Solar Thermophotovoltaic Efficiency Potentials: Surpassing Photovoltaic Device Efficiencies

by

Kathryn M. Barnes

Submitted to the
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ABSTRACT

Solar energy has gained more attention in recent years due to increased concerns about the continued use of fossil fuels. Solar energy is a form of renewable energy, and solar energy technology does not release greenhouse gases responsible for climate change. While photovoltaic (PV) cells, which convert sunlight into electrical energy, are becoming more widely used, they are limited in their ability to convert sunlight into electricity. One of the limitations of PV energy generation is caused by the fact that only a limited portion of the energy spectrum of sunlight contributes to electricity generation.

Solar thermophotovoltaics (TPV) aim to improve the efficiency with which sunlight can be converted to electrical energy by converting solar energy to thermal energy first before generating electrical energy with a PV cell. Instead of direct illumination by sunlight, the sunlight is absorbed by an intermediate material and then reemitted as a means of energy spectrum control, which in theory allows for more photons to generate useful electrical energy. The efficiency of solar TPV systems have been modeled. These models demonstrate that solar TPV devices have a higher potential efficiency than PV device counterparts. Yet, solar TPV devices are not yet suitable for any sustainable use, and there are many engineering challenges that need to be overcome in order to cross over from theory into practical use.

Thesis Supervisor: Sang-Gook Kim
Title: Professor of Mechanical Engineering

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Table of Contents

List of Figures

List of Tables

1. SOLAR ENERGY

1.1 Introduction to Solar Energy

Harnessing the power of the sun as a form of energy is a concept that has existed since ancient times. From the 7^{th} century BC when fire was made from concentrating sunlight through a magnifying glass [1] to the current era of using solar power to generate electricity on a commercial level, the idea of utilizing solar radiation to power human endeavors has persisted. As industrialization has increased, so has the dependence of humans on the generation of energy, specifically in the form of electricity. This in turn has placed exploding demands on the resources used in the electricity generation process, namely fossil fuels. Considering the nonrenewable nature and limitedness of fossil fuel sources, a push towards renewable energy has resulted in a high level of interest in developing more efficient and affordable solar energy technology. Adding to the reasons for solar energy technology explosion is the public discourse on climate change. Solar energy technology development is seen as a solution that if widely implemented, will decrease human dependence on fossil fuels and thus help mitigate the effects of climate change [2].

The appeal of solar energy technology is obvious – the sun shines in many places in the world so many nations had access to the source of energy. Of course, there are limitations to solar energy, since some places are more subject to the sun radiation than others. The lack of carbon dioxide emissions is also a huge plus in today's (somewhat) environmentally conscious political climate. In the past, the United States has hesitated to issue numbers for the reduction of greenhouse gas production. However, the U.S. federal government is now aiming to reduce its greenhouse gas pollution by 28 percent by the year 2020 [3]. This reduction in greenhouse gas pollution is set to happen as energy demand in the United States increases. According to the U.S.

Department of Energy's Annual Energy Outlook for 2012 [4], the demand for energy in the United States will grow by 0.2 percent per year in the transportation sector and 0.8 percent per year in the electricity sector through the year 2035. Additionally, the projected demand of energy worldwide is expected to increase tremendously due to development in nations like India and China. In fact, China lags only the United States in oil consumption and consumes and produces the most coal of any country in the world [5]. Demand is projected to continue to increase with China's rapidly growing economy.

One of the potential solutions to this problem of increased demand in a time where the longer term future nonrenewable energy sources is in question is to simply consume less. Increasing efficiency of current systems is another option. Reliance on fossil fuels should also be decreased to minimize greenhouse gas emissions. Increasing renewable energy use, like solar, has been sought to solve both problems - meeting the energy demands without further increasing greenhouse gas emissions. Photovoltaic (PV) cells that capture the energy from the sun to useful electrical energy – with higher efficiency in these cells as the goal of many research groups around the world.

Thermophotovoltaic (TPV) systems have been developed to achieve higher efficiencies than traditional photovoltaic cell systems. TPV systems make the additional effort to control the spectrum of photons that are emitted in a favorable spectrum range to the PV cell in order to increase the amount of electricity generated compared to simply exposing a PV cell to sunlight [6]. In principle, TPV systems could generate electricity from a variety of heat sources, such as chemical, nuclear, and solar [7], though the focus of this thesis will be on the utility of solar thermophotovoltaics. More importantly, we need to understand how the expected power output of a solar TPV system is greater than that of a PV system.

In this thesis, the potential utility of solar thermophotovoltaic systems is explored and compared with photovoltaic systems, with emphasis on the efficiency of such systems. To start, a brief history of solar technology evolution is explored with particular attention to the development of photovoltaic cell technology. The principles of photovoltaic cell operation, including the limits to photovoltaic cell technology are explained. Then the principle operation and history of thermophotovoltaics is presented in the following chapter, with focus on theoretical and practical efficiencies that can be expected of such systems.

1.1.1 Benefits of Solar Power

Solar energy technology has several advantages over conventional fossil fuel powered technology. These advantages include, but are not limited to, existing as a mostly passive system (mechanical parts are not a big factor), the renewable nature of solar radiation, and being more environmentally friendly. These are all factors that will work in favor of continued research and development in solar energy technology.

The energy infrastructure of the United States is currently centered around the usage of fossil fuels. Fossil fuels are widely used and generally available. Also, the way fossil fuels sources like natural gas, coal, and oil can combust to produce energy is generally well understood. However, the combustion of fossil fuels also results in the byproduct of carbon dioxide. Carbon dioxide is a major greenhouse gas, so it traps solar radiation as heat in the atmosphere [8]. In fact, carbon is the greenhouse gas that the United States emits the most, and it is thought that the additional carbon that traps heat is causing the surface temperature of the Earth to rise. Before the Industrial Revolution, the concentration of carbon dioxide was 228 parts per million, which has risen to 340 parts per million, but an acceptable level of carbon dioxide is considered to be 550 parts per million [8]. In order to prevent the concentration of carbon dioxide from exceeding acceptable levels, carbon emissions will need to be reduced dramatically. This means a reduction of the use of fossil fuels, so the increasing energy demand will need to be met by other sources of energy such as solar. Implementing solar energy as a solution will be a challenge because of the way the energy infrastructure is set up. Nevertheless, solar is a viable source of alternative energy, as a nuclear, geothermal, biomass, wind, and hydro.

The sun is expected to have millions of years left in its lifetime, which makes is a prime source of renewable energy. The amount of solar radiation is actually finite, and the portion of it that reaches the surface of the earth is dependent on a few factors. Clouds, atmosphere particles, and reflection cause about thirty-five percent of solar radiation to Earth to not reach the surface [8]. However, enough solar radiation get through to warm the Earth during the daytime. The energy from the sun can be used not only to heat or cool a surface, but also to induce an electrical current to create electrical power.

1.1.2 Existing Solar Technologies

There are several active solar energy technologies that consist of mechanical systems that capture solar radiation. Solar heat collectors are able to capture incident solar radiation and transfer the energy to a heat transfer fluid, such as water. Solar power plants use mirrors to concentrate solar energy. However, they are not common and require a large area in order to produce as much energy as a power plant operating off of fossil fuels sources [8]. Photovoltaic cells are able to transform light energy into electrical energy, and the installation of photovoltaic devices has been increasing rapidly in the past decade. The principles on which photovoltaic cells operate need to be understood in order to make way to understanding the principles of solar thermophotovoltaics.

1.2 Photovoltaic Cells

Photovoltaic cells were created to convert energy from the sun to electrical energy via the photovoltaic effect. Photons, which light is comprised of, are the packets of energy that undergo this conversion process. The effectiveness of a device that uses the photovoltaic effect to generate electricity depends on both the choice of the material that absorbs the light and the effectiveness of the material's connection to the rest of the electrical circuit [9].

1.2.2 Principles of Photovoltaic Cell Operation

The photovoltaic effect was first discovered by French scientist Edmond Becquerel in 1839. In an experiment with two metal electrodes placed in conductive solutions in an electrolytic cell, he found that the amount of electricity generated increased when the cell was exposed to light [10]. This was just one of the first instances in which the photovoltaic effect was observed. William Adams and Richard Day discovered that a current could be produced between two heated platinum contacts were placed on a selenium without an external power supply [9]. Similarly, Charles Fritts was able to create a solar cell by sandwiching selenium with gold and another metal in 1894 [9].

More clearly, the photovoltaic effect is a result of photons from sunlight being absorbed by a material, which caused them to knock electrons away from the material. These excited electrons do not immediately return to their unexcited state due to some asymmetry in photovoltaic devices that pulls them away and uses them in an external circuit [10]. In photovoltaic cells, the excitation of an electron so that it leaves its unexcited energy state is known as the creation of an electron-hole pair [9]. Figure 1-1 illustrates the photovoltaic effect in a photovoltaic cell.

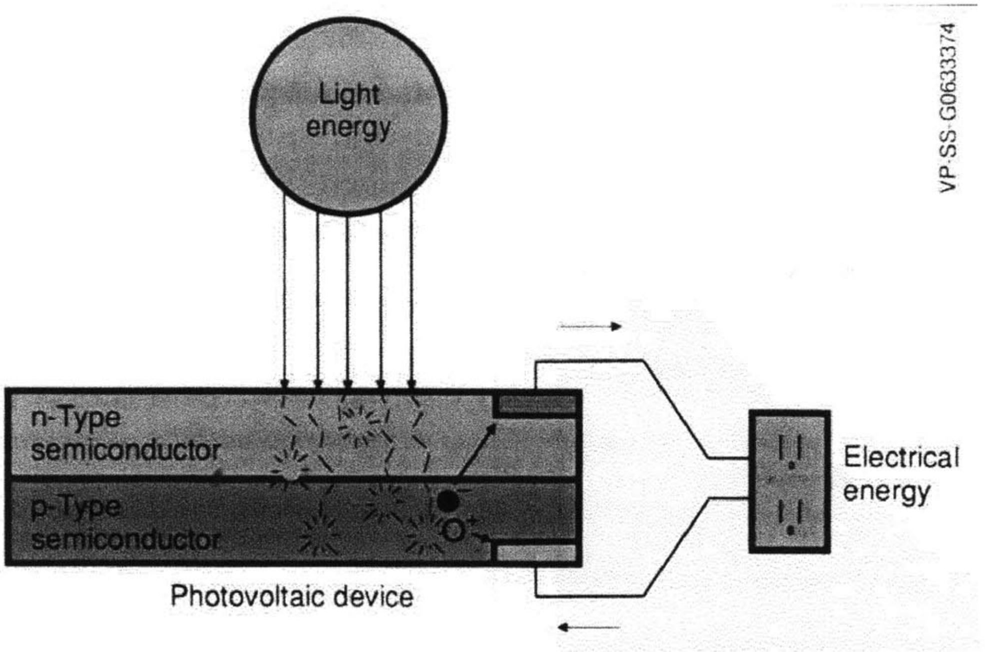


Figure 1-1. Energy from the sun (or another light source) is incident on a semiconducting material. The photons knock electrons from the semiconducting material after crossing the bandgap, creating electron-hole pairs. These pairs is turn generate an electric current, which can then be used for electrical energy [11].

As the Figure 1-1 illustrates, the most typical photovoltaic cell has a single *p-n* junction in a semiconductor material. Silicon electronics boomed in the 1950s, which lead to the discovery of a method of creating a *p-n* junction in silicon. A *p-n* junction showed good photovoltaic behavior upon exposure to light [9]. This enabled the development of useful photovoltaic cell technology.

1.2.2 Development of Photovoltaic Cells

The first photovoltaic module was produced in 1954 by Bell Laboratories [10] using silicon as the semiconductor material. In their infancy through the 1960s, solar cells were seriously used in space vehicles and satellite communication systems, so the market for solar cells was dominated by space applications for the next two decades [12]. The further development of photovoltaic modules and material was continued beyond space exploration, allowing photovoltaic modules to be used for commercial application, especially after the United States was hit by an energy crisis in the 1970s [10]. During this time, the western world became more interested in alternative sources of energy, resulting in an increase in funding for alternative energy research. Many methods of increasing efficiency and lowering cost of photovoltaic devices were explored. Researcher explored the use of different materials, such as polycrystalline silicon, amorphous silicon, organic conductors, and 'thin film' materials [9]. Additionally, the concept of tandem cell was developed during this time. However, the high cost per energy limited the spread commercial deployment of solar cells, but the understanding of fundamental science behind photovoltaic cells was a direct result of this period [9].

A type PV cell is able to generate a direct current voltage of 0.5 to 1 volts with a current of tens of milliamps under short circuit conditions upon exposure to light [9]. The current generated is reasonable, but 0.5 to 1 volts is not high enough to power very much. Therefore, the individual cells are connected in series so that the current remains the same but the voltage is increased with each connected cell. Then, the cells are encapsulated into modules, most typically with enough cells to generate 12 V in standard lighting conditions [9]. This way, a solar cell acts like a current generator in the electrical circuit, providing applications with the power required for operations.

1.2.3 Conventional Photovoltaic Losses

Photovoltaic cells suffer from a number of different losses. The most obvious one of these losses is that of non-absorbed radiation from photons with energy less than the band gap energy of the PV. However, not only do photons with energy lower than the band gap result in losses, electron hole pairs generated by photons with energy greater than the band gap energy contribute to losses through thermalization. The excess energy from the photons ends up being converted to heat since it needs to go somewhere, and this heat is able to cause electrons to revert back to their unexcited state [6].

Additionally, the electron-hole pairs that are created are able to naturally recombine, which means that they are unable to contribute to the electric current. Instead, the energy ends up being used up in electron-photon collisions and electron-electron collisions (also known as the Auger effect). Therefore, the efficiencies that are calculated are often overestimates due to neglect of these losses [13].

1.2.4 Detailed Balance Limit

In order to characterize the efficiency of PV cell technology, several attempts were made at determining the efficiency limit of single junction PV cells. In the landmark paper published by Shockley and Quiesser in 1961, the detailed balance limit (also known as the Shockley-Quiesser Limit) was proposed [14]. Since then, the detailed balance limit has been the widely used measure of maximum theoretical single junction PV cell efficiency.

To calculate theoretical efficiency using the detailed balance limit, several assumptions concerning the process by which PV cells convert solar radiation into electrical energy need to be made. For starters, the sun is assumed to be a blackbody at 6000 K. The solar radiation then impinges upon the PV cells, assumed to be a blackbody at 300K. All of the photons that have an energy that is greater than or equal to the band gap energy are said to be absorbed by the cell. Additionally, for each photon, a single electron-hole pair is created in the cell. Recombination in the cell is assumed to be all radiative, minimizing losses.

The detailed balance limit efficiency is the product of four different efficiency terms. The impedance matching factor is the factor that accounts for the fact that when in operation, a solar cell cannot both be at the short circuit voltage and the no load current. Power, which is the product of the current and the voltage, is maximized at the point where the product of the voltage and current is highest, as this is the definition of power in the electrical context. The ratio of this power to the power if both the short circuit voltage and no load current were achieved at the same time is how to obtain the numerical value of this factor that contributes to the efficiency.

The "ultimate efficiency" of a solar cell is simply determined by the ratio of the number of photons that have energy greater than or equal to the energy of the band gap to the total number of photons. Because solar radiation inherently provides photons of different energy levels, there are always losses in a solar cell as a result of photons have insufficient energy to cross the energy gap of the semiconductor material. Therefore, there is a finite efficiency since solar radiation emits a spectrum of photons.

The ratio of operational output voltage to the band gap energy is the third factor that is taken into account in the detail balance limit. In order to calculate this factor, the ratio of the open-circuit voltage to the band gap voltage is taken.

The last factor is that probability that a photon incident on the solar cell that crosses the band gap will produce an electron-hole pair. This factor is assumed to be unity in the calculations of the theoretical maximum efficiency of a single *p-n* junction solar cell [14]. However, as noted previously, in practice this factor is not unity due to thermalization losses and non-radiative recombination losses due to motion of electrons and photons in the cell.

Using the assumptions provided in this section, the maximum theoretical efficiency of a photovoltaic cell is approximately 30% at band gap energy of 1.28 eV [14-15]. After looking at the detailed balance limit, there are certainly factors that need to be balanced against each other in order to maximize efficiency. Clearly, if the band gap across the semiconductor were 0, all of the photons incident on the PV cell could help generate electrical current. However, the voltage would be zero. A band gap greater than 0 eV does not allow for all photons to contribute to the electrical current, but the output voltage increases as the band gap energy increases. Figure 1-2 illustrates the relationship between the band gap energy and the ultimate efficiency.

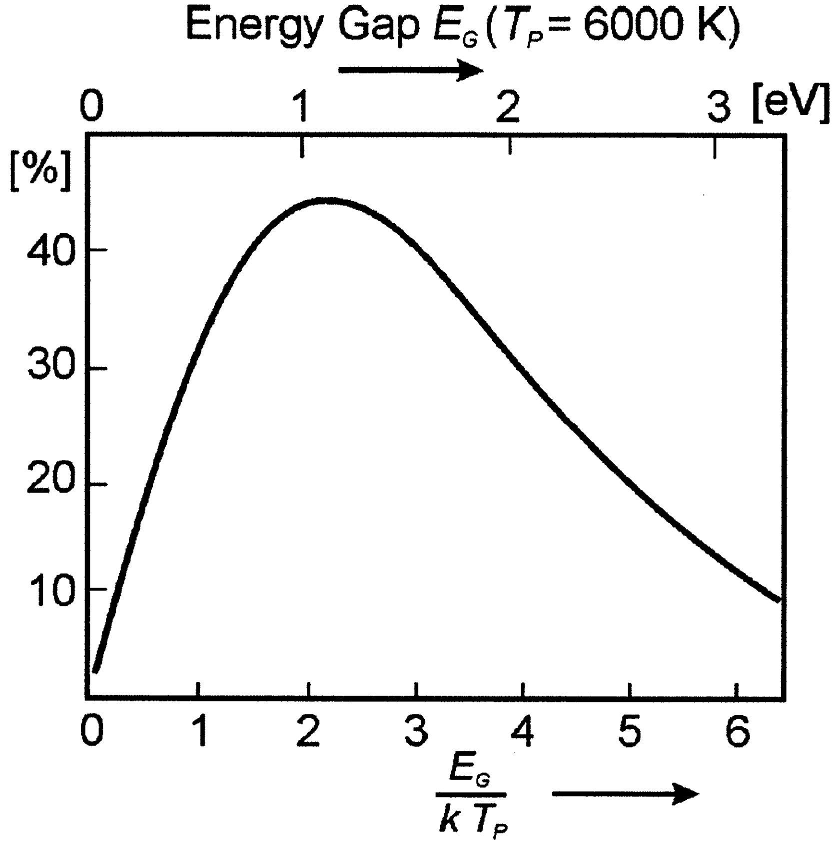


Figure 1-2. The efficiency of a solar cell is plotted against band gap energy of the semiconductor in a solar cell. The maximum efficiency is seen close to a band gap energy of 1 eV. Note that a band gap approaching 0 eV, many photons from solar radiation can be absorbed by the solar cell, but the operational photovoltage approaches 0 V. As discussed in the explanation of the detailed balance limit, the band gap energy needs to be balanced against the photovoltage in order to maximize efficiency [12].

1.2.5 Common Band Gap Materials

As stated previously, photovoltaic cells are most commonly single junction devices. There is a single band gap between and *p*-type and *n*-type semiconductor junction. Only photons that have energy level that is greater than or equal to the band gap energy are able to generate electricity [10]. The band gap energy is shown to have an effect on the efficiency of the solar cell, and different materials have different band gap energies and other properties that contribute to device efficiency.

The most commonly used band gap material in PV cells is crystalline silicon. This is because the cost of using silicon for crystalline solar cells is lower than for other materials [12]. Approximately 94 percent of the photovoltaic market is for crystalline solar cells, of which silicon of any form is a large portion. It has been found that there are high photon absorption capabilities in other materials as well, namely in III-V group semiconductor materials, such as GaAs [12].

1.2.6 Current Commercialization of Photovoltaic Cells

There have been challenges to deploying photovoltaic cells for commercial and home use. Research shows that the price of the technology would need to be reduced by a factor of 1000 from 1973 levels for effective deployment, but the current reduction has only been by a factor of about 100 [12]. However, research on photovoltaic cell technology has continued to progress, and with it, the installation of photovoltaic systems as well. Government incentives in the United States have led to an increase in the capacity of photovoltaic systems installed in the country. Fossil fuels sources of energy are still plentiful enough that most will not turn to install solar cells to generate electricity. Nevertheless, as the demand for energy continues to increase within the United States and globally, the continued development of photovoltaic cells can help meet energy needs.

Growth of the global photovoltaic market has been explosive over the past several years. Shipments have reached 17 gigawatts in 2010, with the United States accounting for 8% of this number (1400 megawatts) for demand and 6% (1000 megawatts) of the supply [16].

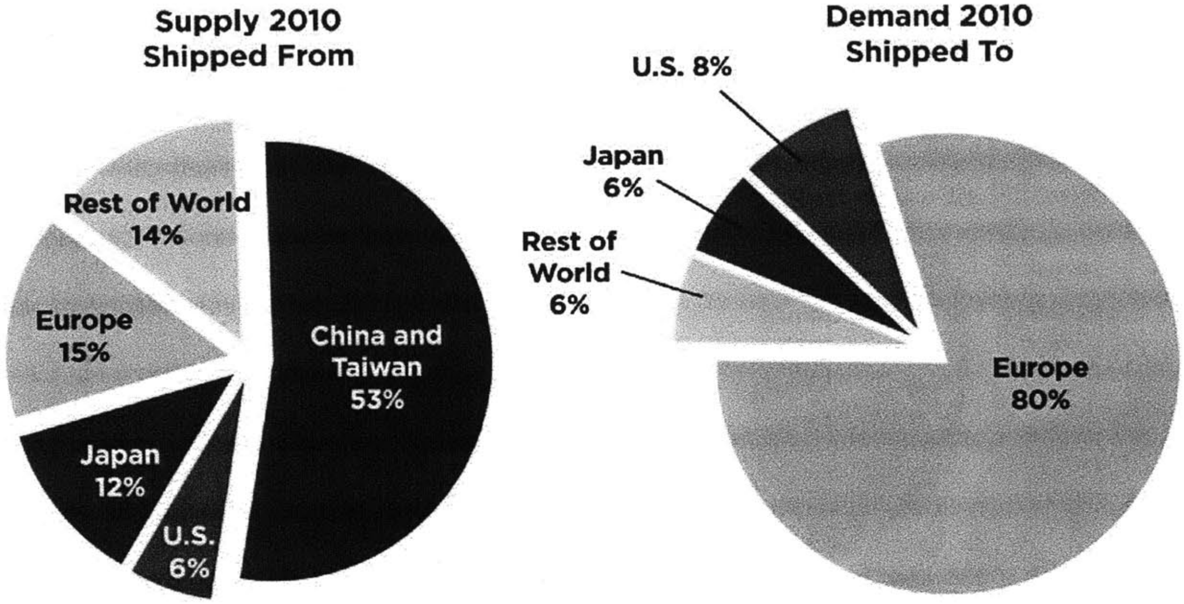


Figure 1-3. The distribution of photovoltaic shipments by region in the year 2010 is shown. The United States accounted for a larger part of the market prior to the year 2010 when China and Taiwan account for 53% of photovoltaic shipments due to rapid development of photovoltaic manufacturing and factories [16].

1.2.7 Efficiencies of Photovoltaic Cells

As mentioned previously, PV cell technology development has continued steadily through the present time. The following table, created from data obtained by the NREL, shows the maximum recorded efficiencies of several different photovoltaic cell technologies. The chart shows that single junction PV cells are coming closer to the detailed-balance limit while some technologies have succeeded in exceeding the limit. A detailed chart of efficiencies of different solar cell technologies between 1975 and 2012 from the National Renewable Energy Laboratory

(NREL) is provided in the Appendix . The chart also makes note of the developers that have achieved the efficiency milestones for each technology.

Table 1-1. Recorded efficiencies of several different solar cell technologies [17].

Type of Cell	Maximum Efficiency Recorded
Three-junction (concentrator)	43.5%
Three-junction (non-concentrator)	28.8%
Two-junction (concentrator)	32.6%
Single crystal silicon	25.0%
Multicrystalline silicon	27.6%
Silicon heterostructures	23.0%
Single crystal gallium arsenide	26.4%
Concentrator gallium arsenide	29.1%
Thin film crystal gallium arsenide	28.8%
CIGS	20.3%
Amorphous silicon	17.3%
Organic cells	10.0%

In principle, the number of photons that can be converted into useful electrical energy can be increased by stacking several different materials with decreasing band gap energies. The photons that are not absorbed by the first material because they did not have sufficient energy to cross the band gap may have sufficient energy to cross the band gap of the next material in series [13].These types of cells are the multi junction cells that are able to beat the detailed-balance limit (which is restricted to apply to a single *p-n* junction) and still operate in a manner similar to that of single junction PV cells. This way, more photons are able to be captured by a photovoltaic device. These cells are not as common as single junction cells because the cost of creating multi junction cells is very high, so though they have a higher efficiency than single junction cells, they are much less common.

Photovoltaic technologies have not only benefited from the experimentation with different semiconductor materials such as silicon and gallium arsenide and the creation of multi junction cells, but there are also emerging photovoltaic technologies that are currently being researched. These include thin-film solar cells, organic cells, dye-sensitized cells, and quantum dot cells to name a few [17]. The efficiencies of GaAs cells some thin-film solar cells, such as CIGS cells, are sufficient to be of practical use [18]. Though they are still less efficient than traditional crystalline solar cells and the most efficient tandem cells, they are lighter than these cells. However, emerging photovoltaic technologies like organic cells, dye-sensitized cells, and quantum dot cells show rather low efficiencies and are not used in practice.

2. SOLAR THERMOPHOTOVOLTAICS

2.1 Solar Thermophotovoltaics Background

Solar thermophotovoltaics attempt to increase the efficiency of conversion from solar radiation to electricity. According to Landsberg [13], the average energy of photons from sunlight is around 1.9 eV while the semiconductor band gap for most materials is closer to 1 eV. The remaining energy from the average photon (0.9 eV) that is not used to cross the band gap energy and excite an electron will be lost to thermalization. This wasted energy can be decreased if an intermediate absorber, decreasing the average energy loss of the photons by reemitting them to the PV. These reemitted photons are generally in a more favorable energy spectrum so that they can cross the energy gap of the semiconductor, which will allow for improved efficiencies.

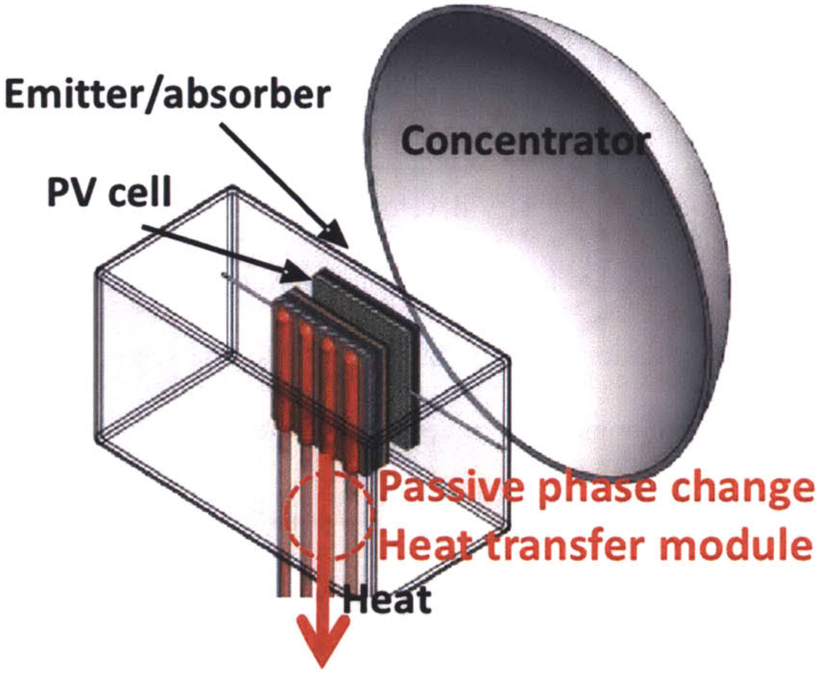


Figure 2-1. This diagram shows the typical components involved in a solar thermophotovoltaic system: sunlight concentrator, emitter/absorber, and PV cell [19].

2.1.1 Birth of a Concept

The definitive event that invented the concept of thermophotovoltaics (TPV) is unclear [20]. In 1956, Henry H. Kolm, working at MIT Lincoln Laboratory, combined a Coleman camping lantern with an incandescent gas mantel and a Silicon solar cell. He reported the results of his experiment in the 1956 Quaterly Progress Report in a one page summary [21]. The parallel of the camping lantern acting as the fuel source and the incandescent gas mantle as the emitter can be drawn. Often, the event that is credited with the birth of TPV is Professor Pierre Aigrain suggested converting IR radiation with a PV converter to produce electricity during his time as a visiting lecturer at MIT during the fall of 1960 [20-21].

After the introduction of the TPV concept, research into the concept was done. At Fort Monmouth, researchers monitored development and did some basic systems development and basic materials studies. GM also developed a photoconverter back surface reflector for spectral control. In 1970s, research into the TPV concept slowed in the United States. The military, which was funding the majority of the TPV development, went with thermoelectric technology instead. Additionally, GM needed to focus on making it through the energy crisis of the decade and meeting government regulations, so their investment into researching the technologies slowed. The low level of development continued through the 1980s [20-21]. However, since that time, there has been resurgence in the development of TPV in the United States.

2.1.2 Themophotovoltaics Advantages

There are several reasons that thermophotovoltaic technology is appealing. For one, TPV offers a unique way of converting sunlight (or other sources of energy) into electricity [7, 20]. TPV lacks moving parts and can be expected to essentially silent, which also causes researchers to expect that TPV systems will be low maintenance. The versatility of TPV systems is also a part of their appeal sinceTPV systems can theoretically be operated by a combustible material, radioactive source, or sunlight [7, 22].

Thermophotovoltaic systems promise a higher efficiency than that seen in PV cells [6]. Because of the design of TPV systems, some of the losses encountered in PV systems can theoretically be eliminated. Instead of solar radiation impinging directly on the PV cells, it is absorbed by a selective absorber/emitter. The energy from the solar radiation causes the selective absorber/emitter to act as a low temperature sun, so it reemits the photons it absorbs so that they imping on the PV cell. The difference between the photons from the sun and those reemitted from the selective emitter is that the selective emitter should emit photons with adequate energies to cross the band gap and produce and electron-hole pair, which in turn allows for the photonic energy to be converted to usable electricity. In addition, photons that are not used in the TPV systems are reflected back onto the emitter, and so the energy of photons can also be recycled in order to avoid loss by radiative recombination [6-7, 23].

2.1.3 Applications

Potential applications of TPV systems are numerous. There are a number of military and non-military applications. Military applications include vehicles, battery charging, and man-portable power. Soldiers in this era are ever in need to carry around more electronic equipment. Therefore, if TPV systems are compact enough, the military could distribute TPV systems for the purpose of traveling as portable power. There are several nonmilitary applications as well. TPV systems could be used in recreational vehicles, uninterruptible power supplies, and remote homes [22].

2.2 Theoretical Operation

Most energy sources operate with the Carnot efficiency as the limiting ultimate efficiency [Bermel]. This efficiency is express by Equation 1:

$$\eta_c = 1 - \frac{T_c}{T_h} \qquad (1)$$

where η_c is the Carnot efficiency, T_c is the temperature of the heat sink, and T_h is the input temperature. A well designed engine would be able to approach this limit. Operating at a high temperature is also advantageous. Real engines suffer from a number of heat losses in addition to the inherent loss as a result of the temperature difference [25]. Just as the Carnot efficiency is a good way to determine how well an engine is designed and operates, having a baseline efficiency measure for thermophotovoltaic operation is important in order to determine how well constructed the system is.

2.1.1 Theoretical Maximum Efficiency

Much like the assumptions made for the Carnot efficiency, a number of assumptions need to be made about a solar TPV to calculate the theoretical maximum efficiency that can be achieved using solar TPV technology. In the paper written by Harder and Wurfel [6], the efficiency is calculated merely as the product of the efficiency from the sun to the selective absorber/emitter and from the selective absorber/emitter to the solar cell. Figure 2-2 from their paper shows the solar TPV system.

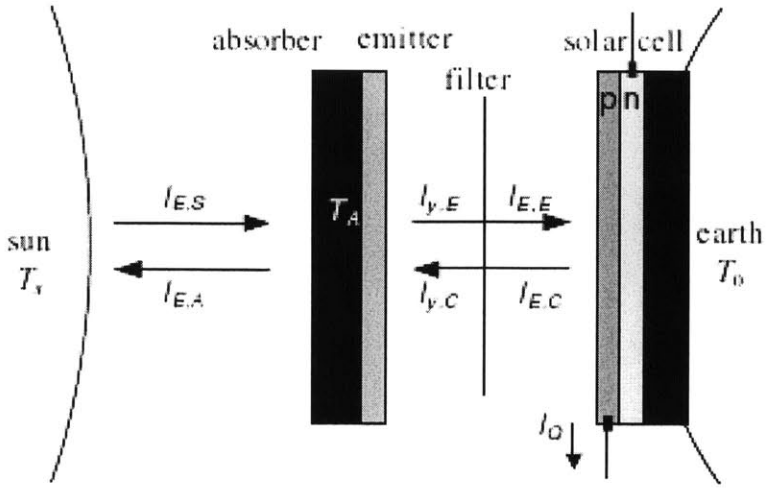


Figure 2-2. This diagram labels the integral components and the three critical temperatures that factor into the calculation of ultimate efficiency [6]. The sunlight is incident on an intermediate absorber/emitter. The absorber absorbs the photons from the sunlight and transfer the energy to the emitter. The emitter then reemits the photons such that more photons have sufficient energy to cross to the band gap in the solar cell and not as much energy is wasted with photons that exceed the band gap energy.

The assumption is that all of the photons that are incident on the selective absorber/emitter are reemitted so that the PV cell can absorb all of the photons. The ultimate efficiency is given by Equation 2:

$$\eta = \left(1 - \frac{\pi}{\Omega_S}\left(\frac{T_A}{T_S}\right)^4\right)\left(1 - \frac{T_0}{T_A}\right) \tag{2}$$

where T_A is the temperature intermediate absorber/emitter, T_0 is the temperature of the cell, assumed to be uniform at 300K, T_s is the temperature of the sun, assumed to be uniform at 6000K, and Ω_s is a factor that ranges from $6.8 \cdot 10^{-5}$ to π from non-concentrated sunlight to fully concentrated sunlight, respectively [6]. Since for full concentration of sunlight, $\Omega_S = \pi$ (which is approximately equal to 46,200 suns), resulting in the maximum theoretical efficiency coming to 85% at an absorber temperature of 2544 K [6] as shown in Figure 2-3.

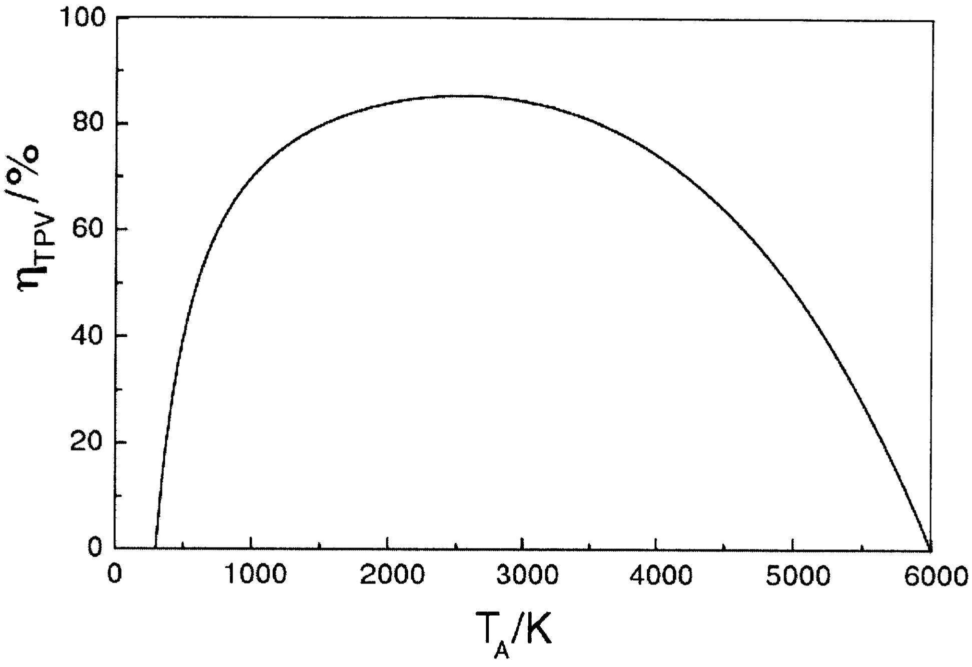


Figure 2-3. This chart [6] shows the ultimate efficiency of a solar thermophotovoltaic system as a function of the absorber temperature. The absorber is assumed to be a black body, the sunlight is fully concentrated, and the monochromatic filter to match the band gap energy.

For no concentration, $\Omega_S = 6.8 \cdot 10^{-5}$, the absorber temperature decreases since there is not as much energy to warm up the absorber. Therefore, for an absorber temperature of 356K the efficiency is only 6.7%, which is the maximum efficiency for non-concentrated light [6]. The absorber temperature and solar cell are much closer to the same temperature, which by inspection of the ultimate efficiency equation is expected to reduce the efficiency significantly.

The first term in the ultimate efficiency equation comes from the differences in temperature in the radiative heat transfer from the sun to the intermediate emitter/absorber. It is assumed that there is no convective heat loss [23] in the case of the maximum efficiency. However, as will be discussed later, a term for heat loss in the solar TPV system is necessary in order to more practical model achievable efficiencies.

The Carnot efficiency is the second term of the ultimate efficiency of a solar TPV system. The heat input is from the selective absorber/emitter that reemits the photons from sunlight into a spectrum more favorable for photovoltaic cells to absorb the energy. The heat sink is the photovoltaic cell. In order to achieve this efficiency, the recombination in the solar cell must only be radiative and the light source must be monochromatic to match the energy of the band gap [6]. Nonetheless, in a more practical calculation of efficiency, there are surely to be losses due to cell efficiency issues as there are in the detailed balance limit. Additionally, the cavity in which the whole solar TPV is enclosed will have some parasitic losses that are not accounted for in the equation for ultimate efficiency.

The derivation of the ultimate efficiency has several implied assumptions associated with it. One of the problems is with the area of the emitter. In order to maximize efficiency, the absorber/emitter needs to emit as many photons as it absorbs, but some of the radiation remitted by the absorber is lost. Due to the filter, emission can be emitted back onto the emitter, which results in a net emission. In order to cancel the effects of the emission, the area of the emitter needs to be increased [6]. This cycle continues until it is realized that an infinite emitter area is needed to sustain the maximum theoretical efficiency. Since clearly the emitter area cannot actually be infinitely large, there will be some losses associate with the limitations of size.

As discussed, the calculation for theoretical maximum efficiency is very simplified, and not just because of non-uniformity of the temperature of the emitter/absorber and solar cell and size constraints of the system. There are several additional terms that will decrease the overall efficiency of the solar TPV systems. Heat loss is an important term to consider. In theory, all photons could be reemitted so that they are absorbed by the PV cell, but in practice there will be spectral losses due to photons emitted that are of insufficient energy to cross the band gap of the

PV cell. Additionally, cavity efficiency within the PV cell will add to the practical efficiency of the solar TPV system. The efficiency of the solar cell itself also needs to be considered.

The solar cell efficiency is not most accurately modeled by the Carnot efficiency. The detailed balance limit has four factors that determine the efficiency [14], which are still relevant to a solar TPV system. The issues that result in a loss of efficiency in a PV system are still relevant to a solar TPV system. A couple of these factors are relatively unchanged. The impedance matching factor still applies as the PV cell is still unable to operate at the both the short circuit voltage and no load current. Additionally, the assumption that a single photon with sufficient energy to cross the band gap will produce a single electron-hole pair can still be used.

There are still spectral losses that need to be considered in the system since the intermediate absorber/emitted and filter are not able to convert every photon to a favorable energy level. However, the ratio of the number of photons that are incident on a solar TPV system to the number of photons that are able to cross the band gap should be higher than the ratio of the number of photons that are incident on a PV cell to the number of photons that are able to cross the band gap [6]. This is, after all, the main premise on which solar TPV promises to deliver higher efficiencies compared to traditional PV cells.

Considering that there are still real losses that are known to contribute to efficiency in a solar TPV system, the question of how an accurate prediction of the upper limit of solar TPV efficiencies remains. The equation from Harder and Wurfel's paper has some value, but the maximum theoretical efficiency of 85% under monochromatic filtering, blackbody absorber, and fully concentrated sunlight [6] is impractical.

A "real" solar TPV model needs to consider "real" losses. There are several proposed considerations in the system in order to form a more realistic model. It is unlikely to be able to concentrate sunlight to the full extent possible. Additionally, the recycling of photons is another plus of the solar TPV system, so some percentage of photons that have insufficient energy to cross the band gap are returned to the emitter, which gives them another chance at being emitted at a high enough energy level to cross the band gap. Therefore, it has been modeled [23] that the efficiency of a real solar TPV system is dependent on both the emitter/absorber temperature (assume that the emitter and absorber are in good thermal contact and thus at a uniform temperature) and the percentage of photons that are of insufficient energy to cross the band gap are recycled. In this model, the photovoltaic cell uses GaSb (band gap energy 0.72 eV) as the semiconductor material and the operating temperature is 323 K. The emitter is a grey-body (instead of a blackbody that was assumed previously). In Figure 2-4, the efficiency peaks at in the middle of the spectrum of temperatures. Low temperatures result in decreased efficiency of the cell to convert photons to electrical energy as modeled by the Carnot cycle in the ultimate efficiency equation while higher temperatures result in a decreased efficiency because of back radiation as modeled by the radiation efficiency term.

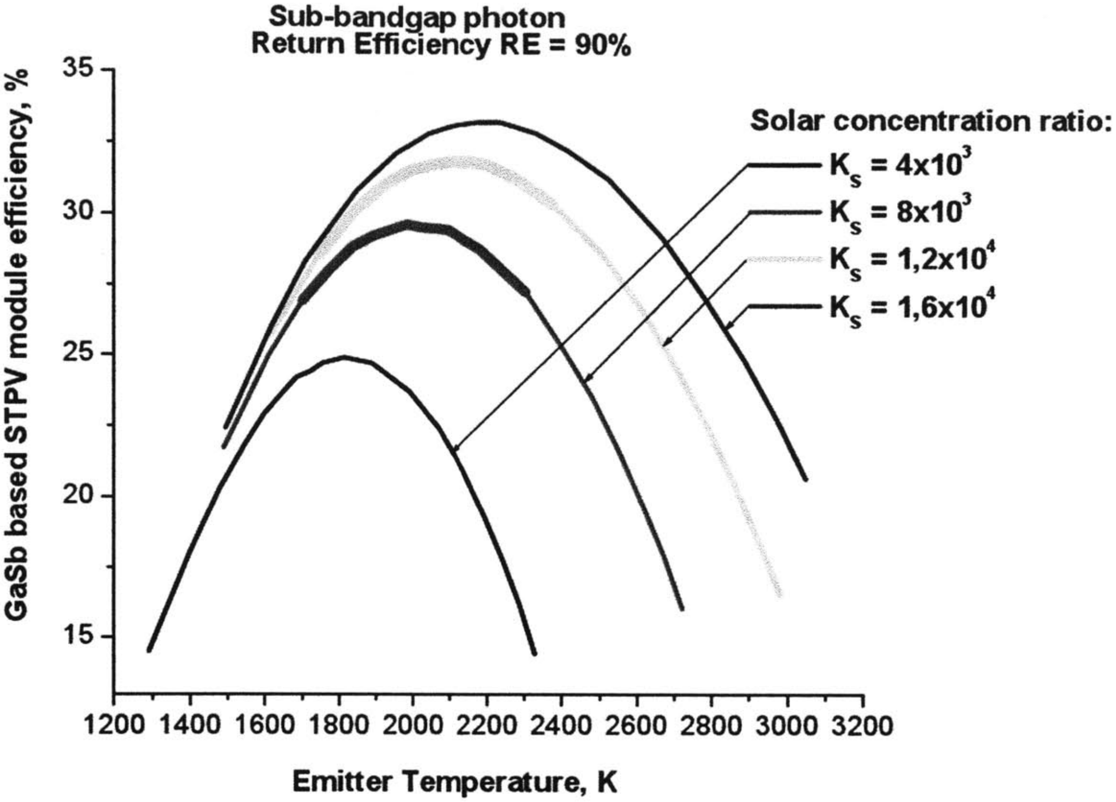


Figure 2-4. The efficiency of a solar thermophotovoltaic system utilizing a GaSb solar cell at different temperatures and solar concentration ratios is shown in this graph [23]. As expected from the equation for ultimate efficiency of a solar TPV system, as the solar concentration ratio (the equivalent number of suns) increases, so does the efficiency of the system. However, the peak efficiency occurs at different emitter temperatures for different concentrations.

In addition to the dependency of the efficiency of a real solar TPV system on the concentration of light, there is also a significant dependence on the return efficiency of photons to the emitter that are unable to cross the band gap because of insufficient energy [23]. This photons recycling process has a significant effect on the achievable efficiency of a solar TPV device. As the return efficiency increases, so does the efficiency of the solar TPV systems. This is clearly illustrated in the Figure 2-5.

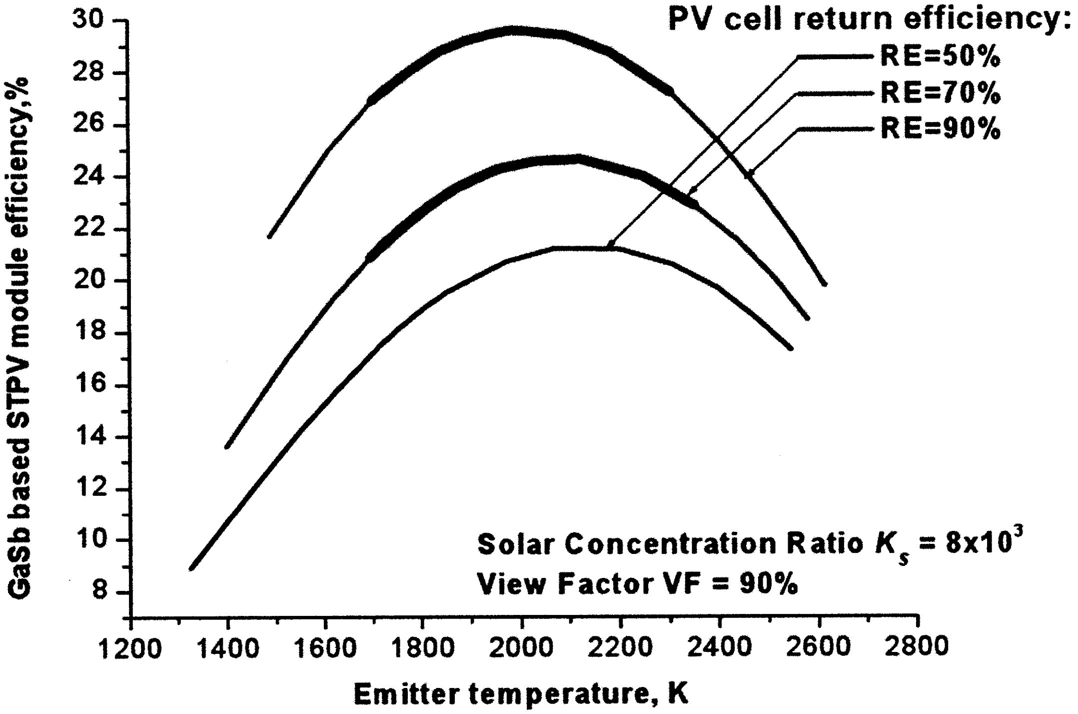


Figure 2-4. The efficiency of a sample solar thermophotovoltaic system is shown to be dependent on the return efficiency. The more photons that are recycled by being sent back to the emitter for another chance of being reemitted to have sufficient energy to cross the band gap, the higher the efficiency. The system efficiency peaks at about 20% at a return efficiency of 50% compared to a peak efficiency of 30% at a return efficiency of 90% [23].

Both Figures 2-4 and 2-5 help illustrate the need for both a high concentration of light and a high return efficiency to maximize efficiency in a solar TPV system. However, there are many assumptions that were not previously stated that were used in the creation of these graphs. The area of the emitter and absorber are assumed to be the same, but this is not necessarily the case in a real system [23]. As discussed before, there are photons that are emitted as a result of radiative losses in PV and solar TPV, but they are not accounted for in these calculations. Additionally, convective losses are ignored. Therefore, there are both non-idealities that are assumed in the calculations in order to obtain values that more closely reflect what is achievable with solar TPV [23] as well as idealities that ignore other losses.

2.2.2 Practical Considerations

Parasitic heat losses are certainly a factor in a practical calculation for the efficiency in solar TPV. These parasitic losses can occur as a result of conduction, convective or radiation, though the primarily loss through radiation is that of back radiation which is duly accounted for in the ultimate efficiency equation. As cited by Bauer [7], the undesirable losses as a result of conduction are gas conduction from the emitter to the PV cell or surroundings. Convective heat transfer losses are more worrisome. The free convection of gas inside the cavity is a loss that is not accounted for in theoretical models, and neither is the free convection heat transfer of the solar TPV system to the environment. Since the solar TPV system, particularly the absorber/emitter, needs to operate at a high temperature of be most efficient, the convective heat loss to the cooler environment is high. Encapulation of the system in insulation can mitigate this particular heat loss, but there will be some convective losses nonetheless. Radiative losses besides that of back radiation also exist.

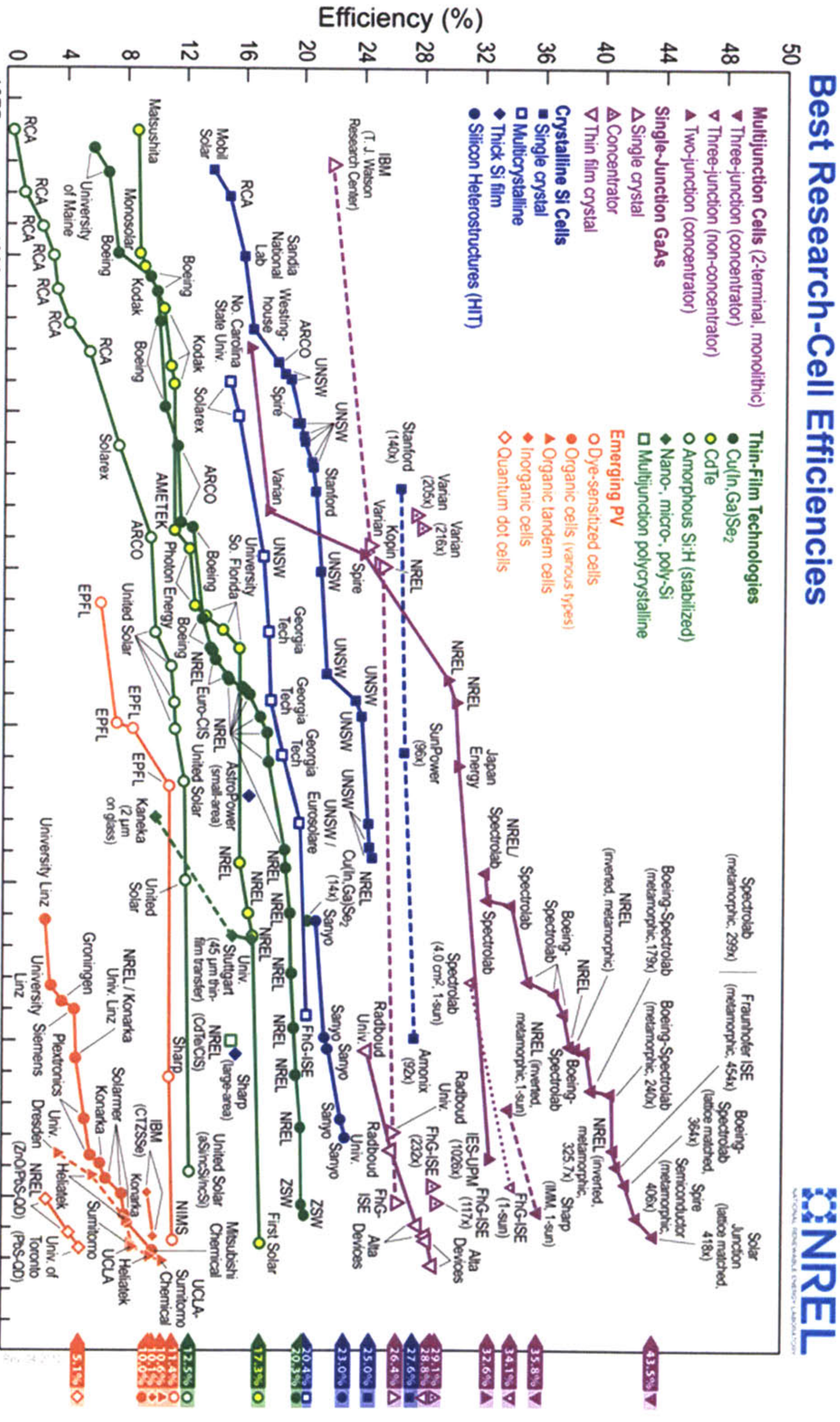
Collectively, these heat losses will prevent the system from reaching the efficiencies modeled in Figures 2-4 and 2-5. Much like how the efficiency of a mechanical engine does not measure up to the Carnot efficiency because of parasitic heat (or friction) losses, in the same way, the efficiency of a well-constructed solar TPV system will not measure up to the theoretical efficiency that the system would achieve. Additionally, the potential for non-radiative recombination still exists, and the radiative recombination of electron-hole pairs is not even considering the previous calculations.

The development and design of solar thermophotovoltaics is a balancing act. On the one hand, researchers know that the more concentrated the light, the higher the theoretical efficiency. Additionally, the temperature of the intermediate emitter/absorber needs to be quite high in order to maintain a high theoretical efficiency. On the other hand, the concentrated sunlight and high absorber/emitter temperature needs to be balance with the optical and back radiation losses. A good concentrator light will run into more efficiency problems as the limits of light concentration are pushed. The back radiation losses that occur at a high temperature serve to lower the efficiency too, even more than what is modeled [23].

Even though the technology has yet to work on a scale that is usable, there is great potential. The first solar cells had relatively low efficiency and could not be used for realistic applications. Perhaps much like the focus on development of photovoltaics in the 1970s, a continued focus on the development of solar TPV technology will lead to a much greater understanding of the best way to design solar TPV systems to work efficiency. Then, there is the potential for use in government sanctioned applications until the price of the technology is driven down so that it is affordable for commercial uses. If successful, solar TPV has the ability to replace PV cells in some applications due to increased efficiency in a climate with direct solar radiation [7].

3. APPENDIX

Chart of Photovoltaic Cell Efficiencies from 1975 to 2012 [17]



4. REFERENCES

[1] U.S. Department of Energy: Energy Efficiency of Renewable Energy. *The history of solar.* http://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

[2] Madrigal, A. (2011). *Powering the dream: The history and promise of green technology.* Cambridge, MA: Da Capo Press.

[3] The White House. (2010). Statements & Releases: President Obama Sets Greenhouse Gas Emissions Reduction Target for Federal Operations. http://www.whitehouse.gov/the-press-office/president-obama-sets-greenhouse-gas-emissions-reduction-target-federal-operations

[4] U.S. Energy Information Administration. (2012). *Annual energy outlook 2012 early release.* http://www.eia.gov/forecasts/aeo/er/

[5] U.S. Energy Information Administration. (2011). *Country analysis briefs: China.* http://www.eia.gov/EMEU/cabs/China/pdf.pdf

[6] Harder, N, and P. Wurfel. (2003). Theoretical limits of thermophotovoltaic solar energy conversion. *Semiconductor Science and Technology*, 18(5). http://iopscience.iop.org/0268-1242/18/5/303/

[7] Bauer, T. (2011). *Thermophotovoltaics: Basic principles and critical aspects of system design.*Heidelberg: Springer.

[8] Fanchi, J. R. (2005). *Energy in the 21st century.* Hackenscak, NJ: World Scientific.

[9] Nelson, J. (2003). *The physics of solar cells.* London: Imperial College Press.

[10] Knier, G. (2002). How do photovoltaics work? *National Aeronautics and Space Administration.* http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/

[11] Sandia National Laboratories. (2012.) *The photovoltaic effect.* http://photovoltaics.sandia.gov/docs/PVFEffIntroduction.htm

[12] Jha, A. R. (2009). *Solar cell technology and applications: Chapters 1-2.* Auerbach Publications. http://dx.doi.org/10.1201/9781420081787

[13] Landsberg, P. T. (2002). Theoretical limits of photovoltaic solar energy conversion. *RIO 02 World Climate & Energy Event.* http://www.rio02.com/proceedings/pdf/061_Landsberg.pdf

[14] Shockley, W. and H. J. Queisser. (1961). Detailed balance limit of efficiency of pn junction solar cells. *Journal of Applied Physics.*

[15] Used as an aid in understanding the content from [14]: Liao, B. and W. C. Hsu. An investigation of Shockley-Queisser Limit of single p-n junction solar cells. *2.997 Project Report.* http://web.mit.edu/bolin/www/Shockley-Quisser-limit.pdf

[16] U.S. Department of Energy: SunShot Initiative. (2012). *SunShot vision study: Chapter 2.* http://www1.eere.energy.gov/solar/pdfs/47927_chapter2.pdf

[17] National Renewable Energy Laboratory. (2012). *Best Research-Cell Efficiencies.* http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

[18] Bubenzer, A, and J. Luther. (Eds.). (2003). *Photovoltaics guidebook for decision makers: Technological status and potential role in energy economy.* Berlin: Springer.

[19] Taken from presentation by Miljkovic, N, and Y. Nam, and A. Lenert, and E. N. Wang. *Thermal management of solar thermal energy conversion systems*

[20] Nelson, R. E. (2003). A brief history of thermophotovoltaic development. *Semiconductor Science and Technology,* 18(5). http://iopscience.iop.org/0268-1242/18/5/301

[21] Guazzoni, G, and S. Matthews. (2004). A retrospective of four decades of military interest in thermophotovoltaics. *AIP Conference Proceedings 738,* pp. 3-12. http://proceedings.aip.org/resource/2/apcpcs/738/1/3_1

[22] Coutts, T. J. (1997). Thermophotovoltaic principles, potential, and problems. *AIP Conference Proceedings 404,* pp. 217-233. http://proceedings.aip.org/resource/2/apcpcs/404/1/217_1

[23] Andreev, V. M, and V. P. Khvostikov, and O. A. Khvostikova, and V. D. Rumyantsev, and P. Y. Gazarjan, and A. S. Vlasov. (2004). Solar thermophotovoltaic converters: Efficiency potentialities. *AIP Conference Proceedings 738: Sixth Conference on Thermophotovoltaic Generation of Electricity,* pp. 96-104. http://proceedings.aip.org/resource/2/apcpcs/738/1/96_1

[24] Bermel, P, and M. Ghebrebrhan, and M. Harradon, and Y. Yeng, and I. Celanovic, and J. Joannopoulos, and M. Soljacic. (2011). Tailoring photonic metamaterial resonances for thermal radiation. *Nanoscale Research Letters: A SpringerOpen Journal.* http://www.nanoscalereslett.com/content/6/1/549

[25] Celanovic, I. and P. Bermel and M. Soljacic. (2011). Thermophotovoltaic power conversion systems: Current performance and future potential. *Invitied Review Article in Oyo Buturi (Japan Society of Applied Physics),* 80(8), p.687.