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Photovoltaic Potential in the City of Guelph

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The use of photovoltaic (PV) arrays to harness the power of the sun and provide electricity has a number of advantages when considering the environmental impact, required maintenance, and fuel requirements of other common energy sources. The history of this technology began with the discovery of the PV effect in 1839 and has now advanced to the point where conversion efficiencies of PV cells have surpassed 40% in a laboratory setting, (albeit specifically for use in a solar concentrator). This paper describes a brief history of PV technology, semiconductors and the operation of a doped silicon PV cell, the build up of PV systems, the current state of the art, factors that affect electricity production of PV systems. The feasibility of using PV arrays to meet the energy needs of the residential sector of the city of Guelph, Ontario (Canada) was evaluated. The case study used actual insolation data with a sun-position model to calculate the amount of sunlight that would be incident on a PV panel at an optimum slope of 37°. It was found that with a 15% efficient PV array the city would require roughly 8.80 km^2 of panels to meet the estimated total energy requirements of the residential sector of Guelph. If the current best available PV cell technology, which has an unofficial efficiency of 42.8%, could be utilized, this requirement would drop substantially to 3.08 km^2.

Nomenclature

c	=	empirical constant
d	=	empirical constant
I	=	Electrical Current *(Amperes)*
$I(\theta_z)_{D+S}$	=	total irradiation
I_0	=	apparent solar flux due to direct solar irradiation
I_{0S}	=	apparent solar flux source due to scatter
I_c	=	exoatmospheric flux
I_i	=	incident irradiation
n_i	=	number of cells in a panel or panels in an array (each of the same design)
n	=	Julian Calendar day of the year (1-365)
V	=	Electrical Potential, Voltage (Volts)
β	=	surface slope
γ	=	azimuth angle
δ	=	declination
θ	=	angle of incidence
θ_z	=	zenith angle
φ	=	latitude
ω	=	hour angle

I. Introduction

Photovoltaic (PV) cells are devices which utilize energy from sunlight to generate an electric current. There are a number of reasons that PV cells are increasingly being utilized around the world. It is recognized that the resource on which it depends is widely available, free, and requires no work to collect. Often times it is more cost effective to install a PV array rather than connect to a distant electrical grid. The operation of PV arrays does not produce

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carbon dioxide in the generation of electricity. Furthermore, PV arrays are mechanically simple with no moving parts. They require minimal maintenance for electricity production. A PV system can be set up and left unattended, and will continue to produce electricity as long as it is exposed to sunlight.

Since the discovery of the PV effect the efficiency with which sunlight can be converted to electricity has steadily increased. There are PV cells in laboratories today with efficiencies exceeding 40%, and it is hoped that the goal of achieving greater than 50% sunlight-to-electricity conversion will be attained in the near future.

The use of PV arrays to electrify our cities and towns may one day become a reality because many of the resources that we currently depend on are finite and will at some point be exhausted. These finite resources include natural gas, uranium, coal, and oil, which currently supply the majority of the energy needs in North America. Furthermore, the emission of carbon dioxide from the use of fossil fuels is being more closely scrutinized due to global climate change. It is for these reasons that renewable energy resources such as photovoltaic technology are beginning to experience a new wave of interest. As PV technology gains ground, it must be recognized that it was not long ago that the PV effect was merely a laboratory novelty, as described here by famed author Isaac Asminov (1966), in his Building Blocks of the Universe:

> *"Recently, solar batteries have been designed which can produce electric current when exposed to light. So far, such batteries are only laboratory curiosities, but the day may come when they will be an important source of power for mankind."*

The following paper is meant to briefly summarize and highlight several aspects of PV technology. The topics discussed include a brief history, semiconductors and the operation of a doped silicon photovoltaic cell, the build up of photovoltaic systems, the current state of the art, and what affects electricity production in photovoltaic systems. The paper concludes with a case study on the potential for the application of PV systems to meet the residential energy demand of the city of Guelph, Ontario (Canada).

II. History of Photovoltaic Technology

PV technology has evolved significantly over the 150 plus years since the ability to develop an electric current from sunlight was recognized. Credit goes to Alexandre-Edmond Becquerel for the discovery of the photovoltaic effect. While working on what is described as a wet cell battery, he noticed an increase in the voltage of the cell when light was incident on the battery that he was examining (Boyle, 2004). He published these results in 1839 and thus interest in the phenomena was born. It was not until just over 30 years later that the PV effect was first observed in the solid state. In 1873 the PV effect was discovered in selenium by Wiloughby Smith (USDOE, 2004). In 1877, W.G. Adams and R.E. Day published a paper on observations of variation in the electrical properties of selenium when exposed to light (Boyle, 2004). Several years later in 1883, American inventor and New York electrician Charles Edgar Fritts constructed a solar module, made from a thin wafer of selenium covered with very thin gold wires and sealed with glass. His cell was less than 1% efficient (Boyle, 2004) and had a configuration similar to PV cells used today. In 1904, Albert Einstein authored a theoretical paper that described the photovoltaic phenomenon (Bellis, 2007). His theories were later validated by experiments performed by Robert Milikan in 1916 (Bellis, 2007). In 1918, Jan Czochralski discovered a method to produce monocrystalline silicon, a breakthrough that would allow for solar cell production (Bellis, 2007). Albert Einstein was awarded the Nobel prize for his explanation in 1921 (USDOE, 2004). However, it was not until several key developments were made at Bell Laboratories that the efficiency of PV cells began to increase significantly. Russell Ohl found that semiconductors could be "doped," or infused, with foreign atoms to alter their behavior (MPower, 2005). Working on this advancement, Ohl, with the assistance of Walter Brattain, discovered the principles behind the P-N junction in photovoltaic cells, a concept which will be discussed later in this paper. Development of the P-N junction also led to the development of the first silicon PV cell (MPower, 2005). In 1948, Bardeen and Brattain produced the first electrical transistor, an electrical switch commonly utilized in many of the electronic devices in use today. Transistors are typically made from ultrapure crystalline silicon doped with boron or phosphorous (Boyle, 2004). The developments at Bell Labs continued; in 1952 Daryl Chapin was leading a research team that was looking for a way to power remote telephones. Chapin suggested the use of PV cells. At the same time, Gerald Pearson and Calvin Fuller were developing a solid-state rectifier to convert AC to DC. They were using doped silicon, and as luck would have it a light was pointed at the device and it was observed that the light induced an electrical current. Several breakthroughs followed, and by 1954 Chapin, Pearson, and Fuller had developed a silicon PV solar cell that was 6% efficient, a sizeable improvement over its predecessors (Boyle, 2004; Ewing and Pratt, 2005). While the scientists had hoped to be able to use the cells to power remote telephones, they were still too expensive for this application. In 1955, Western Electric begins to sell commercial licenses for silicon PV technology, with early application in dollar bill changers and computer punch card decoders (Bellis, 2007).. In 1958 PV cells were used to power a small radio transmitter aboard the US satellite Vanguard I (Boyle, 2004). The development of this technology has come a long way since this time: prices have steadily decreased and the conversion efficiency of the PV cells have greatly increased. By 1999, cumulative installed PV capacity had reached 1000 MW (USDOE, 2004). By the end of 2003, the cumulative installed capacity of photovoltaics had surpassed 1800 MW (CANSIA, 2006).

III. Semiconductors and the Operation of a Doped Silicon Photovoltaic Cell

A. Semiconductors

Based on their electrical properties, materials can be classified as insulators, conductors, or semiconductors. Band theory can be used to understand the difference between these categories. Electrons orbit the nucleus of the atom at the lowest possible energy level; once one level is filled the remaining electrons must then fill the next energy level and so forth until all electrons have been positioned around the nucleus of the atom. The last energy level to have electrons is known as the valence shell or valence band. Chemically, insulators are materials which require a large amount of energy for their electrons to travel from the valence band, the outermost orbit of electrons in the atom, to the conduction band, where the electrons can be readily moved by an electric current. The conduction band is a higher energy level for the electron than the valence shell. When an electron has enough energy to reach the conduction band it is possible for the electron to move from one atom to another rather than remain fixed in its orbital pattern around the nucleus of an atom. As shown in Figure 1, insulators require a relatively large amount of energy for their electrons to overcome the energy gap necessary to transfer from the valence band to the conduction band. The electrons still have the ability to move, but are more likely to simply exchange positions with other electrons in the valence shell, rather than gain enough energy to transition to the conduction band (HSC Online, 1999). This level of energy is too great for the transition to occur and as such insulators do not readily conduct electricity. Unlike insulators, conductors are materials in which the valence band overlaps the conduction band. As a result there is very little energy required for the electrons to move between the valence and conduction bands. Electrons are relatively free to move around the perimeter of the atom and can easily leave the atom. As a result, conductors readily conduct electric current. Finally, there are semiconductors which are materials that have an energy gap between those of an insulator and a conductor. Under some conditions semiconductors will conduct electricity, while under other conditions they behave as insulators. The conductivity of semiconductors can be altered by varying the temperature of the material. At high temperatures the electrical conductivity of semiconductors approaches that of metals, while at low temperatures, or even room temperature, their conductivity is greatly reduced. The conductive properties of semiconductors can also be permanently altered through sufficient doping (HSC Online, 1999).

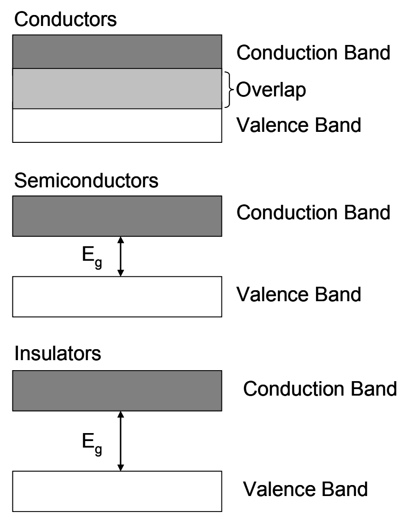

Figure 1. Insulators, semiconductors, and conductors. *Band theory is used to explain the differences between conductors, semiconductors, and insulators which are chemically based on the differences in the amount of energy that it takes for the electrons in these materials to transfer from the valence band, the outermost shell in which electrons in a material travel, and the conductance band, where these electrons can freely move and be part of an electric current.*

B. Doping of Crystalline Silicon

As previously discussed, the doping of silicon with foreign atoms was found to change the electrical properties of silicon relative to its normal semiconductor state. As shown in figure 2, the doping of silicon with phosphorous or boron imparts electrical properties that produce photovoltaic behavior. Silicon is similar to carbon in that it has four valence electrons and, to become electrically balanced, it wants to pair each of these four electrons (Ewing and Pratt, 2005). When in a pure crystalline form, the four valence electrons of silicon are readily shared with its four neighboring silicon atoms, resulting in a valence shell that has eight, or four paired, electrons. In this state, silicon has neither a need for extra electrons nor the need to give up extra electrons. However, this changes when different atoms such as phosphorous or boron are mixed into electrically stable, pure crystalline silicon.

Phosphorous is an element which has five electrons in its valence shell. When crystalline silicon is doped with phosphorous four of the five valence electrons of phosphorous are shared with the four neighboring silicon atoms leaving the fifth electron unpaired. This fifth or extra electron imparts a negative charge on the silicon and is more readily available to move to the conductance band because it is unpaired (Ewing and Pratt, 2005). Boron, on the other hand, is an element with three electrons in its outermost shell. As a result of only having three electrons, there is an incomplete pairing of electrons when a boron atom is surrounded in the crystalline structure of silicon. Here, three of the neighboring silicon atoms share an electron with boron, while the fourth electron from the adjacent silicon remains unpaired. This unpaired electron results in a "hole" or a location where an electron would fit to balance the charge of the neighboring silicon atom (Ewing and Pratt, 2005). This leads to a positive charge on crystalline silicon doped with boron.

A semiconductor which has been doped with an element resulting in an electrically negative charge, such as silicon doped with phosphorous, is termed an "N-type" semiconductor. A semiconductor which has been doped with an element resulting in a positive charge, such as silicon doped with boron, is termed a "P-type" semiconductor.

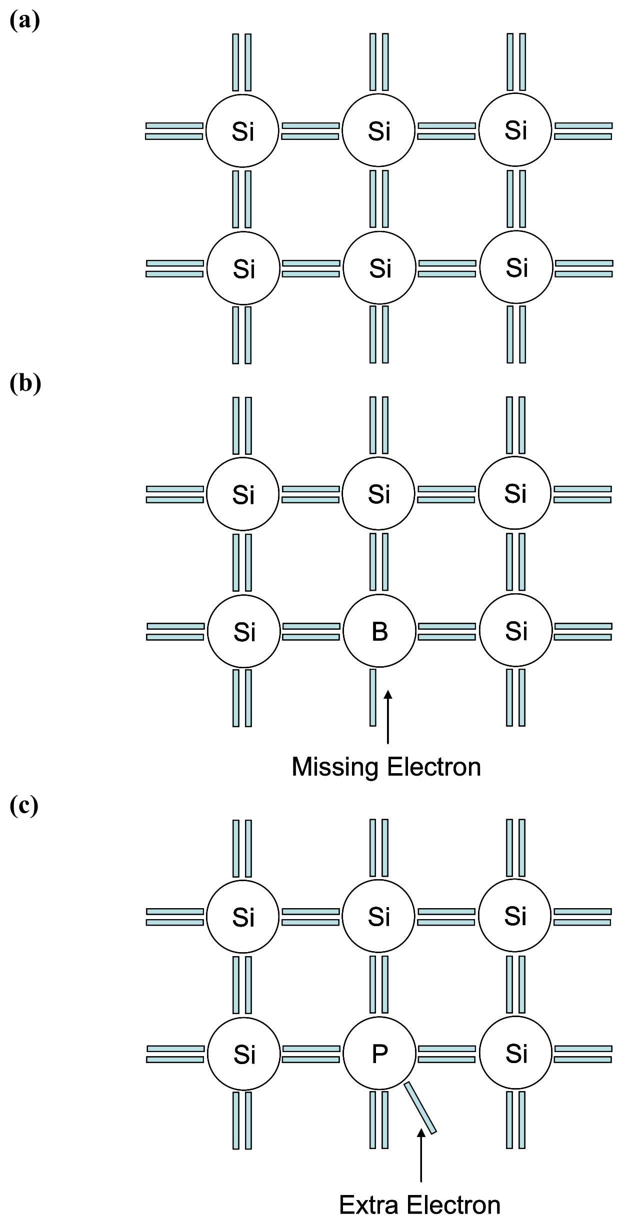

Figure 2. Valence Electrons of Silicon and Doped Silicon. *The valence electron, represented by the grey bars are indicative of the location of electrons shared between the atoms of silicon, phosphorous or boron. In (a) the location of the electrons in pure crystalline silicon is represented; in (b) the effect of the doping of silicon with boron is shown; in (c) the effect of doping silicon with phosphorous is shown.*

C. The P-N Junction

When silicon doped with phosphorus is mated with silicon doped with boron, an interesting shift takes place, as shown in Figure 3. At the intersection, referred to as the "P-N junction," an electric field is formed. Here, the relatively "free" electrons of the N-type silicon migrate to the opposite side of the interface while trying to fill the holes of the P-type silicon. An equal and opposite effect also occurs: there is a shift in the positive charge from the

P-type silicon to the opposite side of the interface. When this happens, it is easy for an electron to travel from the P-type silicon to the N-type silicon, but the reverse of this is not true, it is highly difficult for an electron to travel from the N-type silicon into the P-type silicon beyond the boundary of the interface (Aldous, 2007). This effect that only allows current to pass through the junction in one direction is exploited in diodes.

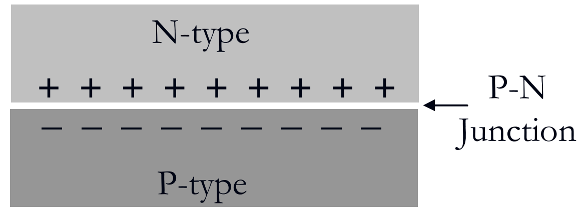

Figure 3. The P-N Junction. *The shift of charges across the interface of the P-N junction of silicon doped with boron (P-type) and phosphorous (N-type).*

The interface of the P- and N-type semiconductors is the heart of a PV cell. It is at the interface, with the establishment of this electric field, that the doped semiconductors are able to utilize the photons in sunlight to produce an electric current. First, an external circuit must be made connecting the P-type silicon to the N-type silicon through an electrical load. Next, the PV cell is exposed to light. When light strikes the P-N junction, photons of light are absorbed by the electrons which have migrated to the P-type side of the interface. This extra energy allows the electrons to enter into the conduction band. The electrons then return to the N-type portion of the photovoltaic cell and travel through the external circuit, while the positive charge, the holes, do the opposite, returning to the P-type side of the photovoltaic cell. After flowing through the circuit, the electrons return to the interface on the P-type side of the P-N-junction and await the next photon to repeat the cycle, all the while being balanced by a shift of the holes from the N-type side of the P-N junction back to the P-type semiconductor.

The photovoltaic effect that occurs in doped silicon has been described. However, there are many materials that can generate an electric current when exposed to light, and not all of these are semiconductors. Furthermore, it must be mentioned that different materials utilize light in different parts of the spectrum to excite and conduct electrons within the material. The significance of this will be discussed in the following section.

D. Types of Cells

Photovoltaic cells can be classified into four categories depending on the materials and structure used in the cell: homojunction, herterojunction, multijunction or P-I-N/N-I-P (USDOE, 2005). The cell described above would be classified as a homojunction PV cell. This type of cell consists of a single photoelectric material, here silicon, which is doped on both sides with different compounds to produce a P-N junction. The second classification is a heterojunction photovoltaic cell, which is one where the N-type and P-type layers consist of two different materials. In this type of cell, neither of the materials used for the layers has to be a semiconductor for the arrangement to work as a photovoltaic cell and, as such, doping is not required. A multijuction PV cell consists of several P-N junctions that are stacked so that each layer absorbs its optimum spectrum of light while allowing light in other portions of the spectrum to pass through to another P-N junction which can in turn absorb its optimum spectrum of light. The result is a photovoltaic cell that absorbs a broader range of the spectrum of incident light in different parts of the cell, thus producing greater amounts of electricity from the same amount of incident light compared to other PV cells. Finally, a P-I-N or N-I-P PV cell is one where there are three distinct layers. Between the P- and N- type layers there is an intrinsic (I) layer which is undoped. This results in an electric field between the N- and P- layers throughout the I-layer. The significance of this layer is that “light generates free electrons and holes in the intrinsic region, which are then separated by the electric field. Depending on the materials used either the P-layer or the N-layer can be the layer exposed to the incident light.

IV. The Build-up of the Photovoltaic cells and systems

A. The Photovoltaic Cell

Before discussing the components of a PV system, an explanation of the remaining components that comprise the rest of a PV cell is in order. The solar cell is the principal unit of a PV system: PV arrays are made up of many cells. As previously described, the heart of the PV cell is the P-N junction. For simplicity, a heterojunction cell will be described, as shown in Figure 4. If we were to start from the bottom of a photovoltaic cell, just below the P-type semiconductor would be a metal backplate through which the electrons would travel back to the doped semiconductor materials. Next, there is the P-type semiconductor, the P-N junction, and the N-type semiconductor. On top of the N-type semiconductor would be a series of conductive metal strips which serve to carry the electrons away from the N-type semiconductor while allowing for light to be incident on the N-type semiconductor through which light is able to reach the P-N junction.

B. The Photovoltaic Panel

A PV panel (or "module") is the next major component of a PV system and is comprised of many cells. A single panel typically contains thirty to thirty-six cells wired in series, but some panels contain even more. Each cell typically produces a voltage of around 0.5 V DC (Gibilsco, 2007). In the PV panel (sometimes called a "solar panel"), the cells are supported by a backing material. The solar cells are covered with an anti-reflective sheet or coating to minimize the loss of light due to reflection. The final component is a piece of glass which serves to protect the cells and other materials from the elements while allowing light to pass through. Between the cell, anti-reflective coating, and glass there may also be a layers of transparent adhesive.

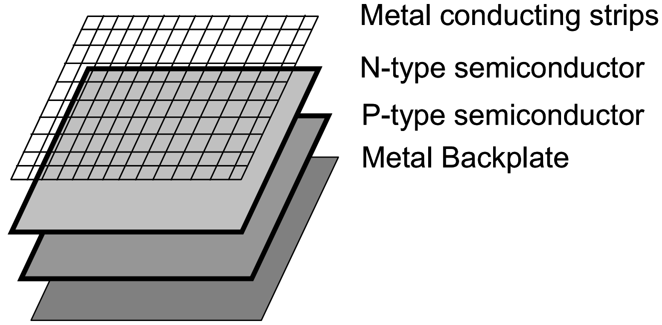

Figure 4. PV Cell components. *The cell primarily consists of four major components: the backplate, P-type semiconductor, N-type semiconductor, and conductive metal strips.*

The panel is usually the primary unit that is purchased when building-up a PV system. As previously stated, the cells in a photovoltaic panel are usually wired together in series. When electrical devices are wired in series (that is positive to negative and negative to positive), the voltage, V, is additive. When devices are wired in parallel, as may be done with multiple panels or sets of panels wired in series, the current, I, is additive. Parallel wiring of cells in a panel is not typically done. General equations for the voltage and current produced when wiring similar cells and panels are given below; here n_i represents the number of cells or panels in the system.

$$V_{series} = n_i V \tag{1}$$

$$I_{series} = I \tag{2}$$

$$V_{parallel} = V \tag{3}$$

$$I_{parallel} = n_i I \tag{4}$$

Here, these values are theoretically achieved values as there may be some system losses, although typically small, related to the wiring of these devices. Also, it must be recognized that the voltage and current produced by the individual cell is not exactly replicated within each cell due to the manufacturing process. As a result of these discrepancies a panel will typically be given a margin of deviation from the rating for maximum potential (voltage) and maximum current (amperage) of the panel. Just as cells are the base unit of a panel, the panel is in turn the base unit of a PV array. Panels are wired together in series or parallel to step up the voltage or current to the level needed in operation.

C. Grid-Tied Photovoltaic System

When using a PV system for electricity production for a home there are two typical strategies for wiring a photovoltaic array. In a grid-tied home (one which is wired to the electric utility grid), the photovoltaic array is usually wired to a DC-to-AC inverter since the electricity produced by the array is DC and the appliances that are typically in the home are AC. Typically between these two devices is a DC disconnect switch that allows the PV array to be electrically isolated from the home. There may also be an AC disconnect switch following the inverter. AC electricity can be used to power the home or fed back into the electrical grid for utilization elsewhere.

In the event that the array is producing more electricity than is required of the home, the utility meter may count backwards, subtracting the electricity that the PV system is supplying to the grid from electricity previously utilized from the grid. In other situations a second meter may be installed to track PV-generated electricity separately from the home's grid-drawn electricity consumption. This is will be done if PV electricity is purchased by the utility at a rate different than the utility charges for grid-supplied electricity.

D. Stand-Alone Photovoltaic System

In a stand-alone system, a battery bank is used to store the electricity from the PV array and provide it to the household. Between the array and the battery bank, a charge controller is utilized to control the charging of the batteries and to insure that the batteries are not overcharged or otherwise electrically damaged. A DC-to-AC inverter will be connected to the battery array if the appliances in the household are AC. The inverter is eliminated from the system if the household appliances are DC. The inverter is wired to the electrical panel of the house from which all of the devices in the house receive electricity. Disconnect switches are put into place to isolate the PV array from the battery bank and to isolate the battery bank from the house.

A standard charge controller can be replaced by a Maximum Power Point Tracker (MPPT) charge controller. An MPPT differs from a standard charge controller in that it adjusts the load on the PV array so that it will produce the most power possible (Blue Sky Energy Inc., 2005). Solid state electronics modify the voltage from the PV array to charge the battery at its ideal voltage and an increased current. This results in reduced charging time for the battery bank. A standard charge controller does not modify the load or voltage, and charges the battery at the operating voltage of the solar panel, which is typically not the ideal voltage for charging.

V. State of the Art in Photovoltaic Technology

Several times per year a document is published entitled *Solar Cell Efficiency Tables (Version ##)*. At the time of this paper, the document, authored by M.A. Green et al., was up to version 30 (Green et al., 2007). This document summarizes the electricity production efficiency from terrestrial cells, submodules, and modules of various types of photovoltaic devices. For the majority of the efficiencies provided, the units are tested at standard test conditions: a Global AM 1.5 spectrum, with an incidence of 1000 W/m^2, and a cell temperature of 25 ºC. This is the commercial standard by which the efficiency of most photovoltaic cells is measured and reported. AM stands for Air Mass. AM 1.5 refers to a spectrum of light associated with sunlight that has passed through one and a half atmospheres.

Version 30 of Green et al. (2007) highlights a new record for PV energy conversion efficiency. A cell from Spectrolab was observed to have an efficiency of 40.7 ± 2.4%, based on an incident intensity of 240 suns (where one sun represents 1000 W/m^2, and thus this is for a value of 240 kW/m^2). Testing used the standard 1.5 AM spectrum and a cell temperature of 25 ºC. This technology is a multijunction cell for use in a terrestrial solar concentrator. Solar concentrators are devices in which multiple mirrors are positioned to reflect the incident sunlight onto the surface of a cell and where the cumulative effect is as if multiple suns where shining on its surface. Green et al. (2007) also reported a large crystalline silicon module with an efficiency of 19.7 ± 0.7%. This module, produced by SunPower, is a cell currently in commercial production.

In reviewing the literature, it was found that there was an unofficial claim of even higher efficiency in a device incorporating another type of technology. Recognizing that different materials have peak absorption at different wavelengths, a research group from the University of Delaware incorporated a dichroic mirror into their system. A dichroic mirror selectively allows the passage of light below or above a certain wavelength while reflecting the remaining portion of light. In this application, the mirror allowed longer wavelength, lower energy light to pass, to one type of PV cell while reflecting shorter wavelength, higher energy light to a different PV cell. The result is an unofficial record of 42.8% efficiency (Kintisch, 2007), approximately 2% above the record previously described. The two cells are linked together in series to provide a cumulative effect of a higher energy output from the incident light. This article was not a scientific report of the advancement made by this group, it is in fact a short notice mentioned in the "News of the Week" in Science. The article also readily admits that the group has not yet built a working prototype of this solar cell, and does not describe how the group has achieved this result. Furthermore, the article fails to mention the incident power of the light applied to this photovoltaic cell; it is assumed that standard test conditions where applied. The article implies that the incorporation of the dichroic mirror is a novel approach to increasing the yield of a photovoltaic cell, but as pointed out in a Letter to Science, this idea is not novel (Bordon, 2007)

VI. What Affects Electricity Production from a Photovoltaic Panel?

There are a number of things that affect the energy production of a PV cell. The amount of light incident on the surface of a PV panel directly correlates to the amount of energy that a photovoltaic panel can produce. The positioning of the panel is critical in optimizing the amount of electricity produced. In the northern hemisphere, panels will produce the most electricity when the panels are pointed due south. Angular deviation of the normal of the surface from the south is referred to as the azimuth angle. Deviation from the south will determine when the panel receives the most amount of light, be it at some time in the morning or afternoon. The slope of a panel represents the angle at which a panel is tilted with respect to the surface of the earth. A slope of 0º represents a panel that is laying flat on (or parallel to) the ground. A panel on the side of a vertical wall would have a slope of 90º.

The temperature of the panel also influences the amount of electricity that can be produced. Typically the power output of a panel decreases in extreme temperatures. Solar panels without adequate ventilation will be heated by the sun and produce less electricity than those that are properly installed.

The accumulation of dust on a PV cell will also reduce the amount of electricity it generates. For this reason, it is sometimes recommended that an array be placed where it can be easily accessed for cleaning. Installation of PV arrays on hard-to-access roofs is sometimes discouraged for this reason. Typically a cleaning procedure and a recommended frequency of cleaning is provided in the manual for the array. Although some experts recommend cleaning the system once per year, some owners have noticed a small jump in the kWh production after cleaning the array (NorCalSolar, 2007).

Shading of even a single PV cell can greatly reduce the amount of electricity produced by an entire array. Shading can be either "hard" or "soft". Soft shading is described as that produced from a distant object, such as a tree limb. It blocks beam (or direct) radiation from the sun but allows diffuse (or sky) radiation to reach the surface of the panel. Hard shading is the result of an object being placed directly on the surface of a panel, such as bird droppings, or a fallen leaf or branch. Hard shading blocks virtually all light. Shading on just a portion of a photovoltaic panel can greatly reduce if not eliminate electricity generation of a panel. For PV modules "cells within modules connected in series produce as much power as their weakest link" (Kintisch, 2007).

A PV system will also experience other losses outside of the panels themselves, including wiring losses, losses due to the conversion of electricity from DC to AC, and if included, losses related to the inefficiencies of energy storage in a battery system.

When examining a system, the cumulative effect of these factors can have a large impact on the amount of energy produced by a PV array. Table 1 gives an estimate of potential losses in a PV system from these factors. The losses within a system can reduce the electricity generated by a photovoltaic array by over 33%. It must be emphasized that the values presented here are only an estimate for a generic system. This example does not take into account possible losses due to shading (hard or soft) that can significantly affect the electricity output of a photovoltaic system.

Table 1. Approximation of System Losses from a photovoltaic system. *With the application of photovoltaic systems there are inherent systematic losses which are cumulative in the amount of electricity that can be recovered from the specified output of the photovoltaic cell. The above is but one example of the possible losses within a photovoltaic system. Data from Xantrex Technology Inc., 2001.*

Description	Losses	
Production Tolerance (5%)		0.95
Temperature (11%)		0.89
Dirt and Dust (7%)		0.93
Module Mismatch Losses (2%)		0.98
Wiring Losses (3%)		0.97
DC to AC Conversion Losses		
Inverter without batteries (10%)	0.90	
Inverter with batteries (23%)	0.86	
Inverter: (14%)		
Batteries: (10%)		
TOTAL SYSTEM DERATING		
Without batteries		**0.67**
With batteries		**0.58**

VII. Case Study: Photovoltaic Potential in the City of Guelph

The feasibility of meeting the energy needs of the residential sector of the city of Guelph, ON (Canada) was selected as a case study for the application of this technology. Specifically, the quantification of the footprint of solar PV panels required to meet this energy demand was to be estimated. A solar insolation model was utilized to determine the optimum slope of PV panels located in Guelph. This model was further utilized to provide simulated data for PV panels at this optimum slope from raw data obtained for a horizontal surface.

A. The Solar Insolation Model

First. a model was developed to quantitatively estimate the solar insolation on a surface in the city. This model was based on the work of Klein (1977) and Korsun and Stranix (1984). The angle of incidence, θ, of sunlight on the photovoltaic panel, was determined as a function of the slope or tilt, β, of the surface with respect to the horizontal plane, the azimuth angle, γ, which represents the deviation from south (for the northern hemisphere, and where East is positive), the latitude, ϕ, of the site (where degrees north are positive), the declination, δ, which is the angle of the sun relative to the equatorial plane, and finally the hour angle, ω, which represents the angular displacement of the sun east or west of the local meridian. The declination, as described below, is a function of the Julian calendar day, n, with hours of the day represented by fractions of n. The hour angle represents an angular deviation of 15 degrees for every hour from solar noon (negative before solar noon, zero at solar noon, and positive after solar noon).

$$\delta = 23.45\sin\left(360\frac{(284+n)}{365}\right) \tag{5}$$

$$\begin{aligned}\cos\theta &= \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ &+ \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ &+ \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{6}$$

$$I(\theta_z)_{D+S} = (I_0 + I_{0S})e^{-c(\sec(\theta_z))d} \tag{7}$$

$$\cos\theta_z = \sin\phi\sin\delta + \cos\delta\cos\phi\cos\omega = 1/\sec\theta_z \tag{8}$$

$$I_0 = I_c(1+0.333)\cos(360n/365) \tag{9}$$

$$I_i = I(\theta_z)_{D+S}\cos\theta \tag{10}$$

When applying the above equations, it was necessary to recognize when the sun was in front of the modeled surface. This occurs only when the angle of incidence, θ from equation (6), is less than or equal to 90º, otherwise the sun is behind the surface and the modeled surface is dark. In equation (7), the total irradiation is $I(z)_{D+S}$ where D represents direct and S represents scattered (or diffuse) sunlight. The empirical constants c and d are 0.357 and 0.678, respectively. The apparent solar flux source due to scatter, I_{0S}, is 214 W/m^2. The accepted value for the exoatmospheric flux, I_c, is 1367 W/m^2 (Page, 2003). Finally, the incident irradiation, I_i from equation (10), on the surface is the product of the total irradiation and the cosine of the angle of incidence. In the use of this model, the total irradiation was set to zero when the zenith angle, θ_z, was less than 0º. Also, the irradiance on the surface was set to zero when the incidence angle, θ, was greater than 90º. It is important to recognize that this model does not account for the effects of shading and/or clouds or any other impacts resulting from atmospheric weather conditions that would affect the amount sunlight incident on a surface.

For the analysis performed in this work, the model was used to establish a correlation between the amount of sun incident on a flat surface relative to that of a surface at an optimum slope. The panel at the optimum slope will receive more solar insulation based on the changing position of the sun throughout the year. The model was used in conjunction with actual insolation data, described later in this section, which takes into account the affect of weather.

B. Meeting Residential Energy Demand for the City of Guelph with Photovoltaic Panels

The global position of Guelph is 43.45ºN and 80.25ºW. The model described above was utilized to determine the optimum surface slope to maximize the incident sunlight on the surface of a photovoltaic panel; the optimum slope obtained was 37.4º. Utilizing the model, an estimate of the total annual insolation for the city of Guelph for a surface at a slope of 0º was 1,834 kWh/m^2. The change of the slope to the optimum position, β = 37.4°, yielded an estimated total insolation of 2,303 kWh/m^2, a relative increase of 26%.

Insolation data for a horizontal surface (slope of 0º) was utilized to represent what an actual surface exposed to the elements would achieve in terms of true solar insolation. The hourly data utilized for this study was recorded at the Elora Research Station, south of Elora, ON (18 km northwest of Guelph at 43.64ºN and 80.41ºW), for the calendar year 2006. Utilizing the model described above, ratios between the amount of sunlight incident on a horizontal surface and one with a slope of 37.4° were determined. The measured data was then multiplied by the obtained factors (obtained for each hour) to estimate the amount of irradiance that could be attributed to tilting the surface to the optimum surface slope. It is important to note that an artificial limit was set on the factors obtained from the tilting of the surface. Here, multiplying factors were limited to 8 as it was not believed that the amount of incident light would exceed this amount. The factors obtained where generally highest during the first and last hours of insolation during the day, with a peak value of 200, and the vast majority of the factors were less than 8. It was expected that the deviation between the amount of light incident on a horizontal surface and one at an optimum angle would be greatest at these times. The measured data obtained from the Elora Research Station provided an annual insolation of 1,325 W/m^2, once again where the surface slope was 0º. When this data was multiplied by the correlating factors, it was found that the simulated annual insolation was 1,640 W/m^2, a relative increase of 24%. Figure 5 provides a graph of the simulated and measured insolation and shows the increase in incident energy on a horizontal surface relative to that at the optimized slope. The measured insolation data were given on an hourly basis (that is each point an average of data measured over an hour time span). It was inferred that the data which was provided in kW/m^2 could be representative of potential energy that could be captured by a PV panel in kW-hr/m^2. The same assumption was made for the simulated data.

Model results were then used as the basis to estimate the potential performance of PV systems deployed in Guelph. First the amount of energy that could be captured if all of Guelph was literally covered with photovoltaic panels was calculated. The geographic footprint of Guelph is 88.66 km^2 (Guelphdirect, 2005). Assuming a system

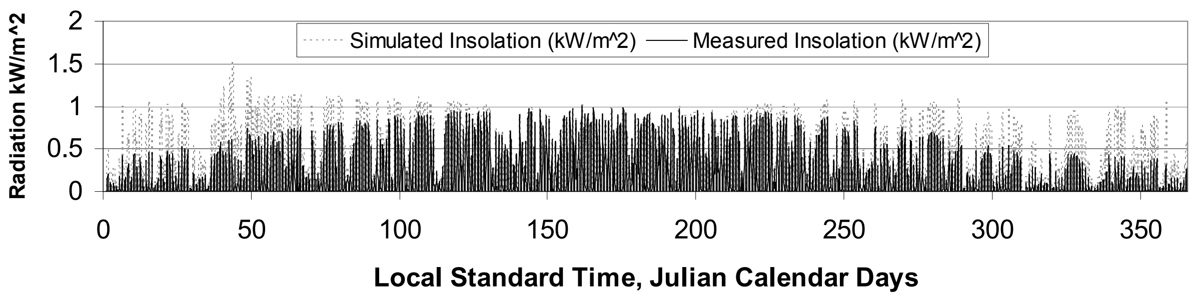

Figure 5. Simulated and Raw Data Insolation. *The model was used to calculate an hourly multiplication factor which was used to convert actual insolation data for a surface with a slope, β, of 0º to that for a surface with a slope of 37.45º. The raw insolation data was obtained from the Elora Research Station (Elora, ON) and was used to provide a basis for solar insolation for the city of Guelph, ON.*

with a typical PV panel efficiency of 15%, having losses as listed in Table 1 (for a system without batteries), an area of 88.66 km^2, and a slope of 37.4º, results in a theoretical annual generation of 1.46×10^{10} kW-hr. If the same system was put into place with a best available technology efficiency of 42.8%, and all other assumptions were the same, the array would theoretically generate 4.18×10^{10} kW-hr annually. It must be pointed out that, for these calculations, the footprint of the photovoltaic array was set to that of the city of Guelph. These calculations did not take into account the effects of shading of one panel on the next which would reduce the actual footprint of panels. The use of the best available technology efficiency of 42.8% has been done here solely for comparison as a means of gauging the impact of its application. It is recognized that the actual application of this type of panel is, at this time, not feasible.

There are 44,710 dwellings in Guelph as of 2006 (Statistics Canada, 2006). Multiplying that value by 119.6 GJ, the average energy intensity per household in Ontario (Natural Resources Canada, 2007), results in an estimated residential annual energy demand for Guelph of 1.49×10^9 kW-hr. The amount of energy theoretically generated by the PV arrays (both 15% and 42.8% efficient) covering the same area as the city of Guelph is an order of magnitude greater than that theoretically required by the residential sector of the city of Guelph.

Next, the PV electricity generation potential was determined for the case where all dwellings capable of supporting a 2 kW PV system were so equipped. The selection of a 2 kW PV array was based on the size of a typical system being offered for installation on residential homes by Guelph Solar, an organization in the city of Guelph advocating for the installation of PV systems (further discussed in the next section). For this purpose, houses of any type were considered capable of supporting a PV system, while apartments of any type or dwellings categorized as "other" were considered unable to support a PV system. It must be pointed out that this did not take into account houses which are partially or fully shaded or for another reason do not allow for the installation of a photovoltaic array which can face south and be tilted at the optimum slope. The number of dwellings that met these criteria was 30,984, or 69.3% of those in Guelph. Specifications of several commercially available photovoltaic panels (Sharp ND-208UF, Kyocera KC187G, BP Solar SX3140 and Evergreen ESL-190) were used to estimate the array area of a 2 kW system. For the systems considered, the array area was 16.9 m^2 (standard deviation: 0.8 m^2). Multiplying the number of available dwellings by this typical array area, it was estimated that 0.524 km^2 of photovoltaic panels, or roughly 0.6% of the land area of Guelph, could be installed on Guelph dwellings. If these panels were of a typical efficiency of 15%, then the electricity generated by these panels would amount to 8.84×10^7 kW-hr annually, (factoring in system losses), which amounts to 6.0% of the total energy demand of the residential sector of Guelph. On the other hand, if these panels were to be of the efficiency of the "best available technology" (42.8%), then the panels would provide 2.52×10^8 kW-hr annually (once again including losses), meeting approximately 17.0% of the total energy demand of the city.

The area of 15% efficient PV panels required to supply the annual energy demand of the residents of Guelph, using the same assumptions as the previous analyses, was 8.80 km^2, equivalent to 10.15% of the footprint of the city of Guelph, assuming that the system losses previously described. This area decreases substantially when panels with the "best available technology" efficiency of 42.8% could be utilized. Then the required footprint becomes 3.08 km^2, or approximately 3.56% of the city.

C. Costs and Incentives of Photovoltaic Panels

Currently in the city of Guelph, there is a grassroots organization called Guelph Solar (http://www.guelphsolar.ca/; formerly known as Guelph Residents Advocating Solar Power, or GRASP), which has been working to organize Guelph residents, as well as commercial and industrial entities, interested in purchasing and installing photovoltaic systems. Specifically, this organization has been registering interested parties and soliciting vendors for the purpose of making a collective bulk purchase of PV equipment. Guelph Solar provided the following information on its website to provide interested residents an estimate of the price that they should expect for a potential system. A quote from Natural Power Products (Kitchener, ON; www.npp.ca) for full installation of a 2 kW system came to $19,000 (assumed CDN) plus taxes. A discount of approximately $3,500 per system would be applied if a sufficient number of systems were purchased (GuelphSolar, 2007). A preliminary quote from the manufacturer United Solar Ovonics for a 2.5 kW thin-filmed photovoltaic system was $15,000 plus tax per kit, without installation (GuelphSolar, 2007).

In looking further at the financial side of these systems, it was found that there are specific incentives for the application of solar photovoltaic systems. Specifically, the Ontario Power Authority has a Renewable Energy Standard Offer Program that pays for electricity generated from solar systems at a rate of $0.42 per kW-hr (Ontario Power Authority, 2007). This rate is significantly greater than the standard rate charged per kW-hr by Guelph Hydro of $0.053 per kW-hr, not including taxes, fees, or distribution charges. It was also found that the Ontario Ministry of Revenue offers a rebate for Retail Sales Tax, also known as Provincial Sales Tax, for its Solar Energy Systems Rebate Program (Ontario Ministry of Revenue, 2007). The refund of this 8% charge is not inconsequential when considering the cost of a photovoltaic system. This rebate was slated to expire on November 25th 2007, but, at the time of this report, it had been extended to January 1st 2010.

VIII. Conclusions

The employment of photovoltaic arrays to harness and utilize the energy from the sun is growing. With that growth there are a number of researchers who are trying to push the envelope to develop the technologies which will allow for greater recovery efficiencies with this technology. There is a great deal of information to be explored when discussing the topic of photovoltaic technology. Along with the technology, there is a need to understand the daily and annual cycles of the sun which dictate how this resource can be utilized. Here a brief introduction into many of the topics has been offered, with a brief case study highlighting the application of this technology. In estimating the footprint of photovoltaic panels need to power the city of Guelph, the question must be raised, is this realistic or possible? There does not seem to be a limitation in terms of production of PV technology which globally has increased sixfold since the year 2000 (Worldwatch Institute, 2007). Only the future can answer that question, and, as seen here, the footprint necessary greatly depends on the efficiency of the applied technology. Once again, only time will tell if, what is now considered to be the best technology in the world will one day be available for mass usage. What is apparent, is that technologies such as this will have increasing importance in the future as a means of reducing the environmental impact that results from the use of conventional energy resources.

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