A Guide
to
Grid-Connected Photovoltaic Systems

prepared by

Cape & Islands Self-Reliance

Our project

Self-Reliance has been providing citizens of Cape Cod, the Islands and southeastern Massachusetts a program to make grid-connected solar Photovoltaic (PV) systems affordable to individual homeowners, small businesses and any other entities that are interested in having a system installed. The sun-generated electricity not used by the building's appliances would flow into the electric utility grid, running the electric meter backwards and, in effect, selling the power to the electric company, through net metering.

This Guide

The purpose of this Guide is to outline the fundamental operation of a grid-connected photovoltaic system, identify its components, and describe the way it works. This is not intended to be an exhaustive exploration of the subject, or to provide design or installation instructions.

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INTRODUCTION

The need

The energy sources we've become accustomed to—the fossil fuels and nuclear fission—have ceased to be the "easy" answers to our ever-growing need for electric power. Burning oil, coal and natural gas (called "fossil fuels" because they have been formed by the decayed remains of prehistoric plants and animals) pumps nitrogen oxide, sulfur dioxide, and mercury and other toxic metals into our atmosphere, directly causing increasing incidents of lung disease, polluting our soils and waters, damaging our crops and rendering our foods unsafe to eat in quantity. Nuclear fission produces radioactive waste, material that will remain deadly for thousands of years, for which we have yet to discover a safe method of storage. As we learn more about the inter-connectedness of all the ecosystems that permit and sustain life on our planet, the poisonous results of the various pollutants created by the use of these fuels are becoming increasingly harder to justify.

The *apparent* costs of oil, gas, coal and nuclear fission do not take into account the *hidden* health, environmental and economic costs to us all. The American Lung Association reports that air pollution from electricity production costs the nation $20 billion per year in health care. The National Academy of Sciences estimates that damage from acid rain causes $6 billion per year of damage to crops, forests, lakes and buildings in the United States. Global warming, no longer seriously disputed, resulting from increased atmospheric carbon produced by burning fossil fuels, is melting arctic and antarctic icecaps and changing global weather patterns.

Scientists and engineers worldwide are harnessing the energies of sun, wind and waves. The proven technologies are in place and in some cases (photovoltaics, for example) all that remains to be done here in the United States is public education and implementation. Japan and Northern European countries are investing in sea power, using wave motion to drive electric generators. Wind farms and solar energy supply electricity across Europe. Our country has not been in the forefront on this issue because of our geological abundance of the old, polluting fuels...but these "natural resources" are becoming increasingly more difficult, more problematic and more costly to retrieve and to use.

A solution

Every bit of energy we generate cleanly reduces the amount of pollution we add to our environment, reduces the burgeoning hidden costs of this pollution in health care dollars and food dollars, and adds to the growth of our economy by providing new technology jobs. Photovoltaics—generating electricity from sunlight—is a clean, affordable and *available* technology. Many utilities are embracing renewable energy technologies. The United Photovoltaic Group, a consortium of 79 utilities, represents more than 40% of the power generating capacity of the United States. Their chairman, Andy Vesey, who is vice president of Niagara Mohawk, says "Solar electricity has moved past the R&D state, and now the electric utility industry is finding profitable uses for PV." And more utilities, including our own NSTAR, are supporting the installation of independent grid-intertied systems, which provide an increasing percentage of their escalating energy demands. This "distributed generation"—many small generating sites distributed across an electricity-supply grid—means that utilities can avoid investing in new large-scale power projects: good for the planet, and good for ratepayers.

PHOTOVOLTAICS: THE BASICS

What are Photovoltaics?

Photovoltaics (PV), or solar cells as they are often referred to, are semiconductor devices that convert sunlight into direct-current (DC) electricity.

A typical silicon PV cell is a thin wafer consisting of a very thin layer of phosphorous-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. An electrical field is created near the top surface of the cell where these two materials are in contact (the P-N junction.) When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the cell is connected to an electrical load.

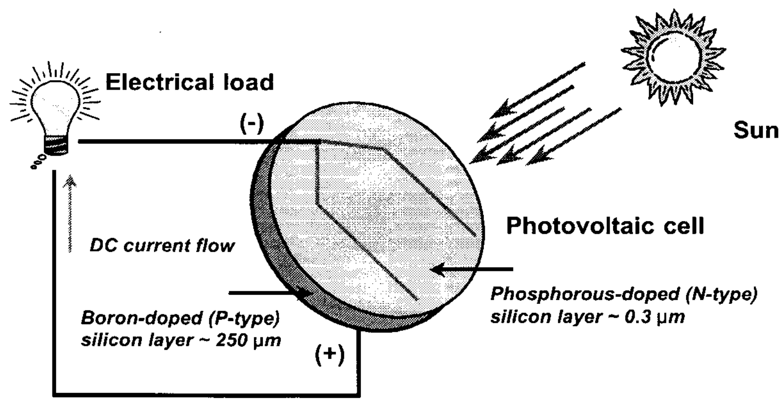

FIGURE 1. DIAGRAM OF A PHOTOVOLTAIC CELL

What is the DC output of a PV cell?

The amount of current generated by a PV cell depends on its efficiency, its size (surface area) and the intensity of sunlight striking the surface. For example, under peak sunlight conditions a typical commercial PV cell with a surface area of about 25 square inches will produce about 2 watts peak power. If the sunlight intensity were 40% of peak, this cell would produce about 0.8 watts of power.

How are PV cells configured to produce usable amounts of power?

Photovoltaic cells are connected electrically in series and or parallel circuits to produce higher voltages and/or currents.

Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building blocks of the complete PV generating unit.

Photovoltaic panels include more than one PV module assembled as a pre-wired, field-installable unit.

A *Photovoltaic array* is the complete power-generating unit, consisting of a number of PV panels.

(See the diagram on the following page.)

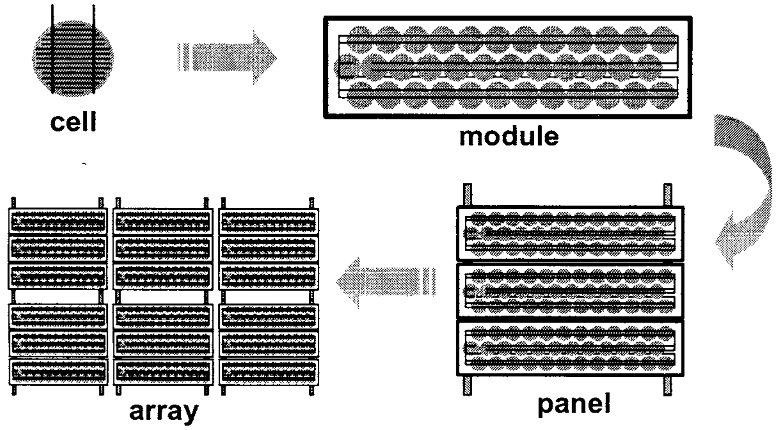

FIGURE 2. PHOTOVOLTAIC CELLS, MODULES, PANELS AND ARRAYS

The different kinds of PV cells

There are three commercial production technologies for PV cells.

For crystalline cell manufacture, 99.999% pure semiconductor-grade polysilicon processed from quartz is heated to melting temperature and trace amounts of boron are added to create a P-type semiconductor material.

Traditionally, a block of silicon is then formed using one of two methods:

1. by growing a pure crystalline silicon ingot from a seed crystal drawn from the molten polysilicon, creating *single crystals*, or

2. by casting the molten polysilicon in a block, creating a *polycrystalline* or *multicrystalline* silicon material.

Individual wafers are then sliced from the blocks. More recently a method has been developed to create polycrystalline cells by drawing up a film of molten silicon the way you create a soap bubble with a film of soapy water. Production is continuous and efficient, without the waste resulting from slicing the solid blocks, and modules made up of cells created this way are thus less costly. The individual wafers are placed in a phosphorous diffusion furnace, which creates a thin N-type semiconductor layer around the entire outer surface of the cell. Next, an anti-reflective coating is applied to the top surface of the cell, and electrical contacts are imprinted on this top (negative) surface. An aluminized conductive material is then deposited on the back (positive) surface of each cell, restoring the P-type properties of the back surface by displacing the diffused phosphorus layer. The cells are individually tested, sorted based on current output, and electrically connected to other cells to form circuits for assembly into PV modules.

3. for *thin-film* or *amorphous* PV modules the polysilicon material is vaporized and deposited in ultra-thin layers on a glass or thin stainless-steel substrate in a vacuum chamber. Laser scribing is used to separate and weld the electrical connections between individual cells in a module.

Single crystal manufacture is the oldest and most expensive technique. The same process used to manufacture transistors and integrated circuits, it is very well-developed, efficient and clean. Silicon crystals are characteristically blue, and single crystalline cells look like deep blue glass. These single crystal cells are the most efficient in converting sunlight to energy.

Multicrystalline or *Polycrystalline* manufacture is less exacting, so costs are lower. The multicrystal patterns can be clearly seen in the cell's deep blueness. These cells have slightly lower conversion efficiency compared to the single crystal cells.

Thin film manufacture costs less than crystalline manufacture but as the cells are also less efficient, more of them are required. Modules are somewhat flexible, and the technology is often used to create PV roofing shingles. While still a developing technology, thin-film PV materials offer great promise for reducing materials requirements and manufacturing costs for PV modules.

How are PV modules and arrays rated?

PV modules and arrays are wattage-rated according to their maximum DC power output under:

Standard Test Conditions (STC):1000 watts of sun power delivered per square meter of surface at 25°C (77°F) at noon on a clear day at sea level (ideal conditions rarely seen "in the field") and/or

Standard Operating Conditions (SOC): 800 watts of sun power delivered per square meter of surface at 20°C (68°F) at noon on a clear day at sea level (more closely related to field conditions.)

These ratings provide a basis of comparison among modules, although real world conditions of airborne dust, water vapor and air pollution, seasonal variations in the amount of sun striking the surface, altitude and temperature affect how much sun power your modules actually receive.

Real-world module performance

Two factors directly affect module performance: amount of full sun, and temperature.

Full sun— Modules will catch the maximum sunlight, and therefore have the maximum output, when they are perpendicular (at right angles) to the sun. Tracking the sun across the sky from east to west and seasonally from north to south will give optimum power output. Tracking mounts, however, are expensive, and are usually only cost effective on larger PV systems of eight modules and more.

In winter, modules should ideally be at the angle of your latitude plus approximately 15 degrees; in summer, your latitude minus 15 degrees. As there is more and stronger sunlight in the northern hemisphere in summer, and correspondingly less in winter, the recommended mounting angle for fixed collectors is latitude plus 15 degrees, to maximize the available winter sunlight.

Temperature— Current output from all types of modules will fade at higher temperatures and becomes a consideration at temperatures over 80°F. Conversely, all modules increase output at lower temperatures, and residential power needs typically peak in winter; it's not unusual for modules to produce 30% to 40% over specifications on clear, cold winter mornings with fresh reflective snow on the ground.

The bottom line: as a general rule of thumb, de-rate STC-rated module output by 15% if the manufacturer's specifications do not state that their ratings have already taken these factors into consideration.

GRID-CONNECTED PV SYSTEMS AND EQUIPMENT

The major components of a grid-connected system:

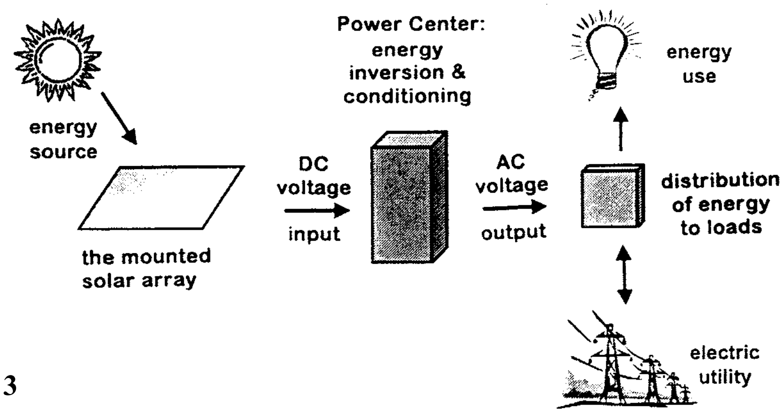

FIGURE 3

1. the *modules* making up the solar array convert the sun's energy to direct current (DC) electrical energy.
2. the *mounting system* supports the solar array at the desired angle to the sun.
3. the *power center*, custom-configured for the system, will include
   a. a low-distortion *inverter* to transform DC into the alternating current (AC) used by most of our appliances and by the utilities;
   b. an *interconnect* with incoming utility power;
   c. a *connection* to your breaker panel.
4. the *system data monitor* shows how much energy is flowing in from the energy sources and how much is flowing out to the loads.
5. the *balance of system* hardware consists of wiring, terminations, Ground Fault Interrupter, surge protections, DC and AC disconnects, etc.

COSTS, SAVINGS AND INCENTIVES

How reliable are PV modules, and what is their useful lifetime?

PV modules that meet IEEE 1262* or equivalent qualification test standards are extremely reliable products, with projected service lifetimes of 20 to 30 years. Major manufacturers offer module warranties of 20 or more years for maintaining a certain percentage of initial rated power output. It is not known how long PV modules will actually continue to produce: cells put into the nasty environment of space in the late 1960s are still functioning well; the oldest terrestrial modules installed in the early 1970s are still going strong. Keeping in mind that PV modules are only seeing six to eight hours of active use per day, we may indeed find that lifespans of 60 to 80 years are normal.

* The IEEE, Institute of Electrical and Electronic Engineers, provides defines specifications that must be met by manufacturers of electrical and electronic components.

How much would a PV system cost?

The price of PV modules, the most costly component of a solar PV system, is generally based on the peak rated power output at Standard Test Conditions. Costs range between about $4.60 per Watt for amorphous or thin-film modules and $6.90 per Watt for single crystal modules.

Roof mounts should be sturdy enough to withstand expected wind loads (remember, we have hurricanes in New England, have telescoping rear legs for easy tilt angle adjustment and adjustable leg assemblies to provide mounting to roof framing. Costs for quality aluminum and galvanized steel construction, with stainless steel fasteners are not high.

Inverters for grid-intertied systems are produced by Trace and by Advanced Energy Systems. Complete with string combiner* ground fault protection and DC and AC disconnects, these run about $1700, with a system monitor adding about $500 more.

Also to be factored in: assorted "balance of system" wiring and connectors, the safety disconnect mandated by the electric power provider, and the cost of installation.

The costs for a 1kW solar PV system would average between $6,000 and $9,000 installed.

*the string combiner assures the series-wired panels are "combined" in parallel to deliver wanted voltage.

How much would a PV system save?

Your electric bill contains a record of your monthly kilowatt-hours of electricity use for the preceding year. We know that residential usage typically peaks in winter. If your average monthly use in winter (an average of the months December through February, for Cape Cod and the Islands) is 524.5 kilowatt hours, average daily use would be 17.5 kilowatt hours, or 17,500 watt-hours per day:

524.5 kWh ÷ 30 days = 17.5 kWh/day

Next we need to know the available sunlight for that period, and the insolation (received solar radiation) charts for Boston latitude plus 15° show an average of 3.3 peak sun hours per day. If we divide our 17,500 watt-hours of usage per day by the 3.3 peak sun hours we find we need to provide 5,303 watts, or 5.3 kilowatts:

17,500 Wh ÷ 3.3 winter peak sun hrs = 5,303 peak watts required

A 1 kilowatt solar PV system would thus provide approximately 19% of the electricity requirements of this residence, in winter, with peak household load requirements, and with worst-case sunlight availability. The percentage of usage provided during the other nine months of the year would be greater, and the percentage of solar generated electricity being net-metered back to the electric company during the other nine months would also be greater.

The electric power provider (NSTAR here on the Cape & Islands) pays you for your solar-generated electricity at the same rate they for the electricity they purchase elsewhere (*not* including the costs of transmission and maintenance.) Given the year-long amount of sun-generated electricity, the amount used by the household and the amount net-metered back to the grid, it is estimated that a household averaging 500 kWh per month can save approximately 25% of its electricity costs with a 1 kW PV system. With smaller average monthly usage, the savings would be correspondingly greater.

Using your own usage figures, you can easily determine how much of your electric load would be covered by a solar PV system and how much you would be saving in terms of direct expenses. It's important to keep in mind that every watt of energy supplied by the sun is a watt that does NOT cost you in terms of your health care, your disposable income, the strength of your local economy, or your children's future.

Federal Tax Incentives

(Consult the pertinent tax codes and/or a certified public accountant or tax attorney to determine exact eligibility.)

For Businesses:

1. *Modified Accelerated Cost Recovery System* (26 USC Sec. 168.)
A 5-year (as opposed to 20-year) accelerated depreciation schedule for all photovoltaic and solar thermal equipment.

2. *Business Energy Tax Credit* (26 USC Sec. 168.)
Tax credit up to 10% can be taken on purchase and installation of photovoltaics and solar thermal equipment when income tax forms are filed.

3. *Business Rebate Tax Exemption*
Only 35% of the value of utility rebates, for solar systems (photovoltaics and solar thermal) and appliances, is taxable.

For Residences:

Residential Rebate Tax Exemption (Energy Policy Act of 1992.)
The rebates received for residential solar systems (photovoltaics and solar thermal) and energy efficient appliances are not taxable.

Massachusetts Tax Incentives

Residential State Income Tax Credit

Massachusetts provides an income tax credit for individuals who install solar or wind-powered renewable energy systems in their residences. The credit is 15% of the net expenditure for the system, including installation, or $1,000, whichever is less. You will need Massachusetts Tax Form Schedule EC.

Residential State Sales Tax Exemption

The sale of equipment directly relating to any solar, wind or heat pump system to be used as a primary or auxiliary power system for heating or otherwise supplying the energy needs of a person's principal residence is exempt from the state sales tax. (See Massachusetts Tax Form ST-12.)

Local Property Tax Exemption

A taxpayer who installs a solar or wind-powered system for heating or otherwise supplying the energy needs of his/her residence or business is eligible for an exemption from local property tax. *This exemption applies to the value added to the property by the installed system, and is not an exemption for the full amount of the property tax bill*. The exemption is good for 20 years from the date of the installation.

MASSACHUSETTS PERMITTING REQUIREMENTS

According to the 1997 Massachusetts Electric Utility Restructuring Act, your local utility (NSTAR for the Cape and Vineyard, Nantucket Electric for Nantucket) must have six months notice of a customer's plans to install on-site cogeneration equipment.

The procedure is roughly as follows: the customer advises both the Department of Telecommunications and Energy and the utility of intent to install a grid-connected PV system, and requests an initial site inspection. The installation design can be submitted at this time or when the inspection is made, usually done within 45 days. Within 1 or 2 weeks, the utility will give an estimate of any costs for any necessary equipment on the utility side of the meter, and may specify design changes. Upon installation, the utility will visit to ascertain design specifications have been met, and approve startup.

Your local codes will probably require local permitting for rooftop installation, and design approval and inspection by the electrical inspector.