BRIGHT IDEAS IN SOLAR ENERGY

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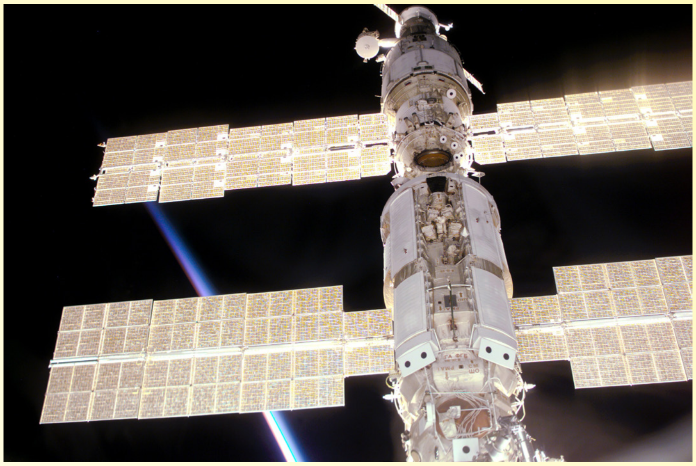
It's no secret that solar power is one of the fastest-growing subsects of the renewable energy industry. In 2011, $150 billion was invested into solar energy -- more than wind, biofuels, and hydroelectric combined, according to Bloomberg New Energy Finance (BNEF, 2011). The reason that solar energy receives such a spotlight, even among other renewable energies, is because it is considered by many investors to have much untapped potential, a belief that backed the 50% growth in investment solar energy saw in 2011. Wind energy is capricious and, like hydroelectric energy, is hugely limited by location; few biofuels can claim to be truly as emission-neutral as other alternative energy sources. Solar energy, on the other hand, can be implemented effectively in many climates, requires little infrastructure, and can be used effectively on a personal or an industrial scale. About 4.2 quadrillion kilowatt-hours (kWh) of solar energy strike the earth every day, of which about 2.1 quadrillion kWh make it to the surface (Quiggin, 2012). As much energy strikes the Earth in 24 hours as is contained in all the petroleum reserves on Earth! The solar power industry is growing exponentially -- more megawatts of solar power have been installed in the last 18 months than in the 30 years before that!

Why is solar power growing so rapidly, and is it destined to last?

To answer those questions -- and to understand what lies in the future for solar energy -- we have to understand the current state of the solar energy industry, the bottlenecks holding it back, and how advances in synthetic materials are helping to overcome those barriers. It is by these innovations that widespread solar power will live or die.



Solar cells have been the dominant method for powering satellites and space stations since the 1960s.

Most types of solar energy collection can be divided up into two broad fields: photovoltaic (PV) and Solar Thermal Energy (STE). Solar Thermal Energy is solar in its most fundamental form -- collection of heat energy from sunlight -- and contrasts with the stereotypical photovoltaic notion of turning energy from the sun into electricity directly. Though STE dates back to ancient times (such as the semi-mythological tale of Archimedes at Syracuse, in which the famous Greek mathematician allegedly defended his home city from a naval siege by deploying large parabolic bronze mirrors to remotely ignite the besieging ships), it is still widely used today -- many modern solar power plants, rather than using solar panels, use mirrors to concentrate sunlight to boil water to spin turbines. In fact, the largest solar power plant in the world, the 354-megawatt Solar Energy Generating Systems works by this very method (for reference, an average coal power plant has an output of about 500 megawatts) (Quiggin, 2012).

Photovoltaic solar collection techniques, on the other hand, are far more contemporary, yet have had a much greater cultural and scientific impact than solar thermal energy. All modern photovoltaic research is based on the photovoltaic effect, discovered in 1839 by Henri Becquerel, that details how light can induce an electric current in certain materials by exciting electrons with rays of incident light. The first photovoltaic cell was created in 1954 at Bell Labs, and was able to convert 4% of incoming solar energy into electrical power (this is known as the cell's conversion efficiency). In 1958, Vanguard I became the first solar-powered satellite, a field in which solar continues to dominate to this day (almost all satellites, including the International Space Station and Hubble Space Telescope, extract power from their photovoltaic arrays). Since then, advances in technology, materials, and methods have each improved the viability and versatility of solar power. Currently, the largest photovoltaic power station is the partially-completed Topaz Solar Farm in San Luis Obispo, with a power output of 300 megawatts, though it is expected to reach 550 megawatts once it is complete (SEIA, 2013).

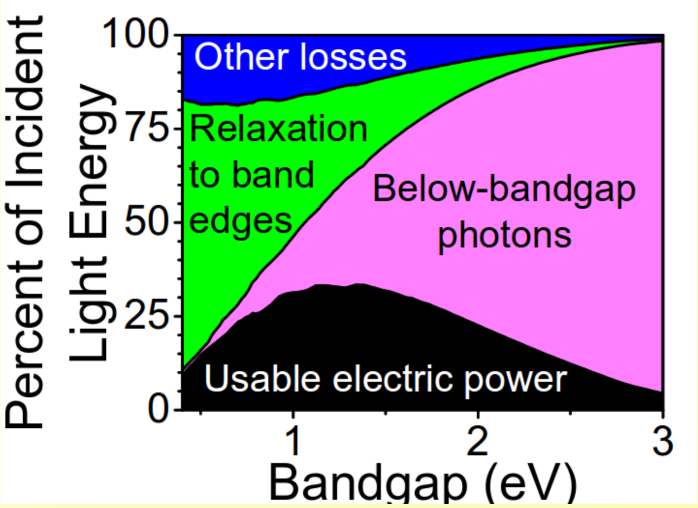
While traditional photovoltaic cells use crystalline structures (often of silicon, because it is easy to work with), the development of revolutionary thin-film photovoltaic devices has drastically increased the potential flexibility (figuratively and literally) of solar photovoltaics. By using vapor-deposited silicon layers instead of bulk silicon wafers, solar cells can be created at much smaller scales than before, though generally with lower conversion efficiencies (Mayer, 2012). Solar photovoltaic devices generally operate in 3 discrete steps: photons are absorbed by a semiconducting material, such as silicon, and used to knock electrons into higher energy levels (known as bands). This action produces a negatively charged electron in the higher energy band, while leaving a positively charged electron "hole" in the lower band; this electron-hole pair is referred to an "exciton". Due to the structure of the photovoltaic cell, excitons can induce a flow of electrons, or current, that can then be harnessed (Fehr et. al., 2014).

At the 1.1 eV band gap of the most common solar cell material, silicon, it is impossible to eke out more than a meager 29% efficiency.

However, despite the amazing breakthroughs that solar photovoltaic energy has achieved in the half-century since its inception, there are still bottlenecks that inhibit its viability as a competitive energy source and must be circumvented for it to become a more significant means of energy production. The most notable is simply that existing solar power stations are not large or efficient enough to produce comparable amounts of power as fossil-fuel or hydroelectric plants. The largest STE power station today has a load capacity of 354 MW, and the largest PV power station is expected to have a capacity of 550 MW by the end of the year; by comparison, the largest nuclear power plant (Kashiwazaki-Kariwa NPP in Japan) has a yield of 8,200 MW, and the largest hydroelectric power plant (the Three Gorges Dam in China) produces a whopping 22,500 MW of power (Quiggin, 2012).

Why do solar power plants fail to measure up to other sources of power? A major factor is the Shockley-Quiesser limit. First calculated in 1961, this limit sets a hard cap on the maximum efficiency of a solar cell in terms of several factors, including the distribution of frequencies in solar radiation, the separation in energy bands of the photovoltaic cell (also known as the band gap), and the precise construction of the cell itself. In its original formulation, Shockley and Quiesser accounted for 3 major factors to determine the maximum efficiency of a solar cell: blackbody radiation, radiative recombination, and spectrum losses. The first, blackbody radiation, accounts for the fact that any substance will inevitably emit radiation depending on its temperature; at room temperature, about 7% of incoming solar energy will inevitably be emitted in such a fashion without being harnessed. The second, radiative recombination, factors in that just as a semiconductor can absorb a photon to produce an exciton, an exciton can relax to emit a photon (or "recombine radiatively"), ensuring that not all excitons that form can produce current. The final and most significant factor is spectral losses, specifically how they relate to band gap. Natural sunlight consists of a set variety of wavelengths of light, each with different energy. When photons of a specific energy strike a semiconductor, they attempt to excite electrons from a low electronic band to a higher one, creating an exciton that can be used to create an electrical current. However, if the energy of the photon is less than the band gap of the material, the electron will not have enough energy to jump the band gap, and thus no exciton will be formed. Additionally, if the energy of the photon is greater than the band gap, the electron excited will jump into the higher energy band, then immediately relax down to the bottom of the band -- essentially, any energy over and above the band gap is wasted. By themselves, spectral losses bring down the theoretical efficiency of an otherwise-perfect solar cell to a mere 48%. Taking into account these three factors, it is possible to calculate the theoretical maximum efficiency of a solar cell as a function of the band gap of the solar cell material. With a perfectly optimal solar cell operating with a band gap of 1.34 eV, only a mere 33.7% of all incident solar energy can be absorbed. At the 1.1 eV band gap of the most common solar cell material, silicon, it is impossible to eke out more than a meager 29% efficiency. Considering modern commercial solar cells are already on average 22% efficient, the Shockley-Quiesser limit tells us that improving the quality of our solar cells can only increase the efficiency so much. Considering how even large solar farms can barely compare to modestly-sized power plants of other sources, the Shockley-Quiesser limit highlights the need for entirely new approaches to solar energy production (Krisch, 2014).

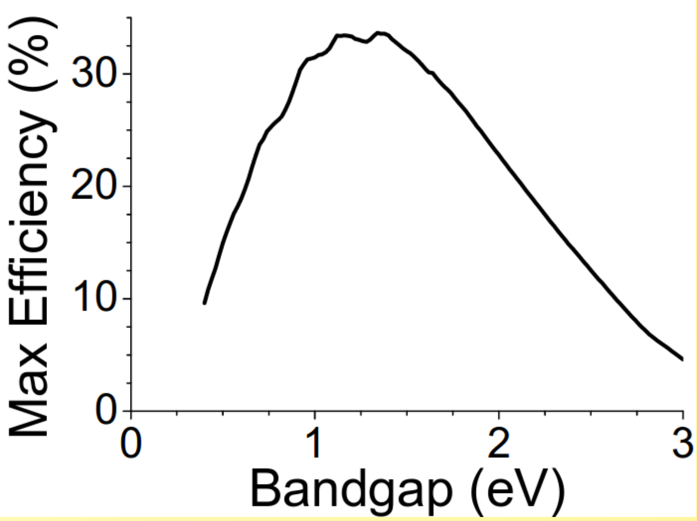
Fortunately, there are a large number of ways to circumvent the Shockley-Quiesser limit to make solar cells with the greater efficiencies. By layering different solar cells with varying absorbance ranges on top of one another, the overall efficiency can be further increased -- as high as 86% as the number of layers approaches infinity. Most "multijunction", or "tandem solar cells", as they are called, have around 3 layers, with a maximum



The Shockley-Quiesser limit puts a cap on the maximum efficiency of a solar cell in terms of the band gap of the cell material. At low band gaps, many electrons are lost to recombination, as the small energy difference enables electron relaxation. As the band spacing increases, fewer incident photons have enough energy to clear the gap.

theoretical efficiency of 49%; unfortunately, the layering process is expensive and tandem solar cells are unlikely to see widespread usage until they become more affordable. Using lenses or mirrors to concentrate solar radiation can also help increase efficiency past the Shockley-Quiesser limit, and since it requires few solar cells per area, it increases the viability of tandem solar cells; tandem solar cells under concentrated sunlight can have theoretical efficiency caps as high as 86% -- almost 4 times current commercial levels! (Graham-Rowe, 2008) Unfortunately, concentrated solar radiation has the unfortunate side effect of heating the solar panels beyond their operational range, requiring special cooling techniques to keep the panels working. Researchers at IBM have proposed a solution: a liquid microlayer of conducting indium-gallium alloy (Bullis, 2008). Because of the liquid nature of the alloy, it can conform to the minute grooves in the cell to efficiently siphon away heat, and the metallic character of the substance gives it the conductivity needed to do so, effectively creating a sort of ultra-efficient thermal paste. Put together, this new solar strategy can circumvent the Shockley-Quiesser limit through analog increases in efficiency, and can even be installed on pre-existing solar panels to retroactively increase their efficiency.

Another approach to bypassing the Shockley-Quiesser limit involves reevaluating the core assumptions made in its calculation. According to Shockley and Quiesser's assumptions, a vast amount of energy loss stems from the fact that energy above the band gap is lost, as excitons with energies above the band gap energy relax downward. For decades, scientists believed that this loss was unavoidable, primarily because it seemed impossible for one photon to produce multiple excitons, the only obvious way to refute this assumption. In the



This curve describes the maximum possible efficiency of a solar cell as a function of the bandgap of the cell material. Efficiency caps out at a mere 33.7% at a bandgap of 1.34 eV.

last ten years, however, Brian Korgel and his team at the University of Texas, Austin have revolutionized the field of multiexciton stimulation. Using copper indium selenide -- a common semiconductor with a high conversion efficiency -- Korgel and his group showed that through a process known as "photonic curing", organic compounds that inhibit multiexciton stimulation can be vaporized off the film (Sagoff et. al., 2014). The study shows that multiexciton production can be induced in mass-produced, real-world materials, though Korgel says the real work is yet to come:

> "The holy grail of our research is not necessarily to boost efficiencies as high as they can theoretically go, but rather to combine increases in efficiency to the kind of large-scale roll-to-roll printing or processing technologies that will help us drive down costs." (Korgel, 2014)

Alternatively, entirely new methods of solar energy collection can be implemented that alter every parameter of the process, sidestepping the Shockley-Quiesser limit: a new field, known as solar thermophotovoltaics (STPV) seeks to combine STE and PV processes to harness solar radiation in an entirely new way. STPV devices first use concentrated sunlight to heat a specific compound (an emitter) that, when at a sufficiently high temperature, radiates energy in a very specific spectrum that is more amenable to photovoltaic capture at high efficiencies by a specialized "absorber". Because almost all of the energy from the sun can be absorbed through the STE process, the theoretical efficiency cap for this process is over 80%. Until recently, experimental prototypes for this technique demonstrated conversion efficiencies below 1% due to difficulty of controlling the spectrum of the emitter; however, a recent breakthrough by Lenard et al. (Lenert, 2014) reports a drastic increase in efficiency to 3.2% by pairing a carbon nanotube absorber with a silicon-quartz

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emitter, with a goal of reaching a commercially-viable 20% efficiency in the near future.

Unfortunately, low conversion efficiencies are not the only problems stymieing the solar industry. Another major problem that must be overcome is the issue of energy storage. Because solar power stations can only produce electricity in the daytime, areas powered predominantly by solar energy must have an efficient means of energy storage to ensure that electricity is available at night or on overcast days. However, current means of energy storage are very inefficient, and pass on this inefficiency to the entire solar process. Batteries have limited capacities and can significantly increase the cost of solar systems, and "storing" the energy as hydrogen gas (a common energy storage mechanism, due to the high energy density of hydrogen and the ease of access of stored energy) requires the use of efficiency-limiting fuel cells to turn electricity into hydrogen (Krisch, 2008). In fact, simple energy density calculations show that without the use of chemical energy storage mechanisms like fossil fuels or hydrogen, storage is impractical just from a volumetric standpoint: even the best batteries can only store about 0.3 kWh of energy per kilogram, whereas conventional fuels like gasoline pack in over 13 kWh/kg. Due to solar's small market share in the energy industry (around 1%) this isn't a problem, because solar energy producers can simply sell their energy to the grid during daylight hours, and consumers can revert to conventional energy sources at nightfall -- but as solar power contributes increasing amounts of energy to the grid, more and more energy storage is required on an almost impractical scale.

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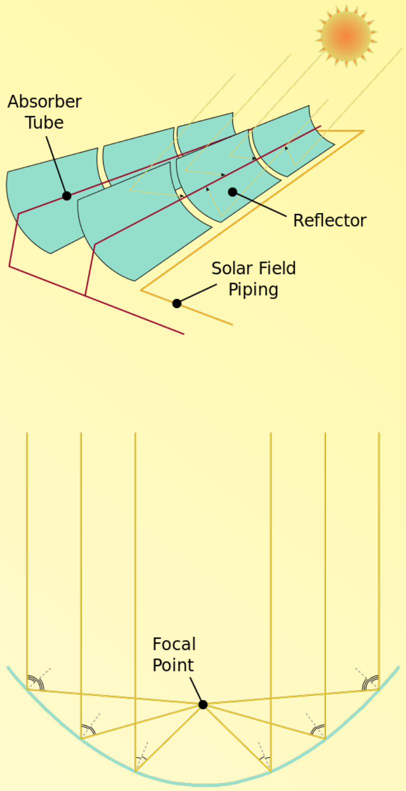
A solution to the fuel storage problem has been proposed by Dr. Daniel Nocera of MIT, and revolves around the production of an "artificial leaf" that is able to harness sunlight to form secondary energy sources such as hydrogen directly, much as how an actual leaf utilizes sunlight directly to form carbohydrates from carbon dioxide and water. Dr. Nocera (2011) details the creation of solar water-splitting cells through the use of a cobalt-boron catalyst. These cells are completely integrated and do not require internal wires, granting them great solidity and flexibility of position. Though the cell created only runs at an efficiency of 5%, this number is constantly being improved by further research, and the direct production of energy-rich hydrogen provides a good solution to energy storage problems in solar energy. Hydrogen is extremely energy dense due to its gaseous nature and low weight, packing in 142 kWh/kg



This class of solar thermal energy collection, known as a parabolic trough, uses parabolic mirrors to focus sunlight onto an insulated tube containing a liquid that is piped off to generate electricity.

-- over 10 times as much energy per pound as gasoline! In addition, hydrogen is also easy to transport and is even easier to extract energy from, and the only byproducts of its combustion are environmentally friendly water vapor. If commercial water-splitting solar cells are able to reach competitive efficiency rates, solar power would become a much more viable energy creation mechanism. (Reece et. al., 2011)

Solar Two was a proof-of-concept solar-thermal energy plant that used molten salt to capture and store the sun's heat, allowing for energy production even at night.

Though many of the largest solar power plants are use solar thermal methods, the Topaz Solar Farm in San Luis Obispo, CA is poised to become the largest solar power plant in the world, delivering a planned 550 MW of power.

The combination of parabolic reflectors and a Stirling heat engine can produce efficiencies upward of 30%, almost double that of competing photovoltaic technologies. These so-called "Dish-Sterling" or "Solar-Sterling" systems provide the highest known efficiencies of any method.

Energy storage, unlike the Shockley-Quiesser limit, extends beyond just photovoltaics -- it is equally hampering to solar thermal methods of energy collection, which are comparably prevalent in the solar industry. Due partially to their overwhelming simplicity, STE methods can demonstrate efficiencies that far outstrip the leading PV technologies, while retaining good scalability and at relatively low cost. Some of the highest-efficiency STE techniques include the Solar Stirling Engine, which uses large parabolic dishes to focus sunlight and drive a heat engine; this deceptively simple process boasts an efficiency of over 30% (NREL, 2007). Though these processes suffer from the same storage problems that plague photovoltaics, an innovative solution has emerged: the use of vast quantities of molten salt (generally a mixture of sodium and potassium nitrates) to store heat until it is needed. Though the energy stored per unit weight of these molten salts leaves much to be desired (0.012 kWh/kg places it below even batteries), this is more than offset by the extremely low cost and long lifetimes of the substance. In early 1988, the Department of Energy (DoE) invested in the construction of a solar power tower to field-test the effectiveness of molten-salt energy storage, in a project known as Solar Two. In a report released in 1996, the DoE (through their branch at Sandia National Labs) reported:

> "These solar plants [Solar Two] operate by using large, sun-tracking mirrors to concentrate sunlight on a receiver that sits atop a tower. The concentrated sunlight heats the molten salt as it flows through the receiver. The very hot salt is then piped away, stored, and used when needed to produce steam to drive a turbine/generator that produces electricity. The system is capable of operating smoothly through intermittent clouds and can continue generating electricity long into the night." (Miller, 1996)

Though the Solar Two plant was deconstructed in 1999, the continued growth of solar-thermal energy as a field, as demonstrated by the success of SEGS and the investment in the larger Ivanpah Solar Power Facility, has led to many plants evaluating or adopting molten-salt storage as a means of levelling their power output levels.

As innovation continues to revolutionize solar power, we can expect to see solar power become more ubiquitous in everyday life. In 1993, the solar-photovoltaic energy capacity was a mere 50.3 MW; in 2003, it had only risen to 275.2 MW; yet by 2013, it had veritably exploded to 11,972 MW and continues to grow at a rate of about 70% per year (SEIA, 2013)! Though solar power only composes about 3% of all US renewable energy sources, that share is rising more rapidly than that of other sources. Solar is quickly reaching cost parity with fossil fuel sources, and has already surpassed nuclear energy in this regard (Quiggin, 2008). With the help of carbon taxes and additional government subsidies, it is likely that solar power will begin to eat an increasingly large portion of the renewable energy pie in the very near future. In the past 10 years solar energy has gained a foothold on the energy industry it is unlikely to relinquish; as more solar power plants (thermal and photovoltaic) continue to be built and solar photovoltaics integrate themselves further into the national infrastructure, solar power has a real chance of displacing oil or coal as a major energy source. Through innovations in synthetic science, solar power has grown exponentially, and continued innovation of this sort will help it overcome the obstacles it faces today. Investments in alternative, renewable energies like solar power help us prepare for the future, and for solar power, the future looks very bright indeed.

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