Powering the Future with Photovoltaics

by Anton Driesse
Queens University, Kingston, ON

Abstract

Photovoltaic cells convert energy from sunlight directly into electricity without moving parts or chemical reactions. The technology of photovoltaic cells and of the components that make up photovoltaic systems continues to evolve and mature, but it is already the technology of choice to provide electricity in many situations. This article provides an introduction to photovoltaics and an overview of the different system components and configurations with reference to applications in which they are used. The article also describes recent developments from the research side, and identifies some starting points for further reading on this subject.

Sommaire

Les cellules photovoltaïques transforment l'énergie solaire en électricité sans moyens mécaniques ou processus chimiques. Cette technologie évolue sans cesse, tout comme celles des autres composantes qui constituent les systèmes photovoltaïques, mais elle est déjà une option privilégiée pour assurer l'approvisionnement en électricité dans de nombreuses situations. Cet article se veut une introduction aux systèmes photovoltaïques : il a pour but d'expliquer leur fonctionnement et de donner un aperçu de leurs différentes composantes, configurations et applications. Des développements récents dans ce domaine de recherche sont également présentés, ainsi que quelques références pour approfondir le sujet.

1.0 Introduction

Photovoltaic cells perform an impressive feat: they transform radiant energy from the most abundant, least expensive and widely available source - the sun - into one of the most versatile energy forms known - electricity. The cells accomplish this without moving parts or chemical reactions; their operation causes no noise or environmental pollution. With such attributes, could they be the solution to the world's energy problems? Despite impressions given by the global petroleum trade and continental electrical grid operators, many energy needs can in fact be met using alternate technologies such as photovoltaics. What's more, the alternate technologies can be better overall solutions.

In the 50 years since researchers at the Bell Labs in New Jersey created the first practical cells, photovoltaic (PV) systems have become the technology of choice for an increasing range of applications - from outer space to pocket calculators, to weekend cottages. Technological advances, declining system costs and rising prices for conventional energy make PV systems ever more viable as a solution to an ever wider range of energy needs.

PV systems are also being used successfully as distributed electrical generation sources feeding into the electrical grid (as opposed to constituting an alternative, such as grid-independent power). Such grid-connected systems can be integrated into building designs to provide secondary benefits such as shading and can also offset other building material costs (Figure 1). Specialized products are already on the market to facilitate integration of PV into various types of roofs, such as shingles or tiles, feasible on a mass-market scale.

Identifying appropriate applications for PV systems is both a business opportunity and engineering challenge, as it requires an understanding of a variety of topics. The challenge is well worth accepting, since a successful PV installation is a win-win-win for suppliers, consumers and our natural environment alike.

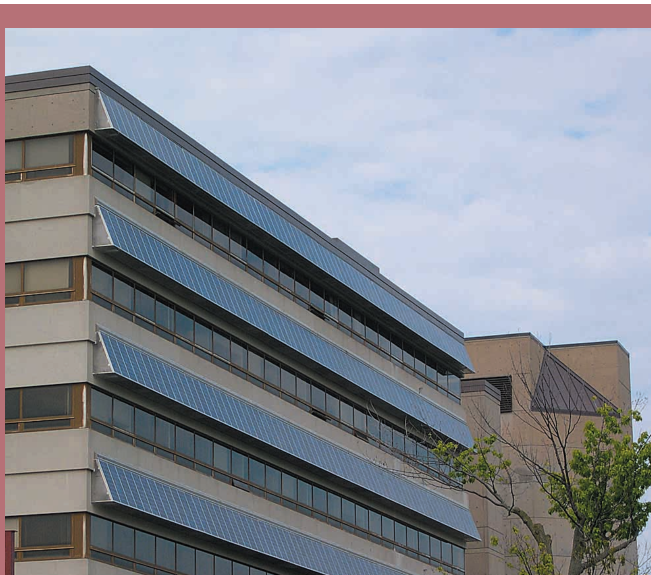

Figure 1: A 20 kW grid-connected, building-integrated PV system at Queen's University provides summer shading and year-round electricity. (Photo: Anton Driesse)

2.0 The Solar Resource

Although sunshine is widely perceived to be variable and difficult to predict, the sun in fact provides the earth with a nearly constant influx of energy. In specific locations this influx is modulated by atmospheric or climatic conditions and of course, the rotation of the earth. At first this variability appears to make the sun a very unreliable source of energy, but is this really so?

The motion of the earth around the sun is very predictable. Sunrise and sunset times can be calculated with high precision and the exact path of the sun in the sky as seen from any position on earth can be determined for any relevant future date. Both daily and seasonal variations are well understood and reliable.

Atmospheric conditions are more difficult to predict, but in this case the accuracy of the predictions depends on how far into the future they are made, and what period of time the prediction represents. For example, it may be possible to achieve a very high accuracy for predictions that are merely one hour in the future; or for predictions several years into the future that represent monthly averages. In fact, long-term monitoring has shown that such averages show only small variation from year to year and can therefore be quite reliably predicted.

The key to using the sun's energy is to understand its variability, and to understand how this variability relates to the energy needs of the application. These may correlate positively, such as in the case of a pump to provide drinking water; or negatively, such as in the case of street lights. When the correlation is less than perfect a PV system requires either a supplementary source of generation (making it a hybrid system) or some form of energy storage. A mechanical tracking system can also be used to keep solar cells facing the sun throughout the day and year, thereby modifying the energy supply profile as well as increasing the capacity factor (Figure 2).

Figure 2: A mechanical tracking system keeps solar cells facing the sun, thereby capturing more of the available solar energy. (Photo: National Center for Appropriate Technology)

Despite this complexity a simplified understanding of the solar resource can be adequate for smaller designs. The available solar energy is therefore often described as an average number of hours of bright sunshine per day in a particular location. This also corresponds to the way sunshine was historically measured and much data is available in this form.

3.0 Photovoltaic Cells

3.1 Fundamentals

By far the most common types of PV cells in use today are made of silicon. Each cell is a large, flat diode with a thin, negatively doped layer facing the sun. Solar radiation striking the cell transfers energy to electrons in the valence band of the molecules. If the energy of a photon exceeds the band-gap energy of the silicon, it will push an electron up into the conduction band where it becomes mobile. The electric field that exists across the diode's P-N junction then causes the mobile electron to migrate to the edge of the diode and travel through an external circuit where it releases its energy.

The band-gap energy of silicon is such that a large fraction of the solar radiation can produce this photovoltaic effect. Energy from photons with insufficient energy (light of longer wavelengths) is converted to heat, as is excess energy from photons that exceed the band gap level (shorter wavelengths). Thus it is impossible for a silicon cell to convert all the available energy to electricity.

Since individual silicon cells produce a relative low voltage, typically 0.5 V under load, a dozen or more are wired in series and then packaged in modules of various design. The module makes a rugged and convenient unit that both protects the cells and facilitates installation.

Commercial silicon cells or modules are commonly available in three basic types: mono-crystalline, polycrystalline, and amorphous (or thin-film). Mono-crystalline cells lead in terms of performance with typical module efficiency of 12-15%, which means that with a nominal radiation intensity of 1000 W/m^2, a module of 1 m^2 would produce 120 to 150 W. Polycrystalline cells are somewhat less expensive to produce and slightly lower performers, typically 11-14%. Specialty low volume, high cost cells have efficiencies of 20 - 26%.

Amorphous silicon cells are not produced as individual cells, but as modules. They consist of a very thin layer of semiconductor material deposited on a substrate such as metal or glass. The reduced material requirements and the simpler manufacturing process lead to cost reductions, but unfortunately module efficiencies are also much lower, typically only 5-7%.

While prices are set per module, the focus of the designer is usually on the price per rated watt of power output, which is relatively uniform for each technology. The module power rating is determined under standard test conditions and is used as the basis for this unit price. In actual installations the modules rarely operate at standard conditions, but the rating does provide a basis for comparison.

High module efficiency would seem to be an important criterion, but it is usually less important than the price per watt since the primary source of energy is free. However in situations where only a limited space is available, or where there are important costs associated with space such as for a complex support structure, higher efficiency modules may be the better choice.

For many researchers higher photovoltaic cell efficiency represents the ultimate challenge, and much work has gone into identifying the limiting factors, both theoretical and practical, and approaching, circumventing, or removing those limitations. For premium applications such as outer space higher efficiencies are particularly valuable, and eventually such advances also find their way into terrestrial products. The following sections provide an overview of some more advanced technologies that promise either higher efficiency, lower cost or other competitive advantage.

3.2 Advances in Cell Technologies

Given their long history it may seem surprising that so few variations of (or alternatives to) the original silicon PV cell are readily available. This lack of variety belies the fact that there is a broad range of new technologies on the horizon. Some are little more than proof of concept but others are in fact already in production; and most of these new designs are significantly different from their precursors.

Both mono-crystalline and poly-crystalline cells are made from thin wafers of silicon, and essentially the only difference between them is the quality of the raw material. The quantity and quality of silicon used to make wafer-based solar cells today constitute one of the big barriers to further cost reduction. Amorphous silicon cells certainly require less material, but at a significant performance penalty. Newer thin-film technologies therefore attempt to capture the best of both worlds. For example, techniques have recently been developed to grow a very thin layer of crystalline silicon on an inexpensive substrate, raising the prospect of achieving the same performance as wafer-based cells with a fraction of the material. Spheral solar cells (a Canadian product) are just becoming available now, and although they are not in the category of thin-films, they also provide better performance using both a lower quantity and a lower quality of silicon raw material.

Flexible PV cells and modules (as opposed to rigid ones) are a category of particular interest since they can be more readily adapted for mobile applications and mounted on curved or irregular surfaces. This is another advantage of the spheral and thin-film technologies.

3.2.1 Alternatives to Silicon

Silicon is not the only semiconductor material, of course. The much lower band gap energy of germanium would result in very low efficiencies, but several compound semiconductor materials have characteristics that make them very attractive for building PV cells. Such materials can be formed of group III and V elements such as gallium arsenide (GaAs), group II and VI elements such as cadmium telluride (CdTe), or even trio of group I, III and VI elements such as copper-indium-diselenide (CuInSe2 or CIS). These compounds typically have band gap energies different from that of silicon, and therefore their theoretical maximum efficiency in converting sunlight to electricity is also different. GaAs cells in particular have shown efficiencies in excess of 25%.

The fact remains, however, that there is no single band gap energy that would permit a PV cell to capture all the available solar energy because this energy is spread over a range of frequencies. For this reason there are designs for multi-junction cells where the materials used to make each junction have different band gap energies, and are thus sensitive to different parts of the solar spectrum. With multiple junctions of compound semiconductors there is an explosion of possible combinations of materials, and thus prospects for new products. Designs exist for as many as 5 layered junctions, and triple-junction cells are already on the market today.

3.2.2 Concentration for Efficiency

While a fundamental limit such as the one imposed by the band-gap energy is hard to break, there exist more than one work-around. Besides the multi-junction approach, greater theoretical as well as practical efficiencies can be achieved by concentrating sunlight before capturing it.

The optical components must track the position of the sun in order to keep it focused on the cells and make this apparatus more bulky and complex than a simple cell, but the economics show some interesting advantages. First, the cost of cells for a given output is reduced by the concentration factor, and then further reduced by the gain in efficiency. Second, potential cell enhancements that would not be cost-effective under direct sunlight also see their payback multiplied. This is why the more expensive but top performing GaAs cells are seen in concentrator systems. Naturally the concentrator components around the cell also have a cost, but particularly in larger systems this cost remains well below the cost of PV cells they displace.

3.2.3 Novel Approaches

What is perhaps most fascinating about recent developments in photovoltaics is that different mechanisms are being discovered to convert sunlight to electricity. Among them are the dye sensitized/activated solar cells, the organic/polymer solar cells, and the photo-electrochemical cells. The time-to-market is still very uncertain for all of these of course, but nevertheless in a press release earlier this year, Siemens AG announced that its researchers had achieved efficiencies of 5% for their experimental organic cells, and they expect to be able to increase this to 7% - which would be comparable to the amorphous silicon cells of today.

3.3 Advances in Module Technologies

While developments in cell technologies are pushing the limits of scientific understanding, the evolution of PV modules is taking place primarily in the realm of product development and is driven by the evolving market. The basic rectangular module is still the mainstay of the industry, but it is now also possible to obtain modules that integrate mechanically, electrically and aesthetically with asphalt shingle (Figure 3), tile, or standing seam metal roofs. There are also triangular modules to more closely fit the shape of a sloping roof; frameless modules to create a nearly continuous surface; semi-transparent modules to double as windows; and custom solution can be assembled as well.

3.4 Environmental Concerns

The potential for lower cost per watt is the major driving force behind innovations in cell technology. Reductions in material requirements also have tangible environmental benefits such as reducing the amount of energy it takes to make the cells, also referred to as embodied energy. Estimates indicate that modules on the market today take about 2-4 years to generate the amount of electricity that went into their production, and are expected to last 30 years or more - which seems exceptional for any product manufactured today.

Another area of concern is that some of the newer compound semiconductor cells contain toxic substances. Although these do not enter into contact with the environment during the lifetime of the product, they must be carefully managed during production and recaptured after decommissioning.

4.0 Photovoltaic Systems and Components

PV modules are the heart of PV systems, but there are several other key components. Exactly which of these components are required depends on the configuration of the system, which in turn depends on the application's requirements. The fundamental options to be considered are: energy storage, additional energy sources, and a grid interface.

4.1 Direct-Powered Loads

The simplest system consists of one or more PV modules connected directly to a load. This is appropriate for applications such as pumping water because the water can be stored in a reservoir and used later; or ventilation fans and other cooling applications because they are most needed when the sun is shining.

The challenge with this configuration is matching the load to the PV modules so that the system will stop and start automatically and run reliably over a range of operating conditions. The fact is that the current-voltage characteristics of PV cells are a very poor match for motor and resistive loads, and the PV component is usually oversized to make this work. Other options are to add a small storage battery to provide extra starting current and voltage regulation, or to add a DC/DC converter to improve the match.

4.2 Autonomous Systems with Storage

Most applications require some energy at times when sunlight is not available. This energy may be supplied by another source, such as a wind turbine, a diesel generator, or the electrical grid, for example, or it may be collected in advance and stored until needed. Applications for systems with storage abound where grid power is not available, unreliable, or too expensive to install, or where the need is relatively small, temporary, or mobile (Figure 4).

Storing electrical energy in significant quantities is notoriously difficult, and methods rely on some form of reversible conversion of energy into another form. And although every method entails energy losses and other drawbacks, storage systems are successfully integrated into many PV systems and enable them to meet a much broader range of needs. Two types of storage are of particular interest: batteries and fuel cells.

Rechargeable electrochemical cells are well known and have myriad applications outside of PV systems. Both lead-acid and nickel-cad-

Figure 3: Photovoltaic modules in the form of shingles for roof integration. (Photo: Warren Gretz)

Figure 4: Small autonomous systems such as traffic signs (shown here), lights, telephones and parking meters are effective in both rural and urban areas. (Photo: Dan Ton)

mium types are common, and the proliferation of portable electronics has led to the development of other types that can store more energy per unit of mass. For most stationary PV applications, however, a bank of lead-acid batteries that is optimized for daily cycling and occasional deep discharge constitutes an adequate storage solution.

The main drawback of all batteries is that the storage capacity is fixed. If this poses a problem, a system comprising an electrolyser, hydrogen storage and fuel cell can be considered instead (see IEEE Canadian Review, No. 44). With expandable hydrogen storage and greatly improved fuel cell efficiencies it should be possible in the future to consider seasonal storage in stand-alone applications using this method.

In addition to the PV modules and a storage system, autonomous systems are usually also equipped with a charge controller to ensure that the storage is not charged or discharged excessively. Furthermore, to permit the use of conventional loads and equipment, an inverter converts the direct current into 120 or 240 V ac. Recent advances in power electronics combined with increased demand and production have resulted in a greater selection of products and lower prices in this category. Nevertheless inverters remain a major cost component and longevity is a concern.

Charge controllers and inverters (for grid connection) may be equipped with a maximum power point tracking function as well. This permits the unit to adjust the electric load that it imposes on the PV modules in order to extract maximum power under continuously varying sunlight and temperature conditions. In all these components high efficiencies are key to minimizing the number of solar panels needed in the system, and thus, minimizing system cost.

4.3 Hybrid Systems

If an application requires more energy than could reasonably be supplied by a stand-alone PV system, one or more other forms of electricity generation such as wind turbines or gas/diesel gensets can be integrated. Each of these has different strengths and limitations, and together they can constitute a reliable and versatile electricity supply system.

Once a genset is involved it may be tempting to eliminate the other generating sources for the sake of simplicity. But genset operating costs are either high or very high, and being sized for peak loads their efficiency at average or small loads is always poor. In a hybrid design the PV modules and storage can be sized to provide the base load, and the genset can provide peak loads and occasionally top up the storage if needed. Particularly in remote locations, where the cost of transporting fuel for the gensets may exceed the cost of running them, this can be a very attractive solution.

4.4 Grid-Connected Systems

Although vast areas of Canada are not supplied by the electricity grid, most populated areas are. When a PV system is connected to the grid it can be simplified a lot: storage is no longer necessary, hybrid solutions do not need to be considered, and control strategies can be simplified since the grid can supply shortages or absorb excesses. It also operates more efficiently on average, since it can always deliver its maximum output.

But if grid electricity is available, why bother? What is the advantage? Certainly from the limited viewpoint of today's electricity prices and today's PV system costs in Canada, there does not appear to be any advantage for the individual. But today's fossil fuel based electricity generation causes significant environmental pollution and is in limited supply, so if electricity from PV systems reduces fossil fuel use it certainly does provide important benefits to society . The fact that there are grid-tied systems in Canada today is evidence that individuals, companies and governments are looking forward and are willing to invest in the future.

At the same time, there are factors that can make a significant positive difference in the economics of grid-tied PV. For example, maximum PV electricity generation usually coincides with summer peak loads, i.e. at times when the market price of electricity also peaks. As a form of distributed generation, grid-connected PV systems are near to their loads, and therefore avoid significant transmission and distribution losses. And finally, when integrated physically and functionally into buildings, PV systems can provide additional benefits by influencing solar heat gain and daylight penetration, while at the same time displacing cost of other building materials (Figure 5).

Figure 5: Grid-connected systems such as these solar roofs in the Netherlands are the way of the future. **(Photo: Alfred Brunger)**

Industry standards for grid-connection have been developed already, and are embodied in inverter products on the market in a wide range of power ratings - from hundreds of watts to tens of thousands. Besides transferring the maximum available solar energy to the grid, these inverters continuously monitor the voltage and frequency on the grid, and shut down automatically within fractions of a second if any of these measurements indicate an anomaly.

5.0 Global Context and Future Trends

Globally the PV industry is experiencing strong, sustained growth, as illustrated in Figure 6. The grid-connected distributed market segment has grown the fastest in recent years, due in large part to incentive programs in Germany and Japan. Yet the cumulative installed capacity is still only a drop in the barrel compared to total fossil fuel based generating capacity, which means there is ample opportunity for this growth to continue and even accelerate.

Canada's relatively low energy prices have not helped encourage investment in renewable energy technologies, and installations in Canada have been primarily of autonomous PV systems as opposed to grid-connected ones, as is clearly seen in Figure 7. The most common application areas are for telecommunications and monitoring equipment in remote locations, and off-grid homes. It seems inevitable that all energy prices will go up, however, and looking into the future may be as easy as looking at what is happening in Europe or Japan today, where energy prices are already much higher.

The first and obvious effect of higher energy prices is that the economics of all PV systems improve, and more applications will be labelled as cost-effective. The second effect is that higher volumes lead to lower PV system production costs, and further improvements in the econom-

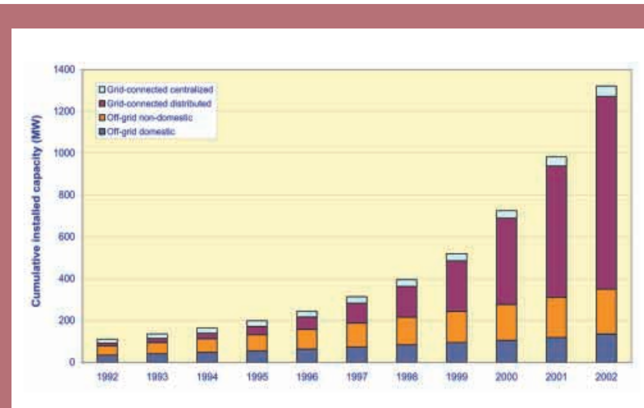

Figure 6: Cumulative global installed PV power by submarket. (Source: IEA Photovoltaics Power Systems Programme)

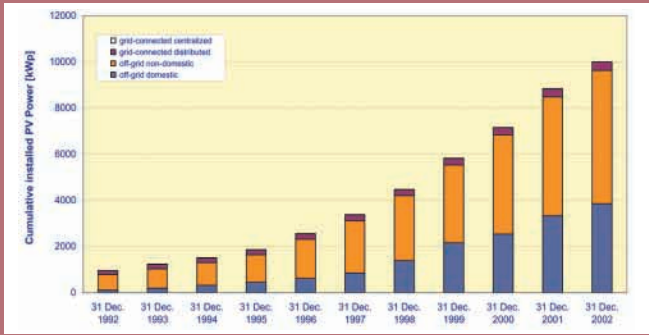

Figure 7: Cumulative installed PV power in Canada by sub-market. (Source: IEA Photovoltaics Power Systems Programme)

ics. Since this is a global industry, Canada is already benefiting from lower costs thanks to high sales volumes in other countries. The third effect is a greater general awareness of the true cost of energy, the true value of conservation, and a greater appreciation for the inherent advantage of a renewable resource such as PV. This in turn drives political agendas and policies, research funding and implementation subsidies - and further growth.

The potential for growth is particularly high in the grid-connected market segment, and it is there that Japan and many European countries show by far the greatest growth. Grid-connected systems have an inherent advantage because of their simplicity and the fact that they can deliver the maximum available energy all the time. And while their presence may encourage awareness of energy use, they do not inhibit or restrict energy users in the same way autonomous systems might, and public acceptance is good.

Regardless of whether Canada follows these trends or charts its own course over the coming years, more PV systems will be installed because more and more people are becoming aware of the possibilities and benefits. As engineers, we should be leading this evolution.

6.0 Suggested Reading

Books

[1]. Ayoub, J., Dignard-Bailey, L. and Filion, A., “Photovoltaics for Buildings: Opportunities for Canada” CANMET, Varennes, 2001.

[2]. Wenham, S.R., Green, M.A., and Watt, M.E., “Applied Photovoltaics”, Centre for Applied Photovoltaics, Australia, 1994.

[3]. Ross, M., and Royer, J. (editors) “Photovoltaics in Cold Climates” James & James, London, 1999.

[4]. “Photovoltaic Systems Design Manual” CANMET, Ottawa, 1991.

Web Resources

[5]. Solar Energy Society of Canada (www.solarenergysociety.ca)

[6]. Canadian Solar Industries Association (www.cansia.ca)

[7]. NRCan Renewable Energy Decision Support Centre (www.retscreen.net)

[8]. US National Center for Photovoltaics (www.nrel.gov/ncpv)

[9]. IEA Photovoltaic Power Systems Program (www.oja-services.nl/iea-pvps)

About the author

Anton Driesse completed his B.Sc. degree in Electrical Engineering at Queen’s University at Kingston in 1988, and subsequently obtained a M.Sc. in Computer Science from the same institution. He was active in the Information Technology sector in Kingston and Montreal for 7 years before turning his attention to Renewable Energy. While he maintains his primary focus on Photovoltaics, his interests encompass the full range of solar technologies, particularly as they complement each other in buildings. He is currently active as a consultant and as an associate researcher at the Queen’s University Solar Calorimetry Laboratory. He is also a director of the Solar Energy Society of Canada.