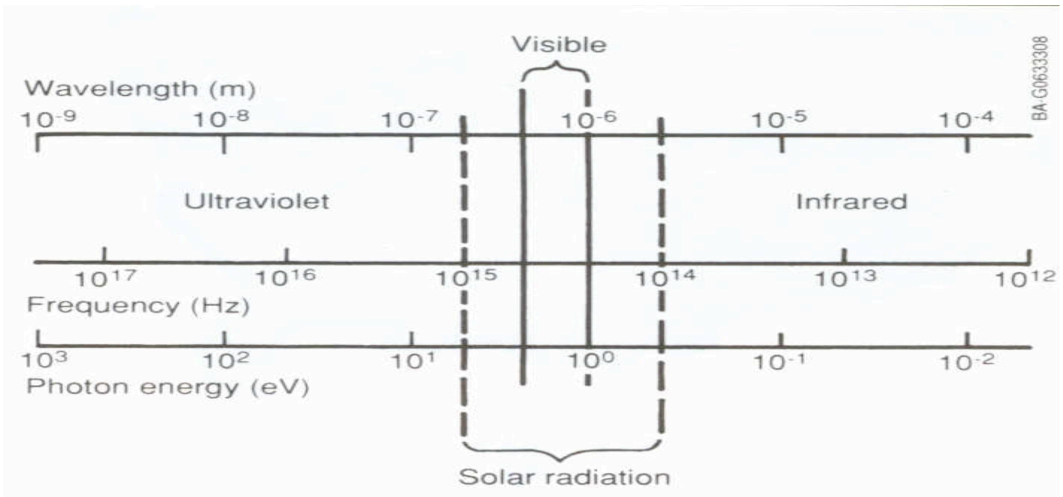


Figure 8. Spectrum of electro-magnetic radiation with: Wavelength, Frequency, and Photon Energy. [8]

create the necessary band gap energies to capture as much of the spectrum as possible. The sun has a broad spectrum as can be seen from figure 8. The sun can be modeled as a black-body at a temperature of 5,800 ^oK. Using Wiens displacement law $\lambda_{max}* T = 2.898*10^{-3}$ [m ^oK], where T is the temperature of the body, it is possible to find the peak wavelength in the spectrum. Plugging in T=5,800 ^oK one finds that λ_{max}=0.50μm, approximately, the color of a yellow-green tennis ball. The human eye is highly sensitive to light of this wavelength. The spectrum of the sun outside of Earth's atmosphere, and also on the surface of the Earth is shown in figure 9. As can be seen in the figure there are portions of the spectrum of the sun that are strongly absorbed while passing through the different layers of Earths atmosphere. The absorption of the photons is primarily due to atmospheric gases. Water vapor is responsible for the absorption of photons with wavelengths close to 900 nm, 1100 nm, and 1400 nm. Ozone (O_3) strongly absorbs photons with wavelengths below 400 nm.

The terrestrial solar spectrum will now be studied in a little more detail. In figure 9 it should be noted that the information is for a cloud free sky. Clouds play a large role in determining the amount of sunlight reaching the surface of earth. Large cirrus clouds with an optical thickness greater then 3 can completely block out the light of the sun. In descending weakness the other classes of cirrus clouds are thin cirrus, and sub-visible cirrus. These clouds have an optical thickness between 2 and 0.2 respectively. At any time approximately half of the surface of the Earth has cloud cover over it.

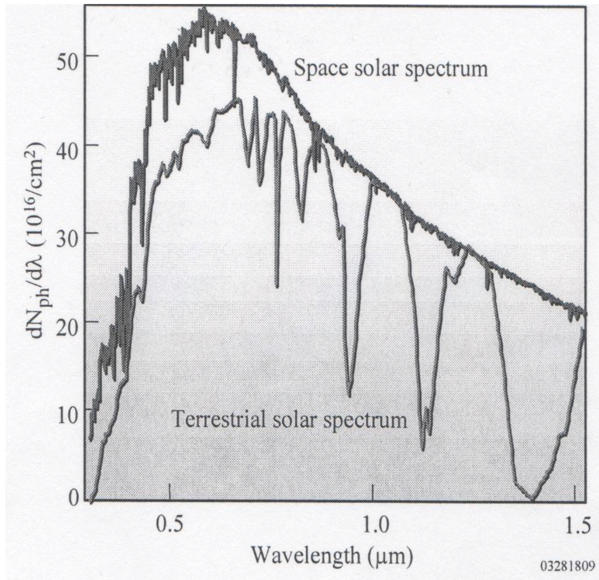


Figure 9. Photon concentration as a function of wavelength. [9]

Other processes of photon energy deposition in the atmosphere include photons interacting with: aerosol particles, molecules (Reyleigh scattering), water vapor, ozone (O_3), molecular oxygen (O_2), nitrogen dioxide (NO_2), and carbon dioxide (CO_2).

The local concentration of aerosol particles is an important parameter in understanding the impact of these contaminants in the atmosphere. The range of aerosols is large encompassing both natural and man-made types. Dust particulates that get blown into the atmosphere by wind illustrate a type of natural aerosols. The combustion of fossil fuels is an example of man-made aerosols; the combustion process results in the release of soot (and other pollutants) into the atmosphere. Aerosols follow an approximate $1/\lambda^2$ scattering dependence (Mie scattering). “Spectral optical depth measurements in narrow bandwidths around wavelengths 0.38 µm and 0.50 µm are data which become more and more available from the meteorology network.” {5}

Rayleigh scattering by molecules of air follows a $1/\lambda^4$ scattering dependence; the scattering is the reason why the sky is blue. Earlier it was determined using Weins displacement law that the peak wavelength of the sun is 0.50 µm, so a large portion of the suns energy is contained within the spectrum between blue light ($\lambda \approx 0.425$ µm), and red light ($\lambda \approx 0.650$ µm). Because of the $1/\lambda^4$ dependence, blue light scatters about 5.5 times more intensely than the red light from the air molecules.

Water vapor (H_2O) has three primary vibrational modes due to the asymmetric shape of the water molecule. “The bending vibration, ν_2, has the lowest wavenumber: both ν_1 and ν_3 have wavenumbers about twice the wavenumber for ν_2. The ν_2 fundamental band of H_2O is centered at 6.25 µm. The ν_1 and ν_3 fundamentals of H_2O produce bands centered at 2.74 µm, and 2.66 µm, respectively.” {6} The concentration of water vapor falls as one goes higher into the atmosphere, so the interaction of photons and water vapor occurs primarily in the troposphere. The atmosphere is separated into different regions determined by the inversion layers of the stratopause and mesopause. The troposphere extends from the surface of the Earth to a distance of approximately 11 km. Next is the stratosphere which goes from 11 km to approximately 49 km. At the top of the stratosphere is the stratopause, a thin layer separating the stratosphere and the mesosphere. Ozone occurs primarily in the stratosphere. The stratosphere is also effected by the interaction of photons with CO_2. After the strato-pause is the menosphere which extends from approximately 50 km to 83 km. The top of the mesosphere is called the mesopause. Finally, the top of the atmosphere is called the thermosphere. A vertical temperature profile of the atmosphere is shown in figure 10.

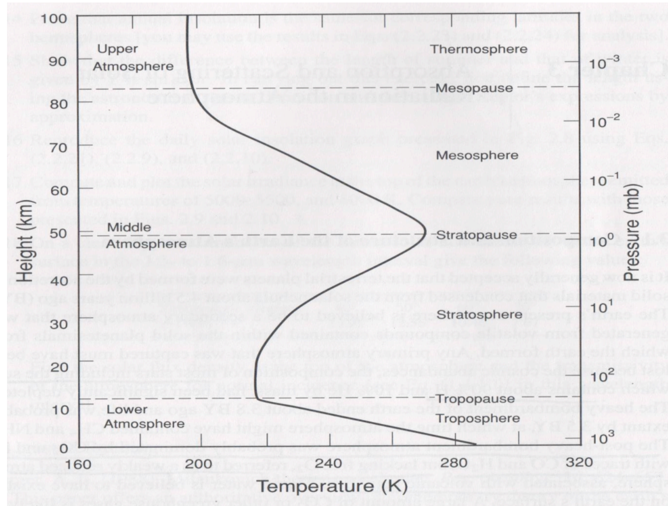


Figure 10. Temperature profile of Atmosphere. [10]

Molecular oxygen (O_2) and ozone (O_3) are responsible for the absorption of light in the ultraviolet spectrum of light from about $\lambda \approx 800$ angstrom to $\lambda \approx 3900$ angstrom. There are many different processes that are involved in this spectrum. The absorption cross sections of O_2 and O_3 as a function of the wavelength are shown in figure 11. The absorption of this high frequency light is important for life on Earth. The energy is proportional to frequency through the equation $E = h\nu$, so this high energy light which is harmful to life is attenuated by absorption due to these molecules.

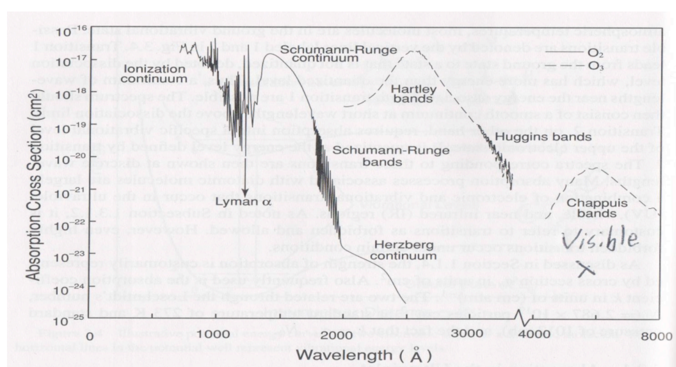


Figure 11. Absorption cross section vs. wavelength. [11]

The last phenomena that will be discussed is the interaction of electromagnetic

The Composition of the Atmosphere[a]

Permanent constituents		Variable constituents	
Constituent	% by volume	Constituent	% by volume
Nitrogen (N_2)	78.084	Water vapor (H_2O)	0–0.04
Oxygen (O_2)	20.948	Ozone (O_3)	$0–12 \times 10^{-4}$
Argon (Ar)	0.934	Sulfur dioxide (SO_2)[b]	0.001×10^{-4}
Carbon dioxide (CO_2)	0.036	Nitrogen dioxide (NO_2)[b]	0.001×10^{-4}
Neon (Ne)	18.18×10^{-4}	Ammonia (NH_3)[b]	0.004×10^{-4}
Helium (He)	5.24×10^{-4}	Nitric oxide (NO)[b]	0.0005×10^{-4}
Krypton (Kr)	1.14×10^{-4}	Hydrogen sulfide (H_2S)[b]	0.00005×10^{-4}
Xenon (Xe)	0.089×10^{-4}	Nitric acid vapor (HNO_3)	Trace
Hydrogen (H_2)	0.5×10^{-4}	Chlorofluorocarbons ($CFCl_3$, CF_2Cl_2 CH_3CCl_3, CCl_4, etc.)	Trace
Methane (CH_4)	1.7×10^{-4}		
Nitrous oxide (N_2O)[b]	0.3×10^{-4}		
Carbon monoxide (CO)[b]	0.08×10^{-4}		

[a]After the U.S. Standard Atmosphere (1976) with modifications.
[b]Concentration near the earth's surface.

Figure 12. Composition of the Atmosphere. [12]

radiation with NO_2 and CO_2. NO_2 absorbs solar radiation between $\lambda \approx 0.2$ µm and $\lambda \approx 0.7$ µm which encompasses part of the UV spectrum and part of the visible light spectrum. CO_2 absorbs light at $\lambda \approx 15$ µm in the thermal infrared spectrum, it also absorbs light at $\lambda \approx 4.3$ µm. The composition of the atmosphere is illustrated in figure 12. All of the various molecules in the atmosphere resonate at different frequencies of the solar spectrum. The phenomena of resonance is important in understanding the interaction of light and matter. The geometry of the molecules is an important parameter in describing resonance. Both NO_2 and CO_2 are linear tri-atomic molecules with three modes of vibration: symmetric, anti-symmetric, and bending. H_2O and O_3 also have three vibrational modes, but they have a different geometry then NO_2 and CO_2, and are known as bent tri-atomic molecules. All of these processes previously described lower the amount of direct sunlight that is received on the surface of the Earth.

Now with a better understanding of the terrestrial light spectrum, the reason for a multi-junction solar cell becomes clear. Two of the most important parameters in understanding the power production of a photovoltaic cell are the photo-voltage and the photo-current. The power production is the product of the voltage and the current given by P = I*V.

The photo-current of a solar cell is related to the absorption of incoming photons. For a large photo-current, it is desirable to use a semi-conductor with a low band-gap energy in order to absorb as many of the incoming photons as possible, promoting electrons in the material into the conduction band. This happens when the energy of the photon matches or slightly exceeds the band-gap energy. The absorption coefficient is also an important factor in the production of photo-current. Materials like silicon and germanium have a low absorption coefficient, while gallium arsenide has a high absorption coefficient. Therefore, thicker layers of silicon and germanium would have to be used to absorb an equal number of photons as gallium arsenide.

The photo-voltage is related to the energy of the electron as it is promoted into the conduction band by the photon. The result of a larger band-gap energy in the semi-conductor is that the electrons that interact with photons will be promoted to the conduction band with greater energy. In order to have a large photo-voltage it is preferable to use semi-conductors with a large band-gap energy.

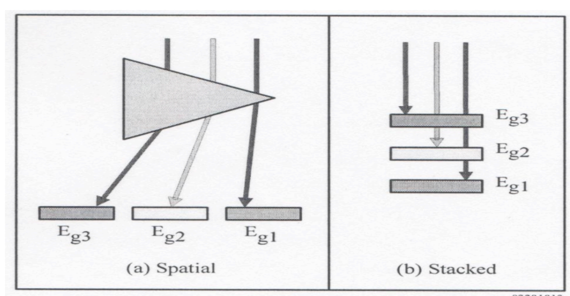


Figure 13. Multi-junction spectral splitting. [13]

One approach of designing multi-junction solar cells is to stack multiple layers of different semi-conducting materials with decreasing band-gap energies as shown in figure 13. The top layer of the solar cell is designed to capture the high energy photons. The photons with energies below that of the first band-gap will pass through to the second layer of the semi-conductor. The photons with the requisite energy will then be absorbed by this semiconductor. The same principal is involved with the final layer of the multi-junction cell.

When mixing different elements from the periodic table to create an efficient solar cell, it is important to use elements that have similar crystal structures. The term lattice constant is often used in describing crystal structures, and it is a measure of the distance between the atoms in the crystal. "Mismatch in the crystal lattice constants creates defects or dislocations in the lattice where recombination centers can occur. Recombination results in the loss of photo-generated minority carriers (e.g. electrons drop from the conduction band into the valence band) and significantly degrades the photovoltaic quality of the device." {2} The triple junction GaInP/GaAS/Ge solar cell is one example of a multi-junction solar cell. Spectrolab designed it with funding by the National Renewable Energy Laboratory (NREL). The advantages of using this mixture are that the semi-conductors are all lattice matched and the band-gap energies of the three semi-conductors covers a broad range of the sun's spectrum. GaInP has a band-gap energy of 1.85 eV and absorbs energy in the ultraviolet and the visible part of the spectrum. GaAS has a lower band-gap energy of 1.42 eV and absorbs in the near-infrared part of the spectrum. And, the semi-conductor Ge has a band-gap energy of 0.67 and absorbs low energy photons in the infrared spectrum. At high concentrations of sunlight,

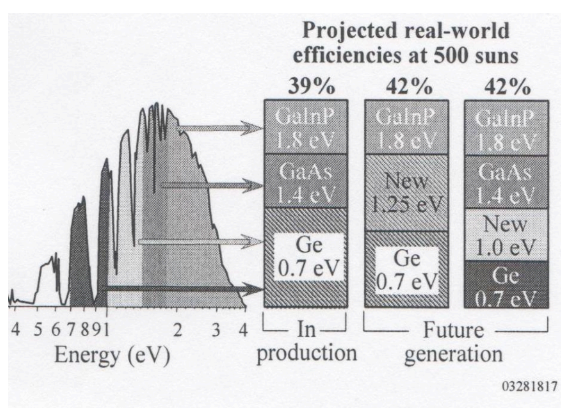


Figure 14. Multi-junction cell efficiencies.

[14]

this cell has achieved efficiencies of 34%. The future direction of multijunction solar cells will consist of finding new semi-conducting materials that efficiently absorb as much

of the spectrum of the sun as is possible. Of particular interest is finding semi-conducting material of badgaps 1.25 eV and 1.0 eV. With these new semi-conductors it might be possible to achieve efficiencies as high as 40% and higher using concentrated sunlight as shown in figure 14.

V. Advanced Photovoltaic Cells

Now, a description of current photovoltaic solar cell design is presented. The three major topics addressed in this portion of the paper are impact ionization solar cells, hot carrier solar cells, and excitonic solar cells.

A. Impact Ionization and Hot Carrier Solar Cells.

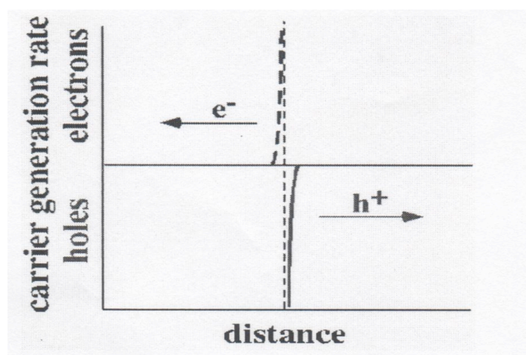
Impact ionization solar cells and hot carrier solar cells are based upon the same principle. The use of high energy photons. A photon whose energy is slightly above the band-gap energy of the semi-conductor can harness more energy. Normally, when a high energy photon is captured by the semi-conductor any excess energy that is left over after the ejection of an electron to the conduction band is lost as heat through phonon emission. The idea of these new technologies is to use high energy electrons, also known as hot electrons, to "enhance the conversion efficiencies of the semi-conductor by allowing electrical free energy to be extracted from the energetic electron and/or holes before they relax to their lowest electronic state and produce heat." {7} With the approach of using hot carriers, it is possible to create a more efficient cell by creating an enhanced photo-current or an enhanced photo-voltage.

Impact ionization is used in the enhancement of the photocurrent, and is the inverse of an Auger process. In an Auger process, two electron-hole pairs recombine to form a highly energetic electron-hole pair. So, in an impact ionization, a high energy photon creates a highly energetic electron-hole pair which becomes two electron-hole pairs increasing the total current available for the production of power. Impact ionization can only occur if the transition rate of the absorption of a photon and the separation of the electron-hole pair across the semi-conductor interface is fast compared to the rate of carrier cooling. The enhancement of the photo-voltage is made possible by extraction of the hot carriers from the photo-converter before they cool. The use of quantum theory in conjunction with nanotechnology holds great promise for this nascent discipline. It would be theoretically possible to create the perfect solar cell that would convert virtually all of the incoming light from the sun into usable electricity. This would be accomplished by finding the correct mixture of elements and putting them together in a geometry that minimized the entropy (heat) loss of the system.

B. Excitonic Solar Cells

An organic based excitonic solar cell (ESC) is different then the solar cells previously discussed. "The key difference is the dominant importance, in ESCs (excitonic solar cells), of the photoinduced chemical potential energy gradiant, $\Delta\mu_{h\nu}$ whereas $\Delta\mu_{h\nu}$ is unimportant, and therefore neglected, in theoretical descriptions of conventional PV cells." {4} In ESCs, the excitons dissociate at the hetero-interfaces resulting in a small spatial separation of the electrons and holes. The hetero-interfaces of a dye sensitized solar cell are created by applying a monolayer of sensitizing dye to an optically thick film of TiO_2. In order for the requisite electrical contact between these two substances, a liquid electrolyte solution of iodine/tri-iodide is often used. The monolayer of the sensitizing dye plays an important role, because it localizes the excitons to a narrow region about the interface. When the excitons dissociate, a photo-induced carrier charge gradient is established. This is proportional to the term $\Delta\mu_{h\nu}$ that was referred to above. Also the electrolyte solution screens all electric fields within <

0.1 nm, so the internal electric fields can be neglected. A quantitative analysis of non-equilibrium thermodynamics shows the current generated by a photovoltaic device under illumination is proportional to the electrical potential energy gradient, and the chemical potential energy gradient. In the ordinary solar cells studied earlier, it was the electric potential energy gradient (i.e. band-gap energy of the cell) that was of prime importance. In these cells, the chemical potential energy gradient was very small, and therefore, usually neglected. This is because "the photogeneration of carriers throughout the bulk, and the high carrier mobilities that allow them to quickly equilibrate the spatial distributions regardless of there point of origin." {4} In the ESCs, where all of the optical acivity occurs at the monolayer, the excitons quickly dissociate across the hetero-interface. This process creates a photo-induced carrier concentration gradient that is proportional to the chemical potential energy gradient. "The charge carrier pairs are already separated across an interface upon photo-generation, creating a large $\Delta\mu_{h\nu}$ which tends to separate them further as in figure 15." {4} This is a powerful driving force for the photovoltaic cell.



The advanced photovoltaic cells have manufacturing costs that are too high at this time to be produced on a large scale. Large scale production of silicon photovoltaic cells is possible, and

Figure 15. The heterointerface is

these cells represent the majority of installed solar panels.

represented by the dashed lines. The arrows represent the force $\Delta\mu_{hv}$ that acts on the carriers. [15]

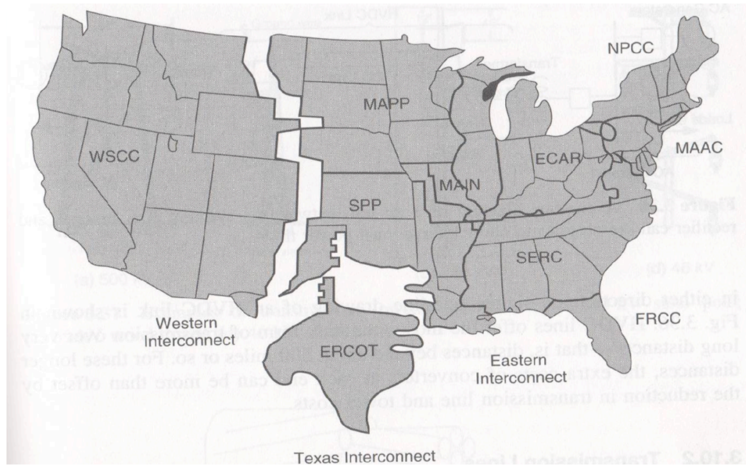


Figure 16. The three power grids in the United States. [16]

VI. Cost Analysis vs. Other Sources of Electrical Power

The electric power industry is one of the largest and most profitable industries in the United States with annual sales of over 300 billion dollars. As can be seen from figure 16 the United States is divided into three separate power grids. The state of Texas thought it would be advantageous to stop selling its electricity across state lines. This way the Federal Energy Regulatory Committee (FERC) would not have jurisdiction over them. Within these territories there are approximately 275,000 miles of transmission lines that carry the electricity from the point of origin to the point of final use. Investor Owned Utilities (IOUs) own about 200,000 miles of the transmission lines; a consortium of federal, state, and cooperative utilities own the remaining lines. These IOUs, which are privately owned with stock and publicly traded, were historically important in deciding which form of electricity generation made it into the marketplace.

In 1935, the Federal government decided to start regulating the utility companies. The companies at the time were rapidly consolidating. By 1929, three companies in the United States were supplying 45% of the total electricity. They also were involved in various pyramid schemes, whereby a holding company would be set up whose sole purpose was to increase the profit of the holding company that created it. Stocks from these sham holding companies were sold to investors who thought they were real companies. In 1929, the Stock Market crashed and many of the holding companies went bankrupt; investors lost a fortune. This created strong public sentiment for the regulation of the utilities. Congress wrote the Public Utility Holding Company Act of 1935 (PUCHA) in order to regulate the gas and electric utilities, and to prevent the formation of sham holding companies from reoccurring.

The oil embargo of the 1970s was the next time that the American public became interested in energy policy. In 1978, President Jimmy Carter signed the Public Utility Regulatory act of 1978 (PURPA). One important provision in this bill made it easier for large industrial consumers of power to create their own energy on site to help supplement the energy they were getting from the grid. Before this bill was passed, it was legal for the utility company to cut off power to a company if it wanted. Another important provision in the bill requires utilities to purchase power from qualifying facilities (QFs) at a fair price. "PURPA, as implemented by the FERC allows interconnection to the grid by Qualifying Small Power Producers or Qualifying Cogeneration Facilities; both are referred to as QFs. Small power producers are less then 80 MW in size and use at least 75% wind, solar, geothermal, hydroelectric, or municipal waste as energy sources. Co-generators are defined as facilities that produce both electricity and useful thermal energy in a sequential process from a single source of fuel, which may be entirely oil or natural gas." {8}

In 1992, the Congress decided to expand the scope of QFs as defined by PURPA. Congress now granted access to the transmission lines to virtually anybody who could create power. For example, it would be possible to generate electricity in the middle of the Nevada desert and sell it anywhere within the United States. One restriction that exists is that the company or individual can only participate in the whole-sale selling of power.

Electricity Source	Generating Costs[1]	External Costs[2]	Total Costs
	(cents per kilowatt-hour)		
Coal/lignite	4.3–4.8	2–15	6.3–19.8
Natural gas (new)	3.4–5.0	1–4	4.4–9.0
Nuclear	10–14	0.2–0.7	10.2–14.7
Biomass	7–9	1–3	8–12
Hydropower	2.4–7.7	0–1	2.4–8.7
Photovoltaics	25–50	0.6	25.6–50.6
Wind	4–6	0.05–0.25	4.05–6.25

[1]For the United States and Europe.
[2]Environmental and health costs for 15 countries in Europe.

Figure 17. Cost of generating electricity. [17]

Now a cost analysis of different energy sources will examined, as can be seen from figure 14, fossil fuels are a very cheap source of electricity in comparison to photovoltaics, but the external costs of the photovoltaic plants are much lower than the fossil fuel plants. Also, it should be noted that both wind power and hydropower are competitive with the fossil fuels. In order for solar to become competitive with fossil fuels, one of two things needs to happen; either the cost of manufacturing the solar cells needs to drop or the efficiency of the solar cell must be raised. Although, if fossil fuel producers are forced to lower their carbon emission the price of their electricity generation will rise giving a boost to renewables.

The recent Supreme Court decision in Massachusetts vs. EPA could prove to be a valuable impetus for the renewable energy program. In the 5-4 split decision the Justices decided on April 3, 2007 that the Environmental Protection Agency (EPA) had the authority under the Clean Air Act to regulate carbon emissions. The case was initiated by the Clinton administration when it brought several civil complaints, through the EPA, against a couple of coal companies under the Clean Air Act. The coal companies disagreed with the administration and fought back in court. When the present Bush administration took control of the Executive branch of government, the EPA reversed course and claimed it did not have authority under the Clean Air Act to regulate carbon emission. Massachusetts and several other states in conjunction with some environmental groups then sued the EPA in order to make it enforce the law. With their victory in court these states will probably begin to enforce carbon emission in their respective territories. If this happens the cost of generating electricity with fossil fuels will rise, because of investment in new power plants with technologies that lower carbon emission. Once again, energy policy is part of the public debate, and more Americans are becoming increasingly conscious of our impact on the environment. Next will be a look at the various by-products of energy production.

VII. Environmental Impact of Energy Sources

The low prices that people pay for energy produced by fossil fuels is a catch 22 situation. On the one hand, people want to pay the cheapest possible price for electricity, but the consequences of the release of massive amounts of carbon into the atmosphere could have profound long term consequences for the inhabitants of the Earth. In order to ensure the long term success of human evolution on Earth, it might be necessary to phase out the use of fossil fuels. If carbon sequestration becomes a viable option for controlling carbon levels in the near term, it will prolong human dependence on fossil fuels, as there is only a finite amount of them on earth. Renewable energy sources must be developed now in order to preserve a sustainable way of life for future generations. The processes by which the different forms of energy production make their way onto the market is shown in figure 18. As can be seen all of the fossil fuels have undesirable byproducts. Solar energy power production has none of these byproducts. Therefore, it is an excellent choice for farsighted government investment.

Using coal as a source of power production is a very big business in the United States; coal powered electricity generators produce roughly half of all electricity. And, it is one resource that America has in abundance, mainly in the northeastern part of the country. But, as can be seen in figure 18 using coal to produce power results in more pollutants being released into the atmosphere then any of the other processes, so the use of coal probably has the highest long term costs associated with it. In time, generating plants using coal will have to invest billions on dollars to install new technology that captures most of the toxic emission that is generated. These toxins

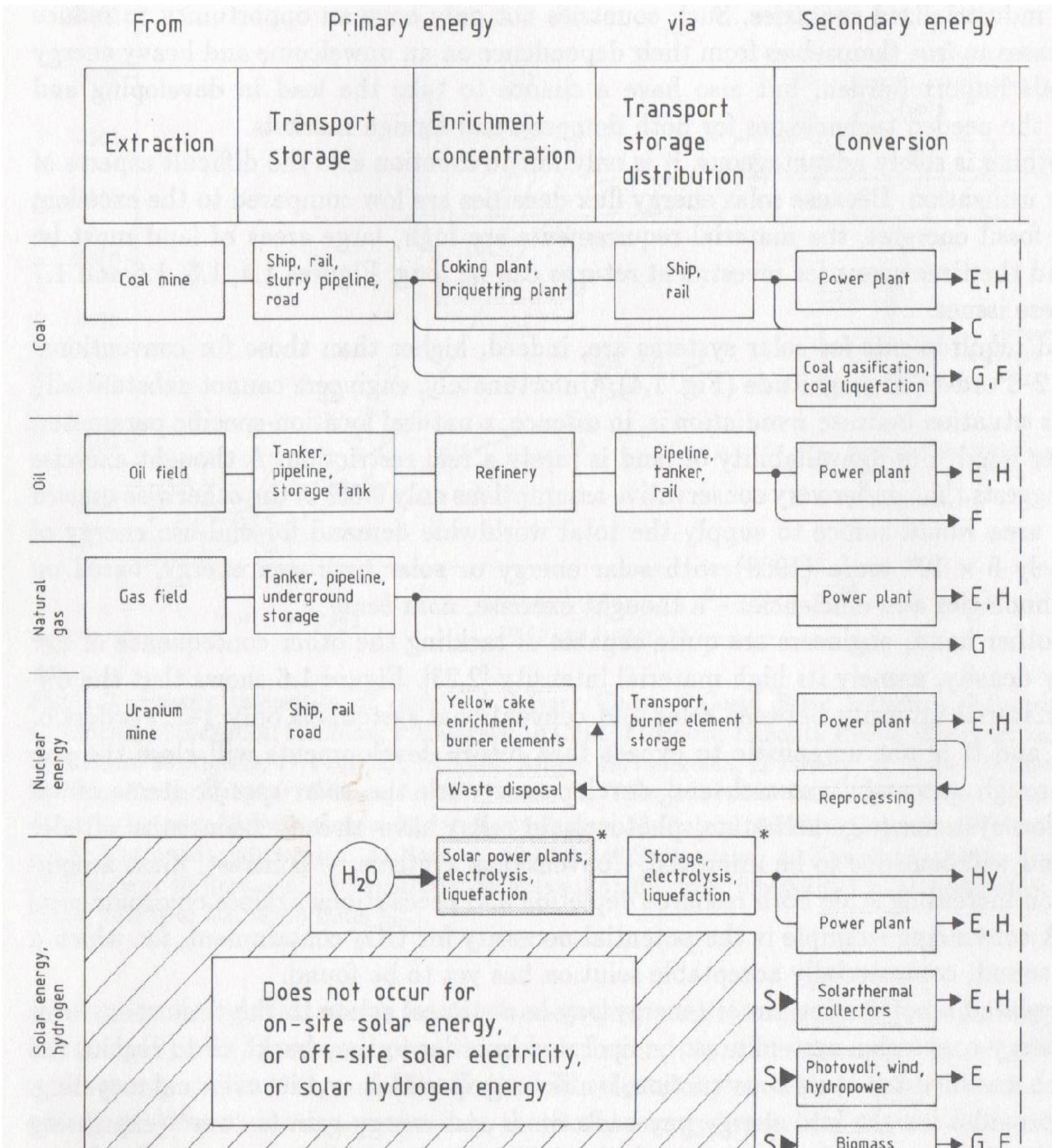


Figure 18. Energy conversion chains. [18]

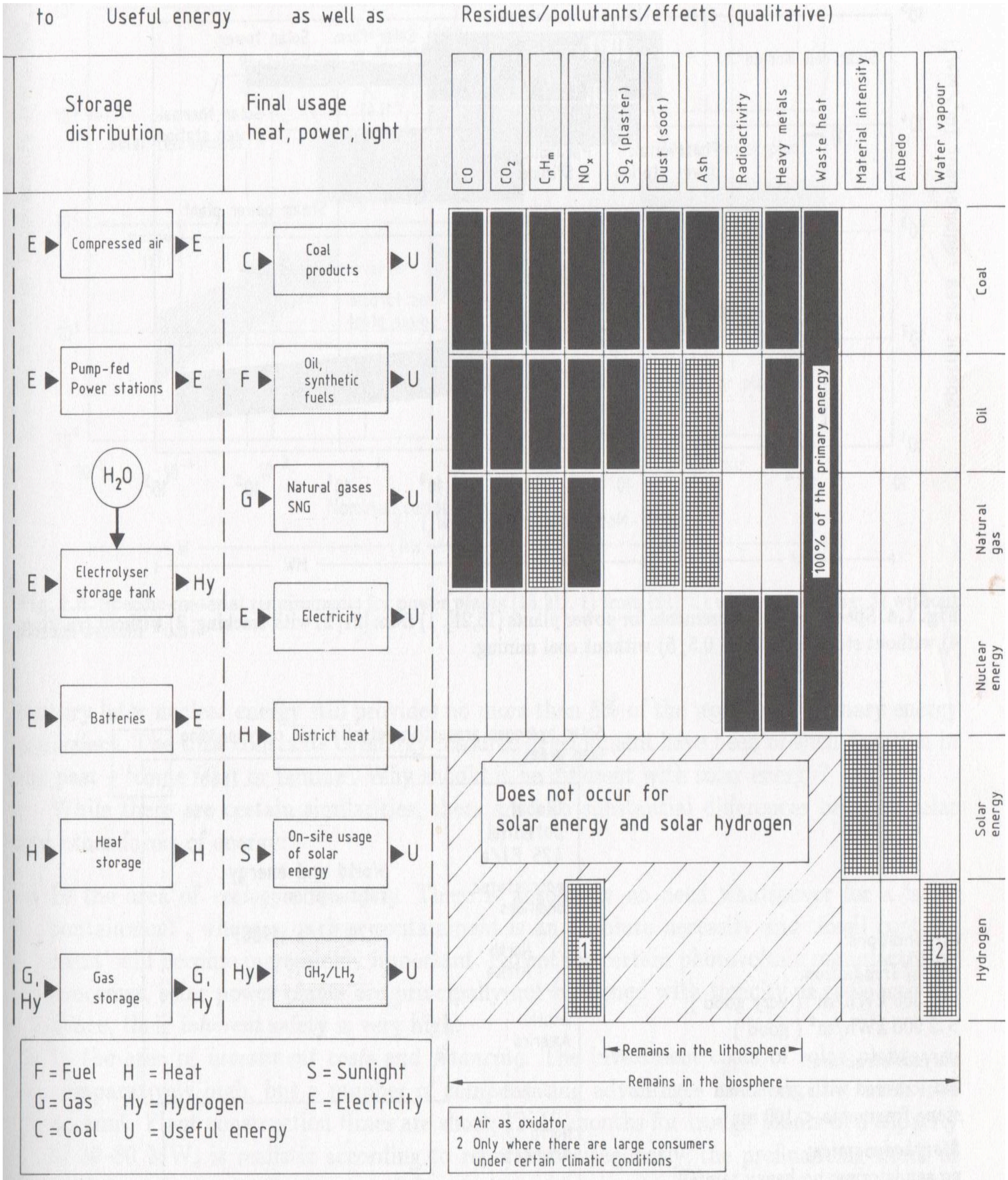

to
Useful energy
as well as
Residues/pollutants/effects (qualitative)
Storage distribution
Final usage heat, power, light
CO
CO2
CnHm
NOx
SO2 (plaster)
Dust (soot)
Ash
Radioactivity
Heavy metals
Waste heat
Material intensity
Albedo
Water vapour
Compressed air
Pump-fed Power stations
H2O
Electrolyser storage tank
Batteries
Heat storage
Gas storage
Coal products
Oil, synthetic fuels
Natural gases SNG
Electricity
District heat
On-site usage of solar energy
GH2/LH2
100% of the primary energy
Does not occur for solar energy and solar hydrogen
Coal
Oil
Natural gas
Nuclear energy
Solar energy
Hydrogen
Remains in the lithosphere
Remains in the biosphere
F = Fuel
H = Heat
S = Sunlight
G = Gas
Hy = Hydrogen
E = Electricity
C = Coal
U = Useful energy
1 Air as oxidator
2 Only where there are large consumers under certain climatic conditions

Figure 18. continued
will then have to stored somewhere safe, or chemically altered to make them safe. The process to make the coal industry as environmentally friendly as it can be will take many years and will be expensive.

Another major contributor to carbon emissions is the use of automobiles. The United States, in particular, is heavily dependent upon automobiles for transportation. One of the main reasons for this is the size of the country. To put together a mass transit system for the entire country would require a substantial amount of money and cooperation between the states. For smaller more densely populated counties like Japan and Germany a mass transit system is easier and cheaper to build. The burning of gasoline creates hazardous byproducts as shown in figure 18. One gallon of gasoline contains about 88 kJ of energy, which is significant. However, most gas engines are only about 16% efficient, so most of this energy gets wasted as heat. Diesel engines have higher efficiencies of around 25%, but they also produce undesirable by-products. Unfortunately, the United States has a small percentage of the worldwide petroleum reserves (about 3%) in its territory. As a result the United States is heavily dependent on foreign countries to supply the needed fuel. An application of solar power in the automobile industry is to create hydrogen for the hydrogen powered car. The production of hydrogen by the dissociation of water using solar power is attractive because after the hydrogen is created it can be transported large distances to the interested buyer.

Natural gas has become increasingly popular because it is efficient and it produces less toxic emissions then coal. A major breakthrough in the transportation of large amounts of natural gas known as liquefied natural gas (LNG) has facilitated the distribution of the product. But the building of huge terminals to offload the gas has been met with strong local resistance, and that has disrupted the plans of investors to begin the projects. Demand is beginning to outpace supply, and the price of natural gas has risen substantially in the last couple of years.

The nuclear power industry is another major player in the electricity generation market. About 20% of electricity in America is produced by the nuclear industry, and the production process does not release any carbon into the atmosphere. The major downside of the industry is disposal of the radioactive waste that is generated. “As of 2003 nuclear reactors in the U.S. had generated 49,000 metric tons of nuclear waste.” {9} In 1982, Congress enacted the Nuclear Waste Policy Act (NWPA), which directed the federal government to assume responsibility for safely disposing the radioactive waste. Three sites in the country were chosen as possible choices. These were: Deaf Smith County, Texas; Hanford, Washington; and Yucca Mountain, Nevada. Yucca Mountain was decided as the best choice, and the various regulatory bodies involved including the Nuclear Regulatory Committee (NRC), the Environmental Protection Agency (EPA), and the Department of Energy (DOE) began the process of getting approval to start moving radioactive material to Yucca Mountain. The state of Nevada and various environmental groups sued the federal government and the case made its way to the United States Court of Appeals for the District of Columbia Circuit. The court decided in Nuclear Energy Institute, Inc. VS. Environmental Protection Agency, that the EPAs 10,000 year compliance period was not “based upon and consistent with” the recommendations of the National Academy of Sciences. So the justices halted the shipment of waste until the EPA complies with the requirement. The compliance period is the time that models show the waste will be safe before the radiation can escape from the storage containers. Until there is a country wide method for disposing nuclear waste, investment in the nuclear industry will be minimal.

It has been said by people in the coal industry that we have enough coal to fuel our nation for 250 years which seems like a very long time. But what will happen when that supply actually does run out. Will Americans have had the vision to plan for that day, and be prepared when it does?

VIII. Future Marketplace for Solar Power

Solar power is one of the most important renewable energy sources that we have, and it must be utilized to the fullest. The amount of solar energy that the earth receives from the sun in locations suitable for solar energy harvest is approximately 600 TW ($1 \text{ TW} = 1 \times 10^{12}$ Watts; $1 \text{ TW-yr} = 31.3 \times 10^{18}$ Joules) annually. This enormous amount of energy, if fully utilized, could power many generations of people. At the present time with around 6 billion people on the planet, energy consumption is around 13 TW-yr. As the world population grows, so will the demand for more electricity, primarily in third world countries.

Using ice core samples, it has been shown that the levels of CO_2 at the time of the Industrial Revolution were around 175 ppm (parts per million). Present levels of CO_2 are around 382 ppm, a number that causes concern with some in the scientific community. If the level of CO_2 reach levels of 750 ppm or greater there is concern about the consequences, which might include an increase in the average temperature of the Earth. This would be a cataclysmic development for many major coastal areas which would be susceptible to flooding. "If CO_2 is to be stabilized at 750 ppm by 2050 (a level considered extremely dangerous and seriously disruptive by many climatologists), and if carbon sequestration is not considered , then about 10 TW-yr of carbon free energy will be required by 2050." {7}

The cost of solar panels continues to drop with the price of $4/Watt in the current market. This is down substantially from the cost in the 1970s mentioned earlier at $30/Watt. One of the reasons that the price is not dropping further is the strong demand for pure silicon that is originating in the electronics industry. Massive amounts of capital need to be invested in high quality material processing plants to meet the future demand in the photovoltaic industry.

America is probably the only country in the world that has the requisite tools available to start a global solar energy revolution. This is due to a number of different things; America is fortunate enough to have a large country with a good portion of it in desirable areas for solar harvest, there is a large pool of technical expertise to draw from, and there is sufficient capital ready to be invested in a good idea. If the United States does decide to invest billions of dollars in the solar power industry, and achieves good results, we will become the leader in this field. With good foreign policy the United States might be able to persuade developing Third World countries to invest in energy production methods that are friendly to the environment. The time for policy makers to act, in controlling carbon emission, and investing in renewable energy sources, is now in order to be responsible stewards of the planet.

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X. Figures