Chapter 5

Integrated Clean Energy and Climate Change

Steady Solar Radiation and a Global Energy Perspective

In recent years, the price of oil has swung between \$34 and \$147 per barrel; in addition, the solar radiation constant has reduced by 20% over the past 50 years as measured by several countries, therefore the statistics cited in this Chapter are at best only an estimate.

Solar radiation measured at the Earth's orbit is approximately 1.35kW/m^2, or more than a GigaWatt (a small nuclear power plant) per km^2, for a total of 10^8 GigaWatts over the Earth's cross sectional area. Compared to the few hundreds of nuclear power plants in operation currently plus the 20 times more for all non-nuclear power sources, solar radiation is thousands of times the total energy consumed, fossil fuels and otherwise, by humanity on Earth. Over the next few hundred years solar radiation will probably become the dominant source of energy in the form of decentralized electric power, from the Earth's surface as well as from outer space. Such a development will require the largest collaboration in the history of mankind. Let us get started.

U.S. annual energy consumption is 72 quadrillion BTUs, 27% of which is imported, mostly as oil. Worldwide energy use is 4.5 times U.S. consumption. Using \$60 per barrel of oil, the annual import of over \$400 billion in recent years contributes heavily to the U.S. trade deficit of over \$600 billion, which will unlikely be improved without curbing such a huge dependency on foreign oil. Note that the costs of adding hydrogen to coal to synthesize diesel fuels has a price tag of approximately \$55 per barrel, including a 10% annual cost of capital. This cost per barrel is similar to that of harvesting from the tar-sand in Alberta (\$62 a barrel) or from the oil shale in Utah and Colorado (\$75 a barrel), but they must be done locally causing additional CO_2 emissions in Canada or U.S. while coal can readily be transported and be converted to oil or gas anywhere, including on board of ships at sea. There are far more coal reserves than oil, implying that the price of oil cannot be maintained much beyond \$65 per barrel over the long haul. But oil prices involve global economic changes as well as geopolitical elements. Certain countries, for example, could produce oil for less than a few dollars per barrel if necessary. Thermal energy for synthesizing oil from coal or distilling oil from tar-sands or oil shale can readily be supplied from nuclear power, which is less expensive and can deliver the oil without additional CO_2 emissions. These considerations go beyond the economic evaluations of competing factors in the current energy perspective, and I shall not elaborate any more here and shall focus instead on the analysis of solar energy.

At 1.35kW/m^2, solar radiation can be harvested in a great variety of ways, directly or indirectly. Weather related indirect solar energy includes wind power and hydroelectric dams powered by river flow derived from snow and rain falls. Energy confined in the carbon compounds from trees or agriculture products are typically at less than 1% of the solar radiation to these vegetations. As their growth is driven biologically with or without human interventions, plants and vegetations can cover the earth's surface and sustain life everywhere, on land as well as in the sea. Note that the Earth was frozen solid 650 million years ago, due mainly to the single cell organisms in the sea which used up all the CO_2 in the atmosphere with photosynthesis and made the air completely transparent to infrared radiation, and the said organisms become mainly today's oil and gas reserves. Only 400 million years ago, life in plants and animals began to appear on the land, initiating photosynthesis and producing oxygen on the land. This means that the coal mines as a fossil fuel has a relatively more recent history than much of the oil and gas reserves.

We will consider some details of solar cells and harvesting the solar energy in an integrated perspective, regionally as well as globally, and the green-house gases in a geophysical point of view.

Is There Sufficient Silicon for Silicon-based Solar Cells?

We shall consider first the non-biological solar energy directly produced from solar radiation, particularly the solar electric power generation from semiconductor devices. Using a nuclear power plant as a comparison, a nuclear power plant occupying an area of several km^2 of land could provide just as much wattages in solar power as it does in nuclear power if the sunlight reaching that land could be converted to electricity by high efficiency solar cells. The solar spectrum, except for several percent in the UV light being absorbed by ozone, is rather similar with or without the atmosphere. In other words, if we could harvest solar energy efficiently, humanity should have no shortage of energy, clean solar energy. Our silicon-based superlattice may precisely be such a low cost, high efficiency vehicle to help realize this dream, which should be our mission.

Over ½ of poly-silicon (polySi) being utilized worldwide is for solar cells which has a worldwide market of more than $10 billion and growing at over 40% annually. It is fast becoming a major business. There are many non-silicon thin film photovoltaic materials, but since polySi sells at $40 per kilogram, it could produce solar panels at $5-10 per watt, and silicon solar cells remain to be the dominant player with over 90% market share. By adding the silicon-based superlattice, the efficiency of photovoltaic cells can increase by a factor of three or more so that solar cells can be made for as little as $1 per watt, thus allowing solar energy to be a cost effective commercial product.

Silicon is one of the most abundant elements in the Earth's crust, second only to oxygen. Electronic devices or chips are mostly made with silicon material. Solar cells also use much silicon, and there will be no long-term shortage of the solar cell materials, nor shortage of solar cell technologies. Solar energy includes direct photovoltaics based on using silicon or other semiconductor thin film devices coated on conductive substrate with or without a solar concentrator, focusing the solar radiation onto the device. What is lacking here is a clear-cut superior arrangement to be the core simple tech. The current messy tech in solar panels needs a breakthrough in order to deliver highly efficient solar cells at very low cost.

Solar Cell Designs According to the Solar Radiation Spectrum

Photons from solar radiation, in a permanent sense, are not renewable. What was radiated from the sun was lost forever from our solar system. Their emissions from the sun as a main sequence star are simply steady over billions of years. Photon energy can either be measured in wavelength (λ) in micro-meters (μ) or in electron volts ($eV=12{,}400/\lambda(\mu)$). The visible light is centered at 0.55μ or 2.25eV. When a photon enters a semiconductor matrix, it can create an electron-hole-pair (e-h), with the maximum e-h energy that can be harvested being the bandgap energy between its conduction band and valence band. The bandgap of pure silicon is 1.12eV. High energy photons can register in silicon at most at 1.12eV, while those below the material bandgap would slip through the material without registering. In fact, photons under 1eV are infrared and are transparent in pure silicon. Harvesting all photons according to the energy distribution of sunlight (the solar spectrum) with energies greater than 1.1eV, the limiting efficiency for silicon photovoltaics in outer space is approximately 22% as energetic UV photons are mostly wasted in silicon. While under the atmosphere without UV participation, the limiting efficiency for the softer spectrum increases to approximately 30%. For practical solar cells, the “sweet zone” of solar photovoltaics is between 0.4μ and 1μ. High quality solar cells can deliver ~2/3 of the limiting efficiency, while an inexpensive solar device from polySi, for example, can deliver ½ of the best laboratory model, or approximately 5-8% at room temperature.

Bandgap Engineered Solar Cell Stack Matching the Solar Spectrum

Another issue in designing the novel superlattice-based solar cells is the stacking order of different bandgap materials in order to take full advantage of the freedom of altering the bandgap of the silicon-based compositions where the concentrations of oxygen and carbon as well as the doping levels, and therefore the bandgap can be controlled as part of the layered superlattice fabrication process. Using the fact that higher energy photons have a shorter penetration depth in semiconductors, solar cells should be arranged like a layered cake with very thin layers of large bandgap materials at the top to harvest only high energy photons, followed by thicker layers of mid-bandgap for medium energy photons, and then thick, low bandgap materials at the bottom to harvest low energy photons, which pass through the upper thin layers without loss. In a semiconductor, electrons move much faster than holes. To balance the charge transports between electrons and holes, an efficient material for solar cells needs far more slower holes than fast electrons, and therefore they are all p-type. Spectrum Labs of the Boeing Corporation, for example, made a world record of ~40.8% efficiency by stacking the layered compound semiconductors with GaInP at a bandgap of 1.8eV at the top, followed by GaInAs at 1.4eV, and by germanium as the substrate supporting material at 0.7eV. The cost of thermal management to maintain all the layers functioning optimally has not been included and their relatively more practical devices could deliver 28% efficiency.

Several material issues must be addressed for constructing a high efficiency solar cell. They relate to “what price efficiency?” For expensive semiconductor materials, relatively low cost concentrators can be incorporated into the panel system to concentrate solar radiation with reduced use of the semiconductor material. Low bandgap materials that suffer from high leakage current would have low efficiency even at moderate device temperatures, and they cannot engage the concentrator to function at high temperatures. If thermoelectric power generation is included in the solar panel, it may have to operate at an elevated temperature of 200ºC or higher, for example, implying that the use of low bandgap semiconductors such as germanium or silicon must be avoided, as pure silicon at 1.1eV bandgap cannot function much beyond 100ºC. Wide bandgap semiconductors such as silicon carbide at 3.1eV bandgap can function beyond 300ºC. But such a solar photovoltaic could harvest only a few percent of the solar spectrum at the highest UV photon energies. The ideal arrangement is, therefore, to use wide bandgap devices such as the p-type Si/C diodes at 2.8eV for high energy photons positioned at the top layer, allowing the lower energy photons to pass through the top layer and be harvested in part by the coupled device at the next layer of Si/CO superlattice at the moderate bandgap of 2.3eV and then by an Si/O superlattice layer at 2eV. Such a stacking arrangement of silicon-based superlattice layers can harvest 10% per each layer and sustain high operating temperatures of over 200ºC. This can be coupled to a silicon-based thermal electric quantum wells and make a combination of a high temperature solar panel together with concentrators incorporating both photovoltaic and thermoelectric generation, which will be explained in the next Section.

Integrating with Thermoelectric Power Generation

Thermoelectric effects were discovered more than 150 years ago, and they include the electromagnetic force generated from a direct wire (the Thomson effect), from the junction of two different materials (the Peltier effect), and the combination of wire and junction (the Seebeck effect). For applications in solar panel effectively, large arrays of junctions are primarily used in devices and are therefore often referred to as Peltier generators.

In recent years, there are also thermoelectric generators based on surface quantum states of semiconductors or based on quantum dots such as nano silicon spheres buried in an insulating matrix material like aluminum oxide. The semiconductor thin film material can also be rolled up like a capacitor to collect charges over a large area. Some claim that they can harvest up to 30% of the latent solar radiation concentrated to an elevated temperature, which is already the efficiency level of a good photovoltaic solar panel.

Assuming that the photovoltaic cells for high energy photons can collect ~25% of the solar energy combined with the thermoelectric for another 15%, totaling more than 1/3 of the solar radiation for practical use. This 1/3 efficiency has already approached the best diesel engines, or more than twice the efficiency of the good conventional solar panels.

Solar Panel Economics

Economics of the silicon-based high temperature solar cell is very favorable. It can engage concentrators for high temperature operation. Using the area of an acre to evaluate the capital costs and yields. The concentrators can easily concentrate 100 times of solar radiation to the solar cells so that an one million dollars of solar cells per acre has already a price tag of over one hundred million per acre, higher that the costs of top-end state of the art computer chips. Even at 10¢ per kWh, and 1,700 hours per year of sunshine, it could already yield more than $300,000 a year.

Land use of the high T solar panel can be the most costly element, particularly for densely populated regions where the power demand is high. The said high T solar system can be placed on buildings or over the walkways as sun shields, for example. For less expensive land regions and under an integrated planning, the large scale use can include, for example, the conversion of solar power to hydrogen fuel to be piped like natural gas, or to pump water, including sea water, uphill to a reservoir and use the hydroelectric power at 90% efficiency upon demand. Detailed planning to optimize the economics goes beyond what we could consider here. The key remains, having a silicon-based high T solar panel would make very good business sense for the generation of clean solar power.

Perspectives of the Historical Range of Weathers, Manmade or Nature

Historical events generally concern those who have contributed at certain periods under certain circumstances. Very rarely do historians include any element of the weather. Indeed, seasonal weather variations change from year to year and they can become an intractable variable and the contribution of weather is usually ignored. Take the recent 400 years of a small, or mini-ice age (1400-1800) as an example. As the ice sheet of Greenland melted, pouring lighter fresh water into the ocean surface in such a volume, that it interrupted the flow pattern of the warm Gulf Stream current at Atlantic Ocean surface from its northern path along American east coast and returned south along northern Europe. Denser cold salty deep ocean water remains largely stationary. Without moderation of a warm Gulf Stream in the Atlantic, and winter in Europe became so cold that the Venice Harbor was frozen (as was New York Harbor). Geologically, 400 years is a very brief instant, but for humans living in that period, it involved as many as twenty generations of persistent cold weather with crop failures, or other kinds of human misery. Such miseries contributed to the French Revolution due in part to failed cereal crops year after year. The Spanish exploration of North America brought back to Europe the potato which grows well in cold climates and could have helped to solve the crop failure problems, but it was largely resisted by farmers on the continent, and only welcomed in Ireland. The potato blight in Ireland, on the other hand, starved the population there, resulting in a massive Irish migration to North America. Much of the American War of Independence was fought during the recent mini-ice age.

During the same period, England had Newtonian mechanics, the industrial revolution, the new found riches of the capitalist class, and Germany had Karl Marx's "Das Kapital" for proletarian revolution. In renaissance Italy Stradivarius violins and cellos were constructed of unusually dense wood grown only in those colder climates, etc.

The mini-ice age brought more snowfall and altered the earth's regional albedo (reflectivity of sunlight). For sunlight, the albedo of ice is 80%, and of the ocean is only 20%. For its impact to global climate, a Russian scientist has simulated the ice-formation on the Earth's surface. If an ice cap extends all the way from 90° at the north and south poles to 23° or so, then the earth would enter into a run-away ice-formation, forming an ice sheet all the way to the equator and render the earth an "ice-cube", which did occur. The mini-ice age continued until the warm ocean current returned to their previous course in the Atlantic and moderated European winters once again. With respect to the present global warming, the melting of polar caps may contribute similarly as the melting of the Greenland ice sheet, and thereby change the Gulf Stream current flow etc. Such a change would probably bring about far more impact to the weather than the recent increase in greenhouse gases. The earth has been gradually warning during the past 12,000 years, reducing the ice-sheet linkages of the continents over the costal shores. There were 4 major ice-ages over the past 400,000 years, or one every 100,000 years or so coincide with the pivoting period of the Earth's rotational axis and we are due for a major ice age according to the swings of the past 4 major ice ages. The use of fossil fuels worldwide adds approximately 34 billion tons of CO_2 a year with 1/5 from U.S. and almost 1/4 from China, mostly due to coal burning. If U.S. nuclear energy generates 80% of the power like France, it could have saved 2.1 billion tons of CO_2 emission. The weight of the global atmosphere is $5x10^{15}$ tons, with CO_2 at $2x10^{12}$ tons, or approximately 400 ppm. The weight of global water is 300 times that of the atmosphere. If CO_2 concentration of the oceans increases by a few parts per billion, it would already equal to the yearly CO_2 emissions from fossil fuels. Note that during the past 50 years, the solar radiation reaching the Earth's surface has been reduced by as much as 20% on average, as monitored by scientists in Israel and other countries, and such a decrease, if true, is far more pronounced than the increase of CO_2 levels in the atmosphere. The change of thermal energy of solar temperature must be measured in tens of millions of years, but the reduction of solar radius by 10% in order to account for the 20% change of solar radiation output over 50 years may be possible. If proven true, it could also explain the missing of heavy neutrinos that are linked to the sun's fusion reactions, implying that the sun may not have a steady thermonuclear reactions or the sun is nearer to the oscillating red giant stage in its life than we thought. If one plots the CO_2 level verses global temperature over time, the rise of CO_2 typically lagged behind the rise of ocean temperature by approximately 150 years. Note that more than 650 Million years ago, the entire Earth was frozen solid with reflective white ice because single cell organisms consumed all the available CO_2 while forming much of today's oil and gas deposits and rendering the atmosphere completely transparent to infrared radiation. There is missing geological data for a period of approximately one billion years before the solid ice data 650 million years ago, and the solid ice coverage may be one of the possible explanations as it occurred at the surface before the Earth's crust moved around in plate tectonic.

Note that the Earth's first plant growth on the land was rather recent, only 400 million years ago, followed by animal lives on the land. They were much younger than the major oil deposits. The cycle of CO_2, from emissions from the deep Earth by various volcanic activities to support the plant growths of which some of them became the coal reserves or to be absorbed by the oceans. Fluctuations of these green house gases and the climate changes in geological time were far larger as compared to those man-made events recently.

Climate Changes and Mega Volcanic Eruptions

In relatively recent Earth history, during the past 500,000 years for example, there were 4 major ice ages at approximately 100,000 years apart, coinciding with the Earth's pivoting period, and had an averaged temperature much cooler than the present. The Earth may be due for another major ice age if the record of the past 4 ice ages is followed. During the ice ages, continents were linked by connecting coastal ice sheets which enabled migrations from one continent to another. Such migrations were particularly important during the last major ice age beginning 100,000 years ago during which the human population had spread all over the globe.

Reasons for the onset of ice ages are not entirely clear. But once substantial cooling gets started, ice formation would increase, and because of the enhanced reflectivity of sunlight (albedo) over ice sheet to 80% from the ocean albedo of 20%, the global cooling would proceed rather rapidly. The Earth was frozen solid 650 million years ago, and perhaps frozen before that time over one billion years because there is no reasonable explanation for the lack of geological data during that period except that the frozen ice would melt and could not preserve any old geological record.

The recent ice ages may be linked to the "mega volcanic eruptions". There are five currently known such mega volcanoes, namely, the Yellow Stone National Park and long valley of west coast in the U.S., the one in Austria and another one in Japan, and the Lake Toba of Indonesia. These mega volcanoes would each typically erupt once every 500,000 years or so (Lake Toba for every 400,000 years and Yellow Stone Park every 600,000 years, with the last eruption of Yellow Stone Park at 640,000 years ago and the Lake Toba at 75,000 years ago.) During the mega volcanic eruptions the CO_2 and SO_2 and SO_3 molecules in the atmosphere would increase by several hundred times or more, would spread and blanket the upper atmosphere and shield much of the sun light from reaching the Earth. This would bring about a dramatic temperature drop of the Earth surface. During the Lake Toba eruption 75,000 years ago, for example, records from the deep ocean temperature indicate a drop of 6ºC and thereby deepened the last major ice age already commenced 25,000 years earlier.

Five currently known mega volcanoes of our planet each having a periodic eruption approximately every 500,000 years, or on the average at 100,000 years per occurrence. This frequency happens to be the period of the last 4 major ice ages. Since there are relatively good records of mega volcanic eruption data in geological and climatic records during the recent Earth history, an investigation of the relationship between the mega volcanic eruptions, the pivoting of the Earth's rotational axis, and the climatic changes, including the green house gases and their dynamic balance from ocean emissions and absorptions would be useful and highly interesting.

The Amazon River used to flow west to the Pacific before the Pacific Plate moved under the South America Plate, raising the coastal line and tilting the continental plate forcing the Amazon river to flow east to the Atlantic. In such geological time scales, the alteration of Gulf Stream currents are really a very recent event, and the ppm change in CO_2 levels are even more immediate. I would love to see a plot of all known ice ages on a logarithmic time scale, including the recent mini-ice ages, explain whatever the cause or "etiology" of them, and then evaluate the possibility that the last mini-ice age would be the final ice age of planet Earth due to the current "global warming". Note that most of human development and human migrations on Earth over the past million years have occurred during ice ages where continents were linked by coastal ice sheets. What are the possibilities that no more ice ages could occur on our planet from now on?

Dealing with "global warming", as favored by recent slogans and media commentators, goes beyond the messy tech; it involves sound bytes and headlines. In this spirit, I would offer some speculation as well.

Integrated Clean Solar Energy, A Hopeful Perspective

Suppose one day, silicon-based superlattice thin film solar cells can be universally adopted, bandgap engineered silicon solar cells constructed on inexpensive polySi substrate material, for example, could cover acres and acres of land area harvesting solar radiation for electricity. They deliver 12volts and 40watts/ft^2 at a production cost of less than one dollar per watt. At a sales price of 10¢ per kWH and delivering $0.3M per acre of electricity, with more value in electricity generation than harvesting most agricultural products. They can be used to charge electric vehicles, and provide hydrogen fuel for fuel cells. They can de-centralize electric power distribution and reduce power transmission lines. They could desalinate oceans for fresh water, and in the process, save fossil fuels for future generations.

Further speculation

As silicon-based power switches are made more powerful and inexpensive, rail-guns with electromagnetic acceleration could launch satellites with greatly reduced payload costs, down from the current $10,000 per pound to perhaps under one hundred dollars per pound. At such launching costs, thin sheets of solar cells can be arranged as veils in space and harvest solar radiation much beyond the Earth. At the synchronous orbit of 23,000 miles high, for example, the area is already many times the Earth's cross section at a diameter of 8,000 miles. Power from space-borne vehicles could be generated in microwaves and beamed back to Earth, to disrupt hurricanes, for example, or to warm up regions where the ground needs warming. A veil of solar cells could readily shield solar radiation and reduce greenhouse warming directly. The cost of shielding from outer space would probably be much less than switching from fossil fuels in order to avoid CO_2 emissions.

Airplanes flying at high altitudes could receive microwaves as a power source directly from the space-borne solar shield and greatly reduce the use of jet fuels. Weather could then be moderated, with addition or subtraction of the equivalent power level of millions of nuclear power plants, not just forecasted. Missions like this would require many dedicated generations to fulfill. A journey of a thousand miles must still start with a first step, however. Such fundamental changes would require a coordinated global effort over many decades or even centuries. Note that the sun will remain a steady main-sequence star for 4-5 more billion years and the continents and oceans will remain in the present geographic distribution for hundreds of millions of years. Therefore a few hundred years of industry revolution plus the required investment and efforts for green-earth adjustment using global solar energy will be a worthwhile human endeavor.

REFERENCES

See Summary Reports by Nongovernmental International Panel on Climate Change.

KEYWORDS

Fossil Fuels
Green House Gases
High Temperature Photovoltaics
Plate Tectonic
Quantum Wells
Silicon-based Superlattice
Solar Cells
Solar Radiation Spectrum
Thermal Electric Power
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