NORTH CAROLINA
SOLAR CENTER

SOLAR CENTER INFORMATION

NCSU • Box 7401 • Raleigh, NC 27695 • (919) 515-3480 • Toll Free 1-800-33-NC SUN

Photovoltaics: Electricity from the Sun

INTRODUCTION

Making electricity without adversely affecting the environment may seem like a dream too good to come true. However, through the use of photovoltaics (PV), sunlight can be converted directly into electricity. No fluids or moving parts are involved.

Solar photovoltaics are made of semiconductor materials that produce voltage and current when exposed to sunlight. These semiconductor materials are made into PV cells. The electricity generated by PV cells is direct current (DC) like that produced by batteries. As more light falls on a cell, more electricity is generated; therefore, a PV system *must not* be shaded (i.e. by shadows, snow, or wet leaves) because such shading can substantially reduce performance.

A typical PV cell made of crystalline silicon is 12 centimeters in diameter and 0.25 millimeters thick. In full sunlight, it generates 4 amperes of direct current at 0.5 volts or 2 watts of electrical power. PV modules consist of PV cells connected in series (to increase the voltage), and in parallel (to increase the current), so that the output of a PV system can match the requirements of the load to be powered. If more power is required, modules can be appropriately connected in series or parallel to form what is called a PV array (see Figure 1). Thin film PV cells are newer forms of PV with different semiconductor materials, geometries, and dimensions but the series and parallel connection of thin film cells and modules is similar to crystalline PV.

The energy output of a PV system can be increased by having the PV modules track the sun as it moves across the sky on a daily basis instead of being fixed in one orientation. Tracking arrays work well with certain applications such as direct PV water pumping. Most tracking systems require climates with a high fraction of direct beam versus diffuse sunlight to work well. Climates with high humidity have lower fractions of direct beam sunlight. The added complexity, maintenance and costs of tracking arrays needs to be compared with the increased energy benefit of tracking arrays in order to make an informed decision of which type of array, fixed or tracking, is the best option for each PV application.

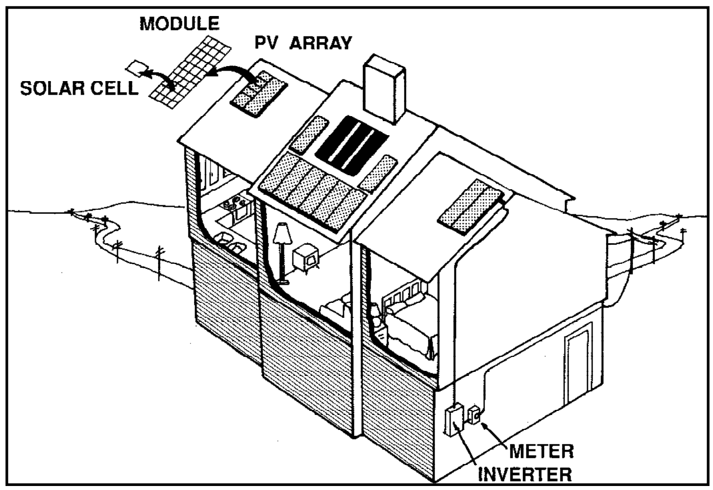

Figure 1. Residential Photovoltaic System

TYPES OF PV SYSTEMS

Stand-Alone PV Systems

PV installations not connected to a utility power line are referred to as “stand-alone systems.” The two basic types of stand-alone systems are: (1) direct systems, which utilize the PV electricity as it is produced, and (2) battery storage systems, which have the capability of storing PV generated electrical energy for use when the sun is not shining. Some stand-alone systems with battery storage include a DC to AC inverter to allow alternating current (AC) appliances to be used. AC appliances are generally cheaper and more readily available. Figure 2 shows the basic layout of a stand-alone system with battery storage and both AC and DC circuits.

State Energy Office
Energy
North Carolina
Department of Administration

INDUSTRIAL EXTENSION SERVICE
IES

NC STATE UNIVERSITY
College of Engineering

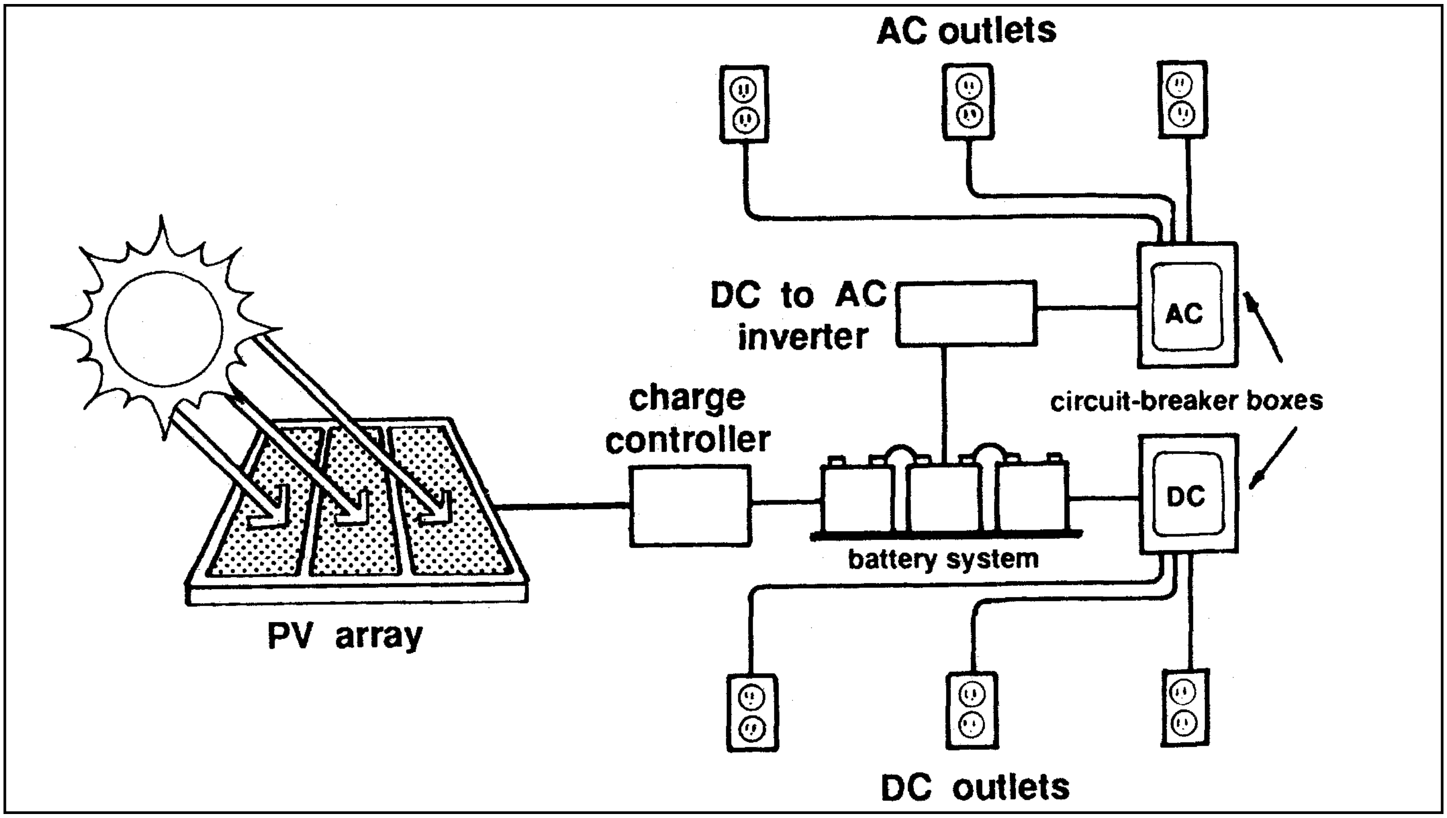

Figure 2. Stand-Alone PV System

An example of a direct system is a water pumping facility which pumps water during the (sunny) day to a storage tank for later use. A battery storage system, on the other hand, stores PV electricity in a battery to power an electrical device (e.g., a light , a pump) even when the sun is not shining.

The range of applications for stand-alone systems is tremendous. Whenever the economics of providing electricity from the utility grid are in question, photovoltaics should be considered. Examples of situations where the economics of grid power are in question are (1) when the utility monthly facilities charge (meter charge) is a majority of a monthly electric bill, (2) when electricity is needed far away from a utility distribution line or (3) where hard surfaces such as parking lots or sidewalks are between a proposed electrical load and a utility connection.

For remote or portable large power needs (greater than 500 watts), it has been common to use gasoline, propane, or diesel powered generators. Associated with this option is the high cost of maintenance, as well as the purchase and transportation of fuel. With low maintenance costs and no fuel requirements, PV is an ideal source of power for remote or portable applications.

It is also possible to couple a PV system with a fossil-fuel generator. In this type of system, the generator is used to recharge the PV battery system during long periods of cloudy weather. This "hybrid" system requires much less fuel and maintenance for the generator, while extending battery life.

Utility-Interactive Systems

Unlike stand-alone systems, utility-interactive systems are connected to the electrical utility grid. These systems are typically located on residential or commercial buildings. The house pictured in Figure 1 has a utility-interactive PV system. Figure 3 shows the basic layout of a utility-interactive system. These systems have a PV array that supplies power to the building through a high quality inverter. This inverter converts PV-generated DC electricity to AC electricity compatible with the utility grid. This AC electricity is supplied to the main electrical service of the building, offsetting the purchase of power from the utility grid. When the PV system is not generating as much power as the building is using, the utility grid provides the additional needed power. When the PV system is generating more power than the building is using, excess power is sold into the utility grid.

Selling power back to an electric utility may not be as attractive as it sounds. Some utilities meter electrical energy purchased and sold separately. Customers pay a retail rate for electricity purchased from the utility but are paid a lower avoided cost (wholesale) rate for electricity sold to a utility. There is usually a significant difference between these two rates. Under current conditions, it is much more cost effective to use a PV system to displace the need for utility power than to generate revenue with it. Until photovoltaic power becomes cheaper relative to utility power, utility-interactive systems should be sized so that very little power has to be sold back to the utility.

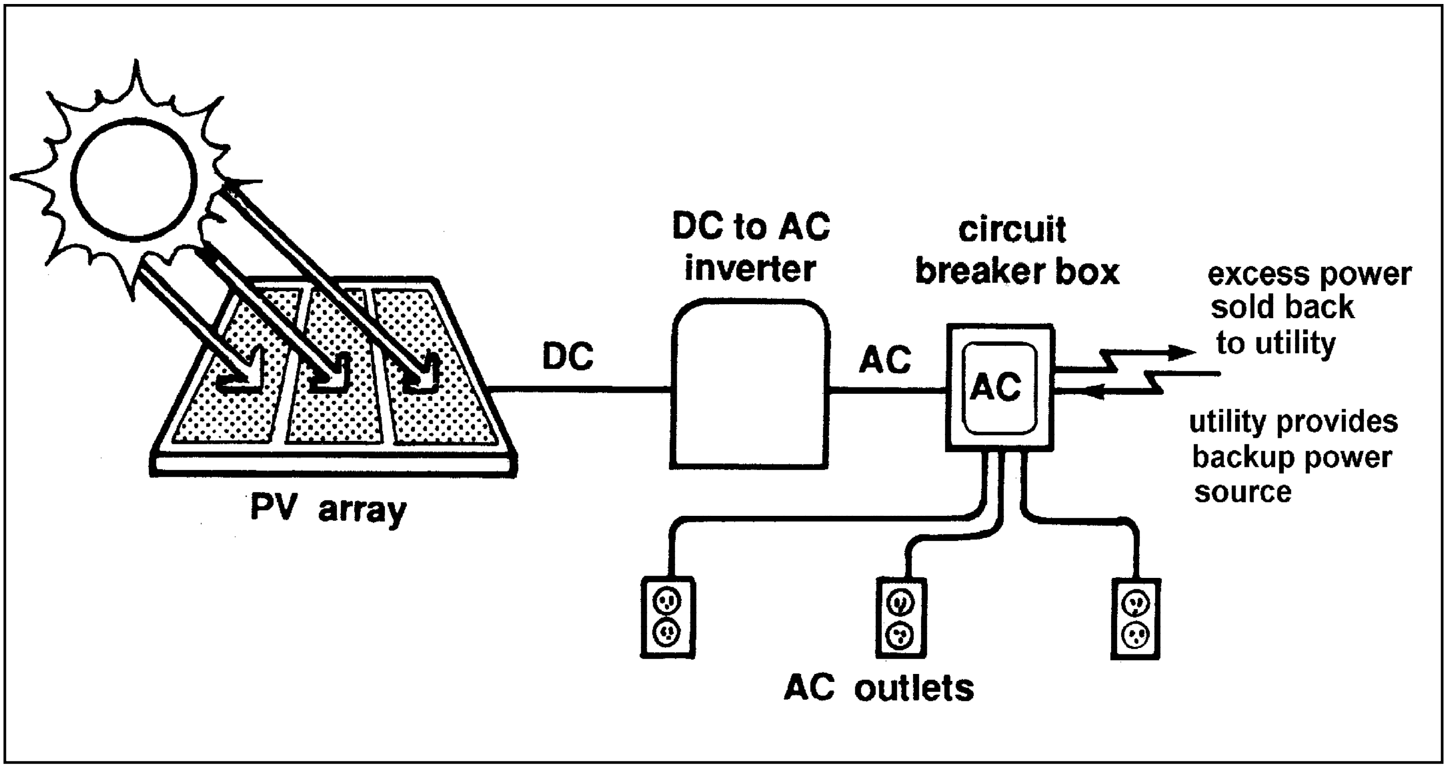

Figure 3. Utility-Interactive System

A major benefit of utility-interactive PV is that it can be widely distributed. This asset will lead to the installation of many small scale "distributed generation" power plants located on buildings. Over time, this could reduce the need for additional large centralized power plant construction and costly utility grid distribution network expansion. The nature of distributed generation can increase national energy security by increasing the number of power plants that would have to be targeted in order to shut down the national utility grid. Other examples of distributed generation technologies are wind turbines, fuel cells and micro turbines.

Another benefit of utility-interactive PV systems is that they produce electrical power when the sun is shining strongest and the electrical utility grid needs it the most. They produce the most electrical power when the demand on the electrical utility grid is highest due to building air conditioning. This benefit is currently not well rewarded but may be in the future through the use of solar load control devices, demand management systems and real time pricing scenarios.

PHOTOVOLTAIC SYSTEM SIZING AND APPLICATIONS

PV Module Electrical Power

PV modules power is rated by peak approximate DC power output at standard testing conditions (STC). STC are laboratory test conditions and are very different from the conditions that the modules will see when operating in the sun. These conditions are solar intensity of 1,000 watts per square meter (317 BTU/hr-ft^2) and a module temperature of 25ºC (77ºF). Actual operating conditions on a sunny day may be solar intensity of 800 Watts per square meter (254 BTU/hr-ft^2) and module temperature of 50ºC (122ºF). PV module power is proportional to solar intensity so it will be less than rated at lower solar intensity levels. Also, PV module power is reduced as the operating temperature increases. Typically, PV module power is reduced by about 5% for every 10ºC (18ºF) increase in operating temperature above STC temperature. Failure to consider this reduction could cause major design errors.

Solar Resource

During July in North Carolina, there are 14 hours between sunrise and sunset. Much of that time the sun does not shine at peak intensity (1,000 Watts/m^2) because clouds, haze and the atmosphere reduces solar intensity. The solar intensity seen by a PV array is reduced when the sun's rays are not perpendicular to the surface. To estimate the output of a PV system, we use “peak sun hours” which is the number of hours the sun would had to have shone at peak intensity on a PV array to equal the amount of radiation that was actually received by the array during the day. This value is often reported as kilowatt-hours per square meter (kWh/m^2). Thus, a PV array receiving solar radiation of 7 kWh/m^2 per day has received the equivalent of 7 hours of sunshine at peak conditions (i.e., 7 peak sun hours).

Tables 1 and 2 show the average daily peak sun hours on a monthly basis for fixed (Table 1) and tracking (Table 2) arrays for the Raleigh-Durham area.

PV Module Electrical Energy Generation

To estimate the energy that a PV module will produce, we have to multiply module power and time. The power is not the STC power rating but instead is the expected power at actual operating conditions.

In the summer under full sun, it is not uncommon for a PV module to operate at 55ºC (131ºF), reducing its power by 15%. Following is an example calculation of the expected daily generation of 100 Watt PV module in June.

Example: 100 Watt module in Raleigh, NC.

Orientation: South facing
Tilt: 35º from horizontal
Operating Temperature: 55ºC
Solar Resource (June): 5.7 hr.
Energy Produced (June):
(100 Watts)*(5.7hr)*85% = 485 W-hr/day

The 85% comes from a 15% power reduction due to operating temperature.

Month	Latitude	Latitude - 15º	Latitude + 15º
JAN	3.8	3.4	4.1
FEB	4.5	4.1	4.6
MAR	5.2	5.0	5.1
APR	5.7	5.8	5.3
MAY	5.7	6.0	5.0
JUN	5.7	6.2	4.9
JUL	5.6	6.0	4.9
AUG	5.5	5.7	5.0
SEP	5.2	5.1	5.0
OCT	4.9	4.6	5.0
NOV	4.1	3.7	4.3
DEC	3.6	3.1	3.8
AVG	5.0	4.9	4.8

Table 1: Solar Availability in Raleigh-Durham, NC for South Facing, Fixed Array (kWh/m^2)

	One Axis Tracking North South Axis			Two Axis Tracking
Month	Latitude Tilt	Latitude - 15º	Latitude + 15º	
JAN	4.5	4.1	4.7	4.7
FEB	5.5	5.2	5.6	5.6
MAR	6.5	6.4	6.5	6.6
APR	7.5	7.5	7.2	7.5
MAY	7.4	7.6	7.0	7.7
JUN	7.5	7.8	7.0	8.0
JUL	7.2	7.5	6.7	7.6
AUG	6.9	7.0	6.5	7.1
SEP	6.4	6.4	6.3	6.5
OCT	6.0	5.8	6.1	6.1
NOV	4.9	4.5	5.0	5.1
DEC	4.2	3.8	4.4	4.4
AVG	6.2	6.1	6.1	6.4

Table 2: Solar Availability in Raleigh-Durham, NC for South Facing Tracking Arrays (kWh/m^2)

Battery Sizing

Stand-alone PV systems typically require high quality “deep-cycle” batteries, such as those used in fork lift or golf cart applications. Automobile batteries are not designed to be deeply discharged and will wear out in just a few months in a typical stand-alone PV application. Deep cycle batteries are usually rated by the number of “amp-hours” (AH) available from full charge to total discharge at a specified rate of discharge while automobile batteries are rated in “cold cranking amps” (CCA).

When a battery stores electricity, it loses energy in the form of heat. A typical “turn-around” efficiency for a deep-cycle battery is 70%. This implies that for every 100 AH of energy stored in a battery, only 70 AH can be recovered.

If all the energy generated by a PV system is to be used during non-solar hours, the system sizing must reflect the 30% loss inherent in battery operation. However, if half of the load is carried directly by the PV modules during the day, the system output need only be discounted by 15%.

The amount of energy that a battery can provide to a load is affected by its rate of discharge. For example, a typical 12 volt deep-cycle battery may have a capacity rating of 100 AH when discharged over 20 hours (i.e., at a discharge rate of 5 amperes). If the discharge rate is reduced to 1 ampere, it may be possible to receive 120 AH from the same 100 AH (i.e., a discharge period of 120 Hours).

Battery capacity (AH) can be converted to stored energy (watt-hours) by simply multiplying the battery voltage by the AH rating. Thus, a 12 volt, 100 amp-hour battery is capable of providing 1,200 watt-hours or 1.2 kWh of energy.

Since batteries are relatively expensive, prolonging battery life is an important aspect of PV system operation.

This is best achieved by discharging the battery only slightly before recharging. Good system design suggests that a battery system be sized so that the daily load does not discharge the battery more than 20%. In the event of an extended cloudy period, the battery should never be discharged more than 80%. Stand-alone systems with battery storage need a good quality *charge controller* to insure that the battery is never over-charged. To prevent the battery from being overly discharged, a *load controller* should be used. Some charge controllers have a built in load controller. Both extremes, over charge and over discharge, can cause permanent damage to a battery.

Battery autonomy refers to the length of time a fully charged battery system can maintain operation of its electrical loads without input from the PV system. In some critical applications, it may be necessary to provide up to seven or eight days of autonomy to insure that the load will never be without power. This typically requires a large (expensive) battery bank. Many applications are not nearly this critical, with two or three days of battery autonomy being sufficient.

Sample Applications

The following are just a few examples of applications that have been powered with photovoltaics:

- On grid Residential and Commercial Buildings
- Off Grid Buildings
- Water Pumping
- Cathodic Protection
- Navigational Signals
- Communications Equipment
- Sign and Area Lighting
- Fence Electrification
- Call Boxes
- Recreational Vehicle Appliances
- Vehicle Battery Charging

A brief description of two PV system designs is provided below. These examples are only intended to demonstrate system configurations and should not be used as a basis for system design. In order to effectively design a system, it is essential to undertake a course of study in PV.

<u>Application 1: Remote Cabin Electrification:</u>

Appliance	Daily Hours of Use	Wattage
4 Fluorescent Lights	4	28
1 Incandescent Light	2	50
1 DC Refrigerator	5	80
1 Portable Stereo System	2	30

Total Power Required: 1,008 watt-hours
Month of Greatest Use: July
Array Tilt: latitude, 35º
Orientation: South facing
Peak Sun Hours: 5.6 per day
Battery Losses: 15%
PV Power Requirements: Five 50 Watt PV modules
Battery Requirements: Four 12V 100 AH batteries
Days of Battery Autonomy: Two Days of No Sun
Max. Battery Depth of Discharge: 44%
Max. Daily Depth of Discharge: 22%

Electrical Energy Generated by PV System:
[(5.6 peak sun hours)*(50 watts/module)*(5 modules)]
-(15% temperature effect)-(15% battery losses)
= 1,012 watt-hours

Note: If this cabin were to be used in December, the system would need eight 50 Watt PV modules rather than five. If AC appliances were used, the PV array would have to be increased by 20% to reflect an 85% inverter efficiency.

<u>Application 2: Residential Utility-Interactive PV System:</u>

A 1,500 square foot residence with gas water heating and an electric heat pump uses 6,000 kWh of electricity per year. The home has a roof mounted utility-interactive PV system with an array STC rating of 2,500 Watts. The system does not have battery backup.

Array Tilt: latitude, 35º
Location: Raleigh, NC
Array Orientation: South Facing
Annual Average Peak Sun Hours: 5 per day

Electrical Energy Generated by PV System:
(2.5 kW STC)*(0.65 kW AC/ kW STC)*(5 peak sun hours/day)*(365 days/year)
= 2,966 kWh/year

PV Generation as Percentage of Annual Household Electrical Use: 50%

New Developments

There are some exciting new developments that are making PV systems more attractive in residential and commercial buildings and other applications.

One idea that is growing more popular is building-integrated PV where the PV is built into a building's roof and walls, displacing building materials. These installations can be much more attractive than more traditional installations. Several building integrated PV products already exist including PV metal roofing, PV roof tiles, PV curtain wall systems and PV atrium glass.

Another new development is the "AC module." AC modules have small inverters mounted on the back-side of the PV module to immediately convert PV generated DC electricity to AC. These modules are simply wired to the electrical service panel of the building. AC modules can simplify wiring and reduce installation costs.

Many of the new PV products are using thin film PV. Thin film PV cells are manufactured using vapor deposition, sputtering and other thin film processes that allow very thin layers of semiconductor PV materials to be produced. Because these PV cells are so thin, they can be made as flexable modules that conform to curved surfaces or be used in ways that rigid chystalline PV cells can not. The amount of semiconductor material used to produce thin film PV is far less than that used to produce crystalline PV. Because less material is used, thin film PV can be produced faster and cheaper than crystalline PV. Currently, thin film PV modules have lower sunlight to energy conversion ratios than crystalline PV, but that may change as more advanced thin film PVs are developed.

CONCLUSION

The ability to generate electricity wherever the sun shines is a capability unique to photovoltaics. As the value of this capability is better understood, the market for PV will grow significantly. Over the last 25 years, the cost of PV modules has dropped from $100 to $4 per peak watt. This, combined with newer electrical technologies, has resulted in the development of hundreds of thousands of electrical systems that are now powered by PV. As developments are continually made, this truly unique power source is sure to play a significant role in our energy future.

This publication is available for download and printing from the list of information factsheets on the NC Solar Center's web-site at www.ncsc.ncsu.edu. To reduce paper waste, this publication was not mass reproduced in hardcopy. Printed copies can be mailed to those who do not have access to the Internet.

NORTH CAROLINA
SOLAR CENTER

North Carolina Solar Center
Box 7401, NCSU, Raleigh, N.C. 27695-7401
(919) 515-3480, Toll free in N.C.: 1-800-33-NC SUN
Fax: (919) 515-5778
E-mail: ncsun@ncsu.edu
Web: www.ncsc.ncsu.edu

State Energy Office
Energy
North Carolina
Department of Administration

State Energy Office, N.C. Department of Administration
1340 Mail Service Center, Raleigh, NC 27604-1340
Phone: (919) 733-2230, Fax: (919) 733-2953
Toll free in N.C.: 1-800-662-7131
E-mail: Doa.Energy@ncmail.net
Web: www.energync.net

The NC Solar Center is sponsored by the State Energy Office, NC Department of Administration, and the US Department of Energy, with state Energy Program funds, in cooperation with North Carolina State University.