Photovoltaic Development Assessment

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PHOTOVOLTAIC DEVELOPMENT ASSESSMENT

This course covers the assessment of potential photovoltaic developments including a technology history and a detailed description of the computation methodology.

Photovoltaic History

The world-wide requirement for solar electric energy schemes has enhanced steadily over the last 20 years. The requirement for reliable and low cost electric energy in isolated areas of the world is the primary force driving the world-wide photovoltaic (PV) industry today. For a big number of applications, PV technology is simply the least-cost option. Typical applications of PV in use today include stand-alone energy schemes for cottages and remote residences, navigational aides for the Coast Guard, remote telecommunication sites for utilities and the military, water pumping for farmers, and emergency call boxes for highways and college campuses.

Requirement for cost effective off-electricity network energy schemes, environmental and longer-term fuel supply concerns by governments and electric utilities are beginning to help accelerate the market for demonstration programs for PV schemes connected to central electric electricity networks in industrialised countries.

This course defines photovoltaic schemes (PV modules, batteries, energy conditioning, electric generators, and pumps) and discusses the photovoltaic markets including on-electricity network, off-electricity network and water pumping applications.

Description of Photovoltaic Schemes

The primary article of commerce in the PV market is the PV module. PV modules are sized on the basis of the energy provided under Standard Testing Circumstances (STC) of 1 kW/m² of sunshine and a PV cell temperature of 25 degrees Celsius (°C). Their generation measured under STC is showed in terms of “peak Watt” or Wp nominal capacity. Note that annual industry shipments of 165 MWp indicates that PV producers made modules with the ability to generate 165 MWp of electric energy (nameplate capacity) under STC of 1 kW/m² of sunshine, 25°C cell temperature, and an air mass of 1.5.

PV modules are sized for schemes designed for specific applications. The elements added to the module constitute the “balance of scheme” or BOS. Balance of scheme elements can be classified into four categories:

- Batteries - store electricity to provide energy on requirement at night or on overcast days;
- Inverters - required to convert the DC energy generated by the PV module into AC energy;
- Controllers - manage the energy storage to the battery and deliver energy to the load; and
- Structure - required to mount or install the PV modules and other elements.

Not all schemes will require all these elements. For example in schemes where no AC load is present an inverter is not required. For on-electricity network schemes, the utility electricity network acts as the storage medium, and batteries are not required. Batteries are typically not required for PV water pumping schemes, where a water reservoir “buffers” short-term requirements and supply differences. Some schemes also require other elements which are not strictly related to photovoltaic. Some stand-alone schemes, for example, include a fossil fuel generator that provides electricity when the batteries become depleted; and water pumping schemes require a DC or AC pump.

PV modules

To make modules, PV producers use crystalline silicon wafers or advanced thin film technologies. In the former, single crystal silicon (single-Si), polycrystalline silicon (poly-Si) or ribbon silicon (ribbon-Si) wafers are made into solar cells in production lines utilizing processes and machinery typical of the silicon semiconductor industry.

Solar cell producers then assemble the cells into modules or sell them to module producers for assembly. Because the first important applications of PV involved battery charging, most modules in the market are designed to deliver direct current (DC) at slightly over 12 Volts (V). A typical crystalline silicon module consists of a series circuit of 36 cells, encapsulated in a glass and plastic packet for protection from the environment. This packet is framed and provided with an electrical connection enclosure, or junction box. Typical conversion (solar energy to electrical energy) efficiencies for common crystalline silicon modules are in the 11 to 15% range.

There are four advanced thin film technologies. Their names are deducted from the active cell materials: cadmium telluride (CdTe), copper indium diselenide (CIS), amorphous silicon (a-Si) and thin film silicon (thin film-Si). Amorphous silicon is in commercial production while the other three technologies are slowly reaching the market. Thin film modules are made directly on the substrate, without the requirement for the intermediate solar cell fabrication step.

Some producers are developing PV modules that concentrate sunshine onto small area high efficiency PV cells using lenses. The concept here is that the lens material will be less expensive per unit area than conventional silicon modules thus resulting in a $/Wp advantage. To ensure that the concentrating lenses are always focused on the PV cells, these modules must always be focused at the sun and therefore must be applied in conjunction with sun trackers. These modules are fixed to areas of the world where there is a considerable amount of direct beam sunshine, such as in desert areas.

Batteries

If an off-electricity network PV scheme must provide energy on requirement rather than only when the sun is shining, a battery is required as an energy storage device. The most common battery types are lead-calcium and lead-antimony. Nickel-cadmium batteries can also be applied, in particular when the battery is subject to a wide range of temperatures. Because of the variable nature of solar radiation, batteries must be able to go through many cycles of charge and discharge without damage. The amount of battery capacity that can be discharged without damaging the battery depends on the battery type. Lead-calcium batteries are suitable only in “shallow cycle” applications where less than 20% discharge occurs each cycle. Nickel-cadmium batteries and some lead-antimony batteries can be applied in “deep cycle” applications where the depth of discharge can exceed 80%.

Depending on site circumstances, and on the presence of a backup generator, battery banks are sized to provide a period of scheme autonomy ranging from a few days to a couple of weeks (in some very specific applications such as schemes above the arctic circle). Batteries are characterized by their voltage (which for most applications is a multiple of 12 V) and their capacity (expessed in Ampere-hours (Ah)). For example a 50 Ah, 48 V battery will store 50 × 48 = 2,400 Wh of electricity under nominal circumstances.

Note that optimizing battery size is vital in getting good battery life, suitable scheme performance and optimal scheme life-cycle prices. Unnecessary battery replacement is costly, particularly for remote applications.

Energy conditioning

Several electronic devices are applied to control and modify the electrical energy generated by the photovoltaic array. These include:

- Battery charge controllers - regulate the charge and discharge cycles of the battery;

- Maximum energy point trackers (MPPT) - maintain the operating voltage of the array to a value that maximises array generation;

- Inverters - convert the direct current (DC) generation of the array or the battery into alternating current (AC). AC is required by many appliances and motors. It is also the type of energy applied by utility electricity networks and therefore on electricity network schemes which always require the use of an inverter; and

- Rectifiers (battery chargers) - convert the AC current generated by a generator into the DC current required to charge the batteries.

Electric generators

For off-electricity network applications it is also possible to have both a photovoltaic scheme and a fossil fuel generator running in parallel. The use of a generator eliminates the requirement to oversize the photovoltaic array and the battery bank in order to provide energy during periods with little sunshine. The photovoltaic array and the generator supplement each other, the PV array reduces the fuel use and maintenance cost of the generator, and the generator replaces the part of the photovoltaic scheme that would require to be oversized to ensure an uninterrupted provision of energy.

Electric generators can use a variety of fossil fuels, such as gasoline, diesel, propane or natural gas. The requirement for a generator, and the fraction of the load met respectively by the photovoltaic scheme and the generator, will depend on many factors, including the capital cost of the PV array, operating prices of the generator, scheme reliability, and environmental considerations (e.g. noise of the generator, emission of fumes, etc.).

Pumps

For water pumping applications, several types of pumps may be applied. They can be categorized according to their design type (rotating or positive displacement pumps), to their location (surface or submersible), or to the type of motor they use (AC or DC). Rotating pumps (e.g. centrifugal pumps) are typically preferred for deep wells or boreholes and big water requirements. The use of displacement pumps is typically fixed to low amounts. Positive displacement pumps (e.g. diaphragm pumps, piston pumps and progressive cavity pumps) typically have good lift capabilities but are less accessible than surface pumps and are more sensitive to dirt in the water. Figure 1, suggests possible pump choices as a function of the head (total height the water has to be lifted) and the daily water requirement.

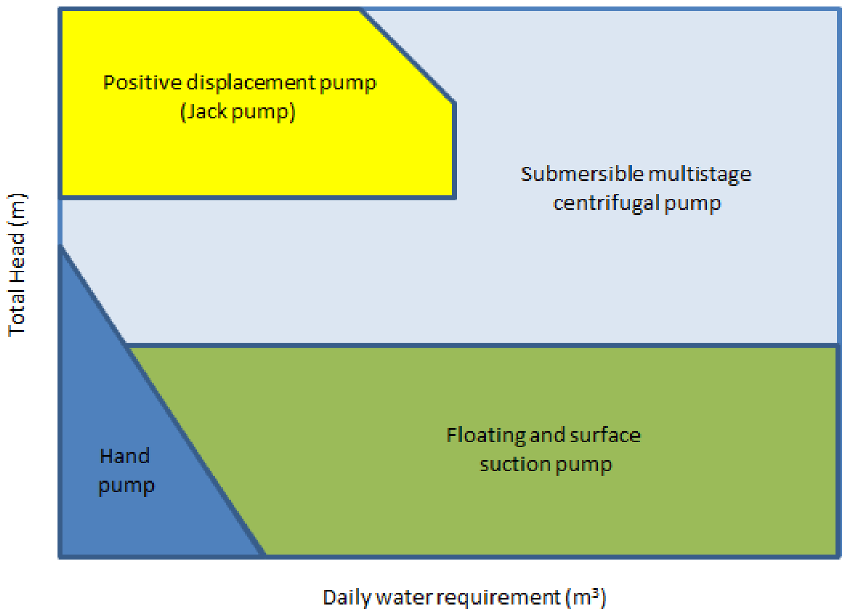

Figure 1. Pump type selection

Finally the choice between a DC and an AC motor to drive the pump will depend on many factors, including price, reliability and technical support available. DC motors are typically very efficient and are easier to match with the photovoltaic array. AC motors, on the other hand, are cheaper and more readily available, but they require an inverter to be connected to the array.

Photovoltaic Application Markets

Photovoltaic markets can be classified based on the end-use application of the technology. The most common PV developments are off-electricity network applications. Water pumping also redelivers an important application of PV, particularly in developing countries. The biggest long-term market potential for PV, in volume of sales, is with on-electricity network applications.

On-electricity network applications

In electricity network-connected applications, also called “On-electricity network” applications, the PV scheme feeds electrical energy directly into the electric utility electricity network (this includes central-electricity networks and isolated electricity networks). Two application types can be distinguished, distributed and central energy plant generation. An example of a distributed electricity network-connected application is building integrated PV for individual residences or commercial buildings. The scheme size for residences is typically in the 2 to 4 kWp range. For commercial buildings, the scheme size can range up to 100 kWp or more. Batteries are not necessary when the scheme is electricity network-connected. Another application is the installation of “PV electric generators” by utilities at energy substations and “end-of-line” sites. These applications can be on the threshold of cost competitiveness for PV, depending on the location.

The advantages of electricity network-connected PV energy generation are usually evaluated based on its potential to reduce prices for energy production and generator capacity, as well as its environmental advantages. For distributed generation, the electric generators (PV or other) are located at or near the site of electrical consumption. This helps reduce both energy (kWh) and capacity (kW) losses in the utility distribution network. In addition, the utility can avoid or delay upgrades to the transmission and distribution network where the mean daily generation of the PV scheme matches with the utility’s peak requirement period (e.g. afternoon peak requirement during summer months due to air conditioning loads). PV producers are also developing PV modules which can be utilized into buildings as standard building elements such as roofing tiles and curtain walls. This helps reduce the relative cost of the PV energy scheme by the cost of the conventional building materials, and allows the utility and/or building owner to capture distributed generation advantages. The use of PV in the built environment is expanding with demonstration developments in industrialized countries.

Central generation applications are not currently cost-competitive for PV. Several multi-megawatt central generation schemes have however been installed as demonstration developments, designed to help utilities acquire experience in the management of central PV energy plants. Installations of central PV generation, like distributed electricity network connected PV, represent a long-term strategy by governments and utilities to support the development of PV as a clean energy with a guaranteed fuel provision.

Off-electricity network applications

Currently, PV is most competitive in isolated sites, away from the electric electricity network and requiring relatively small amounts of energy, typically less than 10 kWp. In these off-electricity network applications, PV is usually applied in the charging of batteries, thus storing the electrical energy generated by the modules and providing the user with electrical energy on requirement.

The key competitive arena for PV in remote off-electricity network energy applications is against electricity network extension; primary (disposable) batteries; or diesel, gasoline and thermoelectric electric generators. The cost of electricity network extension in the US, calculated by the Utility Photovoltaic Group (UPVG) ranges from $20,000 to $80,000 per mile. Thus, PV competes particularly well against an electricity network extension for small loads, far from the utility electricity network. Compared to fossil fuel, electric generators and primary batteries, the key advantage of PV is the reduction in operation, maintenance and replacement prices; these usually result in lower life-cycle prices for PV schemes.

Off-electricity network applications include both stand-alone schemes and hybrid schemes, which are similar to stand-alone schemes but also include a fossil fuel generator to meet some of the load requirements and provide higher reliability.

Water pumping applications

Photovoltaic water pumping is one of the most common PV applications around the world, with thousands of photovoltaic-energized water pumps installed both in industrialized and developing nations. Typical PV water pumping applications include domestic water, water for campgrounds, irrigation, village water supplies and livestock watering. PV pumps are increasingly applied for intermediate sized pumping applications, filling the gap between small hand pumps and big engine-energized schemes and increasingly replacing mechanical wind pumpers. In water pumping applications, water pumped during periods of sunshine can be stored in a tank for future use, making the use of batteries usually unnecessary. PV water pumping schemes are relatively simple, require little maintenance, and provide independence from fossil fuels. They are usually the scheme of choice for locations far from the utility electricity network (e.g. ranches) or for settings where the electricity network is non-existent and water resources scarce (e.g. developing countries). There is also a good synergy between irrigation and PV water pumping as the water requirements by the plants and the solar availability match (e.g. during the “rainy season” less sun is available, but less irrigation and water pumping is required).

Photovoltaic Development Modelling

The photovoltaic development model can be applied to evaluate the energy production and financial performance of photovoltaic developments, from small-scale water pumping schemes to intermediate residential off-electricity network schemes to big electricity network-connected schemes, anywhere in the world. There are three basic applications that can be evaluated with the PV model:

- On-electricity network applications, which cover both central-electricity network and isolated-electricity network schemes;

- Off-electricity network applications, which include both stand-alone (PV-battery) schemes and hybrid (PV-battery-generator set) schemes; and

- Water pumping applications, which include PV-pump schemes.

To help the user characterize a photovoltaic scheme before evaluating its cost and energy performance, some values are suggested for component sizing. Calculated values are based on input parameters and can be applied as a first step in the assessment and are not necessarily the optimum values.

This course defines methodology applied to compute, on a month-by-month basis, the energy production of PV schemes. A flowchart of the algorithms is displayed in Figure 2. The basics of solar energy that are covered in the following sections define the tilted radiation computation algorithm which is common to all three application models (i.e. on-electricity network, off-electricity network and water pumping applications). It is applied to compute solar radiation in the plane of the PV array as a function of its orientation, given monthly mean daily solar radiation on a horizontal surface. The following sections present the photovoltaic array model which computes PV array energy production given ambient temperature and available solar radiation.

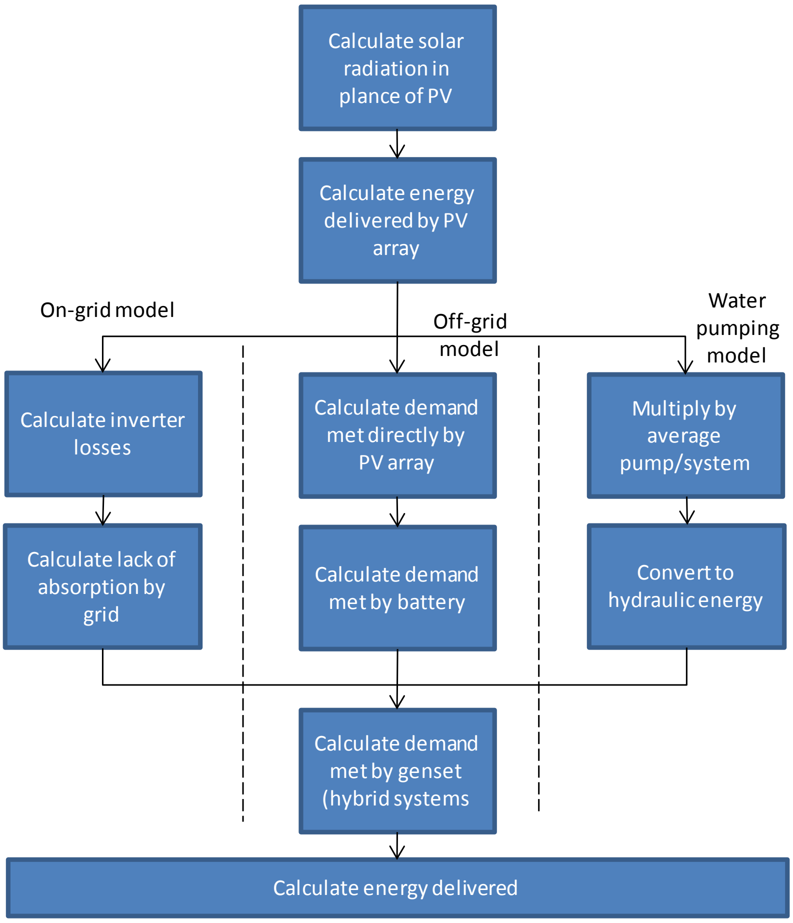

Figure 2. Photovoltaic energy model flowchart

The computation process is also common to all three application models. Then three different application models are applied to evaluate the interaction of the various elements of the PV scheme and predict how much energy (or water, in the case of a pumping scheme) can be expected from the PV scheme on an annual basis.

Photovoltaic schemes have relatively few elements; but the behavior of these elements is non-linear and their interactions are complex. Given computation method uses simplified algorithms to minimize data input requirements and to speed up the computations, while maintaining an acceptable level of accuracy. The solar radiation model is that of Klein and Theilacker extended to include the case of moving surfaces.

The PV array model is based on work by Evans and takes into account temperature and orientation implications. The on-electricity network and water pumping models are straightforward algorithms based on assumed mean efficiencies. The off-electricity network model is the more sophisticated one. It uses the concept of daily utilizability to find out the part of the load that can be met directly by the PV array. Correlations deducted from hourly computer simulations are applied to check how the battery can provide for the rest of the load. Finally, an energy balance checks the part of the load met by the generator set, if there is one.

The two main limitations of the method chosen are that solar concentrator schemes currently cannot be evaluated and that the model does not provide a loss-of-load probability for off-electricity network schemes. For the majority of applications, these limitations are without consequence.

Basics of Solar Energy

Before entering into the details of the PV model, it will be useful to review briefly some basic concepts of solar energy engineering. Many of the variables deducted in this section will be applied in several parts of the computation methodology.

Declination

The declination is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by Cooper’s equation:

$$\delta = 23.45 \sin\left(2\pi \frac{284+n}{365}\right) \tag{1}$$

where n is the day of year (i.e. $n = 1$ for January 1, $n = 32$ for February 1, etc.). Declination varies between -23.45° on December 21 and +23.45° on June 21.

Solar hour angle and sunset hour angle

The solar hour angle is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon. For example at 7 a.m. (solar time) the hour angle is equal to –75° (7 a.m. is five hours from noon; five times 15 is equal to 75, with a negative sign because it is morning).

The sunset hour angle ω_s is the solar hour angle corresponding to the time when the sun sets. It is given by the following equation:

$$\cos\omega_s = -\tan\psi\tan\delta \qquad (2)$$

where δ is the declination, computed through Equation (1), and ψ is the latitude of the site, specified by the user.

Extraterrestrial radiation and clearness index

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface, H_0, can be computed for day n from the following equation:

$$H_0 = \frac{86400 G_{sc}}{\pi}\left(1 + 0.033\cos\left(2\pi\frac{n}{365}\right)\right)(\cos\psi\cos\delta\sin\omega_s + \omega_s\sin\psi\sin\delta) \qquad (3)$$

where G_{sc} is the solar constant equal to 1,367 W/m^2, and all other variables have the same meaning as before.

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index. Thus the monthly mean clearness index, $\bar{K}_T$, is defined as:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \qquad (4)$$

where $\bar{H}$ is the monthly mean daily solar radiation on a horizontal surface and $\bar{H}_0$ is the monthly mean extraterrestrial daily solar radiation on a horizontal surface. $\bar{K}_T$ values depend on the location and the time of year considered; they are typically between 0.3 (for very overcast climates) and 0.8 (for very sunny locations).

Tilted Irradiance Computation

Radiation in the plane of the PV array is computed using a method similar to the Klein and Theilacker algorithm. However the algorithm is extended to tracking surfaces and, for that reason, is implemented in a slightly different form.

Description of algorithm

The algorithm can be defined as a succession of three basic steps (see Figure 3):

- Compute hourly global and diffuse irradiance on an horizontal surface for all hours of an "mean day" having the same daily global radiation as the monthly mean;
- Compute hourly values of global irradiance on the tilted (or tracking) surface for all hours of the day; and then;
- Sum the hourly tilted values to get the mean daily irradiance in the plane of the PV array.

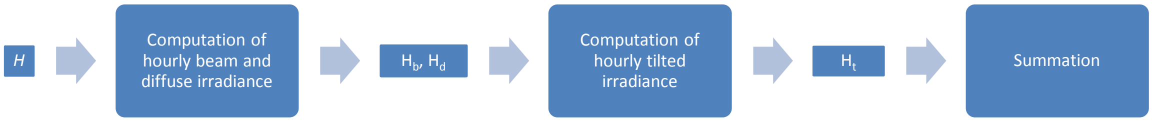

Figure 3. Flowchart for tilted irradiance computation

Computation of hourly global and diffuse irradiance

Solar radiation can be broken down into two elements: beam radiation, which emanates from the solar disk, and diffuse radiation, which emanates from the rest of the sky. The computation method requires the knowledge of beam and diffuse radiation for every hour of a "mean day".

First, monthly mean daily diffuse radiation $\overline{H}_d$ is computed from the monthly mean daily global radiation $\overline{H}$:

$$\frac{\bar{H}_d}{\bar{H}} = 1.391 - 3.560\bar{K}_T + 4.189\bar{K}_T^2 - 2.137\bar{K}_T^3 \tag{5}$$

when the sunset hour angle for the mean day of the month is less than 81.4º, and:

$$\frac{\bar{H}_d}{\bar{H}} = 1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.821\bar{K}_T^3 \tag{6}$$

when the sunset hour angle is greater than 81.4º (the monthly mean clearness index, $\bar{K}_T$, is computed through Equation 4).

Then, mean daily radiation is then broken down into hourly values. This is done with calculations from Collares-Pereira and Rabl for global irradiance:

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \tag{7}$$

$$a = 0.409 + 0.5016\sin\left(\omega_s - \frac{\pi}{3}\right) \tag{8}$$

$$b = 0.6609 - 0.4767\sin\left(\omega_s - \frac{\pi}{3}\right) \tag{9}$$

where r_t is the ratio of hourly total to daily total global radiation, with ω_s the sunset hour angle, expressed in radians (Equation 2), and ω the solar hour angle for the midpoint of the hour for which the computation is made, also expressed in radians; and with the formula:

$$r_d = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \tag{10}$$

where r_d is the ratio of hourly total to daily total diffuse radiation. For each hour of the "mean day", global horizontal irradiance H and its diffuse and beam elements H_d and H_b are therefore given by:

$$H = r_t\bar{H} \tag{11}$$

$$H_d = r_d\bar{H}_d \tag{12}$$

$$H_b = H - H_d \tag{13}$$

Computation of hourly irradiance in the plane of the PV array

Computation of hourly irradiance in the plane of the PV array, H_t, is done using a simple isotropic model. This is not the most accurate model available, however this is sufficient at the pre-feasibility stage:

$$H_t = H_b R_b + H_d \left(\frac{1+\cos\beta}{2}\right) + H\rho \left(\frac{1-\cos\beta}{2}\right) \qquad (14)$$

where ρ redelivers the diffuse reflectance of the ground (also called ground albedo) and β redelivers the slope of the PV array. Ground albedo is set to 0.2 if the mean monthly temperature is greater than 0°C, and 0.7 if it is less than –5°C, with a linear interpolation for temperatures between these values. R_b is the ratio of beam radiation on the PV array to that on the horizontal, which can be written as:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad (15)$$

where θ is the incidence angle of beam irradiance on the array and θ_z is the zenith angle of the sun.

The advantage of the algorithm above is that it can accommodate situations where the position of the array varies through the day, as is the case with tracking arrays.

Summation

Once tilted irradiance for all hours of the day is computed, the daily total H_t is obtained by summing individual hours. A special case is that of months near polar night, where the above algorithm fails; in that case tilted irradiance is set equal to global horizontal irradiance.

PV Array Model

The PV array model is displayed in Figure 4. It is based on work by Evans and is common to all types of PV applications.

Figure 4. Flowchart for PV array model

Computation of mean efficiency

The array is characterized by its mean efficiency, η_p, which is a function of mean module temperature T_c :

$$\eta_p = \eta_r\left[1 - \beta_p(T_c - T_r)\right] \tag{16}$$

where η_p is the PV module efficiency at reference temperature T_r (= 25°C), and β_p is the temperature coefficient for module efficiency. T_c is related to the mean monthly ambient temperature T_a through Evans' formula:

$$T_c - T_a = (219 + 832\bar{K}_t)\frac{NOCT-20}{800} \tag{17}$$

where NOCT is the Nominal Operating Cell Temperature and $\bar{K}_t$ the monthly clearness index. η_r, NOCT and β_p depend on the type of PV module considered. They can be entered by the user or, for "standard" technologies, are assumed to take the values given in Table 1.

PV module type	$\boldsymbol{\eta_r}$(%)	**NOCT** (°C)	$\boldsymbol{\beta_p}$(%/°C)
Mono-Si	13.0	45	0.40
Poly-Si	11.0	45	0.40
a-Si	5.0	50	0.11
CdTe	7.0	46	0.24
CIS	7.5	47	0.46

Table 1. PV module features for standard technologies

The equation above is valid when the array's tilt is optimal (i.e. equal to the latitude minus the declination). If the angle differs from the optimum, the right side of Equation (17) has to be multiplied by a correction factor C_f defined by:

$$C_f = 1 - 1.17 \times 10^{-4}(s_M - s)^2 \tag{18}$$

where s_M is the optimum tilt angle and s is the actual tilt angle, both expressed in degrees.

Other corrections

The energy provided by the PV array, E_p, is simply:

$$E_p = S\eta_p\bar{H}_t \tag{19}$$

where S is the area of the array. It has to be reduced by “miscellaneous PV array losses” λ_p and “other energy circumstancing losses” λ_c:

$$E_A = E_p(1 - \lambda_p)(1 - \lambda_c) \tag{20}$$

where E_A is the array energy available to the load and the battery. The overall array efficiency η_A is defined as:

$$\eta_A = \frac{E_A}{S\bar{H}_t} \tag{21}$$

On-Electricity network Model

The on-electricity network model is the simplest scheme model (see Figure 5). In particular no load is specified and no array size is suggested. Instead, the latter is suggested by the user. The suggested inverter is simply equal to the nominal array energy. The energy available to the electricity network is what is generated by the array and reduced by inverter losses:

$$E_{grid} = E_A\eta_{inv} \tag{22}$$

where η_{inv} is the inverter efficiency. Depending on the electricity network configuration not all this energy may be absorbed by the electricity network. The energy actually provided is:

$$E_{dlvd} = E_{grid}\eta_{abs} \tag{23}$$

where η_{abs} is the PV energy absorption rate.

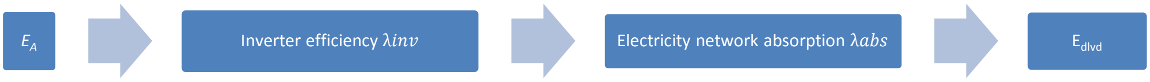

Figure 5. Flowchart for PV on-electricity network model

Off-Electricity network Model

The off-electricity network model redelivers stand-alone schemes with a battery backup, with or without an extra genset. The conceptual framework of the model is displayed in Figure 6. Energy from the PV array is either applied directly by the load, or goes through the battery before being provided to the load. The remainder of the load is provided by the genset if there is one; that is, stand-alone and hybrid schemes differ only by the presence of a genset that supplies the part of the load not met directly or indirectly by photovoltaics.

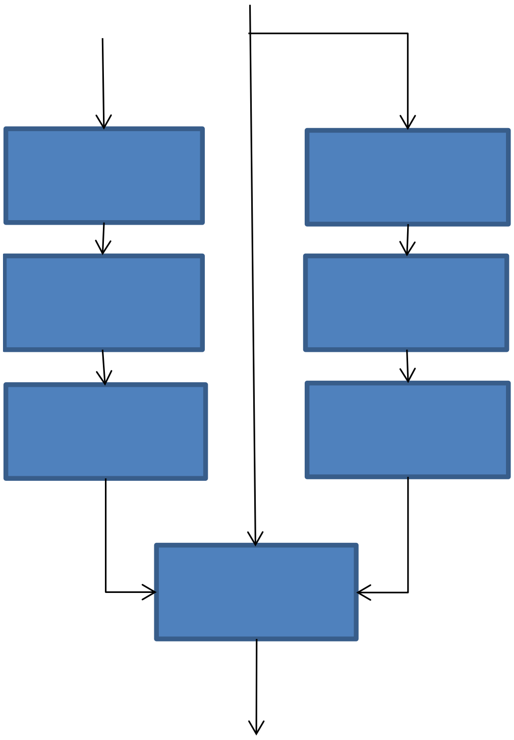

Figure 6. Flowchart for PV off-electricity network model

Load computation

Equivalent DC requirement

The user specifies the total DC requirement, D_{DC}, and the total AC requirement, D_{AC} (both are expressed in kWh/d). AC energy requirement is converted to a DC equivalent by dividing it by the inverter efficiency.

Hence the total equivalent DC equivalent $D_{DC,equ}$ is:

$$D_{DC,equ} = D_{DC} + \frac{D_{AC}}{\eta_{inv}} \qquad (24)$$

where η_{inv} is the efficiency of the inverter.

Types of loads

In some cases, part of the energy requirement can be met directly by the photovoltaic scheme without any energy flowing through the battery. (This has some important consequences in terms of energy provided by the scheme, because inefficiencies in the battery storage can then be ignored.) How much of the energy requirement can be met directly depends on the solar-load correlation specified by the user:

- Positive. This is, for example, the case of a fan connected directly to a PV module; the fan works only when there is solar energy supplied to it. (Water pumping also falls into that category, even though a separate model is applied.)

- Zero. This is treated as the case of a constant load, i.e. a load that has the same value throughout the day. This of course requires the use of a battery. Examples are cathodic protection or monitoring schemes.

- Negative. In this case all the energy flows through the battery first before being provided to the load. This matches to all cases not falling into the Positive and Zero categories. Note that daytime intermittent loads (e.g. refrigerator) also fall into this category.

The final result of this computation is a division of the DC equivalent electrical requirement in three parts:

$$D_{DC,equ} = D_{matched} + D_{continious} + D_{battery} \tag{25}$$

where:

- $D_{matched}$ is the part of the requirement that is met directly by the PV modules whenever there is enough energy generated;

- $D_{continious}$ is the part of the requirement that is constant during the day; and

- $D_{battery}$ is the part of the requirement that will be met primarily by the battery.

Note that $D_{continious}$ will be met either directly by the PV modules (during the day when there is enough sunshine) or through the battery (at night, or when there is not enough sunshine). The method applied to compute this is defined in the next section. It makes use of the vital PV absorption level, P_{crit}, defined as the load corresponding to the constant energy requirement:

$$P_{crit} = \frac{D_{continious}}{24} \tag{26}$$

where $D_{continious}$ is expresed in Wh and P_{crit} in W.

Utilisability method

The load may be considered in part or in whole as constant. Finding which part of that constant load can be met directly by the photovoltaic array, without first being stored in the battery, is the object of this section. The utilisability method is applied to perform this computation.

Monthly mean daily utilisability

A vital radiation level, I_{TC}, is defined as the level of radiation that must be exceeded in order for the PV array to produce more energy than can be immediately applied by the constant load. It is defined as:

$$I_{TC} = \frac{P_{crit}}{\eta_A S} \tag{27}$$

where P_{crit} is the vital PV absorption level (Equation 26), η_A is the overall array efficiency (Equation 21), and S is the area of the PV array.

The monthly mean vital radiation level, $\bar{X}_c$, is defined as the ratio of the vital radiation level to the noon radiation level on a day of the month in which the day's radiation is the same as the monthly mean. It is equal to:

$$\bar{X}_c = \frac{I_{TC}}{r_{t,n} R_n \bar{H}} \tag{28}$$

The meaning of $r_{t,n}$ and R_n will be explained later. Finally, the monthly mean daily utilisability $\overline{\emptyset}$, i.e. the sum for a month, over all hours and days, of the radiation incident upon the array that is above the vital level, divided by the monthly radiation, is:

$$\overline{\emptyset} = exp\left\{\left[a + b\frac{R_n}{R}\right][\bar{X}_c + c\bar{X}_c^2]\right\} \tag{29}$$

with

$$a = 2.943 - 9.271\bar{K}_T + 4.031\bar{K}_T^2 \tag{30}$$

$$b = -4.345 + 8.853\bar{K}_T - 3.602\bar{K}_T^2 \tag{31}$$

$$c = -0.17 - 0.306\bar{K}_T + 2.936\bar{K}_T^2 \tag{32}$$

where $\bar{R}$ will be explained later, and $\bar{K}_T$ is the monthly mean clearness index.

Intermediate amounts

Amounts of interest that appear in Equations (28) and (29) are:

- $\bar{R}$ - the monthly ratio of radiation in the plane of the array to that on a horizontal surface ($\bar{R} = \overline{H_t}/\bar{H}$);
- R_n - the ratio for the hour centred at noon of radiation on the tilted surface to that on a horizontal surface for a mean day of the month. This is expressed as:

$$R_n = \left(1 - \frac{r_{d,n}H_d}{r_{t,n}H}\right)R_{b,n} + \left(\frac{r_{d,n}H_d}{r_{t,n}H}\right)\left(\frac{1+\cos\beta}{2}\right) + \rho_g\left(\frac{1-\cos\beta}{2}\right) \qquad (33)$$

where $r_{t,n}$ and $r_{d,n}$ are the ratio of hourly total to daily total radiation and the ratio of hourly diffuse to daily diffuse radiation, respectively, both for the hour centred around solar noon. This equation is computed for a "mean day of month", i.e. a day with daily global radiation H equal to the monthly mean daily global radiation; $H_d$is the monthly mean daily diffuse radiation for that "mean day" (Equations 5 and 6); ρ_g is the mean ground albedo; and β is the slope of the array (for tracking surfaces, the slope at noon is applied). Accordingly,

- $r_{t,n}$ is computed by the Collares-Pereira and Rabl equation, written for solar noon (Equation 7 with ω=0); and
- $r_{d,n}$ is computed by the Liu and Jordan equation, written for solar noon (Equation 10 with ω=0).

Energy breakdown

The energy provided directly to the continuous load is simply:

$$E_{continious} = (1 - \emptyset)E_A \qquad (34)$$

where E_A is the energy available from the array, and the energy provided to the matched load is:

$$E_{matched} = \min(D_{matched}, E_A - E_{continious}) \qquad (35)$$

The energy provided directly to the load is therefore:

$$E_D = E_{continious} + E_{matched} \qquad (36)$$

and the energy provided to the battery is:

$$E_A - E_D \qquad (37)$$

Energy going through the battery

The fraction of the load that a scheme with battery backup will provide depends on two variables: the array size and the battery size. The probability that the scheme will fail to meet the load is called the loss of load probability (LOLP). Several methods for LOLP computation exist in the literature.

The mean battery efficiency as revealed by series of study findings is about 85%. The array/load ratios were multiplied by this quantity to reflect the loss of energy in the batteries; the idea here being that, since all the energy provided to the load has to go through the battery first (night-only load), the effective energy generated by the array has to be reduced by battery inefficiencies.

Storage/load ratio SLR and the array/load ratio ALR are defined mathematically as:

$$ALR = \frac{E_A'}{L'} \qquad (38)$$

$$SLR = \frac{Q_U}{L'} \qquad (39)$$

where L' is the part of the load not met directly by the PV scheme:

$$L' = L - E_D \qquad (40)$$

and E_A' is the available array generation reduced by the energy provided directly to the load, and then by the charge controller efficiency η_c and battery efficiency η_b:

$$E_A' = (E_A - E_D)\eta_c\eta_b \qquad (41)$$

The usable battery capacity Q_U is related to the nominal capacity Q_B:

$$Q_U = Q_B f_B \qquad (42)$$

where $f_B(T_B, r)$ is the usable fraction of capacity available, which depends on battery temperature T_B and on discharge rate r.

The mean discharge rate is taken as $24n$ where n is the number of days of autonomy. Energy provided by the genset is simply the difference between the load and what can be provided by the PV array, either directly or through the battery:

$$E_G = L - E_D - E_B \qquad (43)$$

This quantity is capped by the actual size of the generator, i.e. the generator cannot deliver more than $24C_G\eta_R$ Wh per day, where C_G is the capacity of the generator in W, and η_R is the charger efficiency.

The energy applied by the genset, Q_G, expressed either in L/d or m^3/d, is simply:

$$Q_G = \frac{E_G}{\eta_R\eta_G\eta_b} \qquad (44)$$

where η_G is the mean generator set efficiency. The presence of the battery efficiency, η_b, in the denominator of Equation (44) simply accounts for the fact that most of the energy from the generator set will be stored in the battery before reaching the load.

Array, battery and generator set sizing

For stand-alone schemes, the array is sized so that its generation, as defined in previous sections, is greater than 1.2 times the load for all months of the year. For a hybrid scheme, the suggested array size is 25% of that for the stand-alone scheme. In addition the size is capped so that the array never provides more than 75% of the load.

Battery sizing is based on the desired number of days of autonomy. If L is the equivalent DC load, n the number of days of autonomy and d the maximum depth of discharge, the usable battery capacity should be:

$$Q_U = \frac{Ln}{d\eta_B} \qquad (45)$$

where η_B is the battery efficiency. As seen before, the usable fraction of the capacity available depends on battery temperature T_B and on discharge rate. If $f_B(T_B, r)$ is the usable fraction of the capacity available, then the design battery capacity is:

$$Q_B = \frac{Q_U}{f_B} \quad (46)$$

This quantity is computed on a monthly basis, and the maximum over the year is taken as the suggested battery size. Finally, the suggested generator set capacity is taken as the maximum of the AC requirement and:

$$\frac{1}{8}\frac{Q_B}{\eta_R} \quad (47)$$

where η_R is the charger efficiency. This matches to the energy required to charge the battery in 8 hours.

Water Pumping Model

The water pumping model is based on the simple formulas found in Royer et al. and is displayed schematically in Figure 7. The daily hydraulic energy requirement E_{hydr} (in J) corresponding to lifting water to a height h (in m) with a daily volume Q (in m^3/d) is:

$$E_{hydr} = 86400 \rho g Q h (1 + \eta_f) \quad (48)$$

where g is the acceleration of gravity (9.81 ms^{-2}), ρ the density of water (1000 kg/m^{-3}), and η_f is a factor accounting for friction losses in the piping. This hydraulic energy translates into an electrical energy requirement E_{pump}:

$$E_{pump} = \frac{E_{hydr}}{\eta_{pump}} \quad (49)$$

where η_{pump} is the pump scheme efficiency. If the pump is AC, this equation has to be modified to take into account the inverter efficiency η_{inv}:

$$E_{pump} = \frac{E_{hydr}}{\eta_{pump}\eta_{inv}} \quad (50)$$

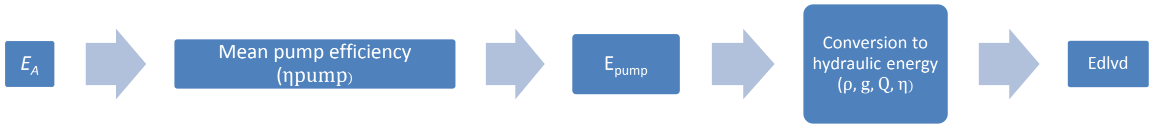

Figure 7. Flowchart for PV water pumping model

The energy provided is simply:

$$E_{dlvd} = \eta_{pump} \min(E_{pump}, E_A) \qquad (51)$$

where E_A is the energy available from the array (this quantity should be multiplied by η_{inv} in the case of an AC pump), and the daily water provided is obtained from:

$$Q_{dlvd} = \frac{E_{dlvd}}{86400 \rho g h (1+\eta_f)} \qquad (52)$$

Suggested array size is computed simply by inverting the above formulas and is therefore equal to E_{pump}/η_A where η_A is the overall array efficiency (Equation 21). This quantity is computed on a monthly basis, and the maximum over the season of use is the suggested array dimension.

In the case of an AC pump, suggested inverter capacity is simply taken equal to the nominal array energy. This is the only method possible since it is assumed that the pump energy rating is not known (only the energy requirement is known).

Summary

In this course, the computation methodology applied for photovoltaic development modelling have been displayed in detail. The tilted irradiance computation algorithm and the PV array model are common to all applications. The tilted irradiance computation uses an hourly model extended to take into account tracking surfaces. The PV array model taken into account varies in array performance induced by ambient temperature. The on-electricity network and the water pumping models are relatively simple models based on assumed mean efficiencies. The off-electricity network model is more complex and allows for a distinction between matched, continuous and intermittent loads which may have an influence on the amount of energy going through the battery.

References:

Clean Energy Development Assessment RETScreen® Engineering & Cases Textbook, Third Edition, © Minister of Natural Resources Canada 2001-2005, September 2005