PDHonline Course E503 (4 PDH)

Photovoltaic Project Analysis

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1. Photovoltaic Project Analysis

This course covers the analysis of potential photovoltaic projects including a technology background and a detailed description of the calculation methodology.

2. Photovoltaic Background

The worldwide demand for solar electric power systems has grown steadily over the last 20 years. The need for reliable and low-cost electric power in isolated areas of the world is the primary force driving the worldwide photovoltaic (PV) industry today. For a large number of applications, PV technology is simply the least-cost option. Typical applications of PV in use today include stand-alone power systems 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.

Demand for cost-effective off-grid power systems, environmental and longer-term fuel supply concerns by governments and electric utilities are beginning to help accelerate the market for demonstration programs for PV systems connected to central electric grids in industrialized countries.

This course describes photovoltaic systems (PV modules, batteries, power conditioning, generators, and pumps) and discusses the photovoltaic markets including on-grid, off-grid and water-pumping applications.

3. Description of Photovoltaic Systems

The primary article of commerce in the PV market is the PV module. PV modules are rated on the basis of the power delivered under Standard Testing Conditions (STC) of 1 kW/m^2 of sunlight and a PV cell temperature of 25 degrees Celsius (°C). Their output measured under STC is expressed in terms of "peak Watt" or

Wp nominal capacity. Note that annual industry shipments of 165 MWp indicate that PV manufacturers made modules with the ability to generate 165 MWp of electric power (nameplate capacity) under STC of 1 kW/m^2 of sunlight, 25°C cell temperature, and an air mass of 1.5.

PV modules are integrated into systems designed for specific applications. The components added to the module constitute the “balance of system” or BOS. The balance of system components can be classified into four categories:

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

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

4. PV modules

To make modules, PV manufacturers 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 manufacturers then assemble the cells into modules or sell them to module manufacturers 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 package for protection from the environment. This package 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 derived 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 need for the intermediate solar cell fabrication step.

Some manufacturers are developing PV modules that concentrate sunlight 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 directed at the sun and therefore must be used in conjunction with sun trackers. These modules are limited to areas of the world where there is a considerable amount of direct beam sunlight, such as in desert regions.

5. Batteries

If an off-grid PV system must provide energy on demand 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 used, 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 used in "deep cycle" applications where the depth of discharge can exceed 80%.

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

Note that optimizing battery size is critical in obtaining good battery life, suitable system performance, and optimal system life-cycle costs. Unnecessary battery replacement is costly, particularly for remote applications.

6. Power conditioning

Several electronic devices are used to control and modify the electrical power produced by the photovoltaic array. These include:

- Battery charge controllers - regulate the charge and discharge cycles of the battery;
- Maximum power point trackers (MPPT) - maintain the operating voltage of the array to a value that maximizes array output;
- Inverters - convert the direct current (DC) output of the array or the battery into alternating current (AC). AC is required by many appliances and motors; it is also the type of power used by utility grids and therefore grid systems always require the use of an inverter;
- Rectifiers (battery chargers) - convert the AC current produced by a generator into the DC current needed to charge the batteries.

7. Generators

For off-grid applications, it is also possible to have both a photovoltaic system and a fossil fuel generator running in parallel. The use of a generator eliminates the need to oversize the photovoltaic array and the battery bank in order to provide power 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 system that would need to be oversized to ensure an uninterrupted supply of power.

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 system and the generator, will depend on many factors, including the capital cost of the PV array, operating costs of the generator, system reliability, and environmental considerations (e.g. noise of the generator, emission of fumes, etc.).

8. Pumps

For water pumping applications, several types of pumps may be used. They can be categorized according to their design type (rotating or positive displacement pumps), their location (surface or submersible), or the type of motor they use (AC or DC). Rotating pumps (e.g. centrifugal pumps) are usually preferred for deep wells or boreholes and large water requirements. The use of displacement pumps is usually limited to low volumes. Positive displacement pumps (e.g. diaphragm pumps, piston pumps, and progressive cavity pumps) usually 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.

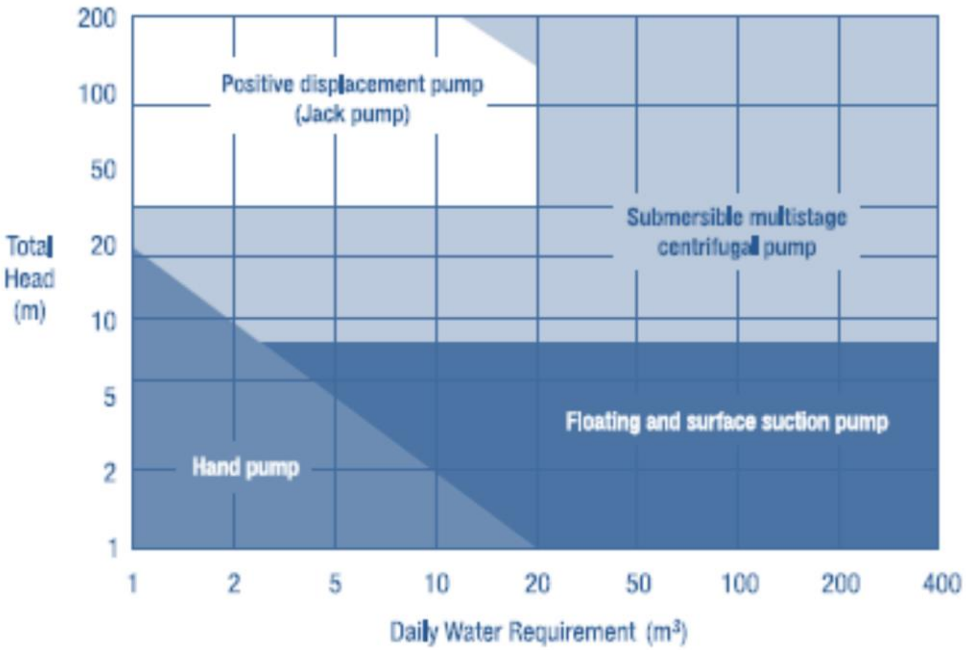

Figure 1. Pump type selection

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 usually 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.

9. Photovoltaic Application Markets

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

10.On-grid applications

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

The benefits of grid-connected PV power generation are generally evaluated based on its potential to reduce costs for energy production and generator capacity, as well as its environmental benefits. For a 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 average daily output of the PV system corresponds with the utility’s peak demand period (e.g. afternoon peak demand during summer months due to air conditioning loads). PV manufacturers are also developing PV modules that can be incorporated into buildings as standard building components such as roofing tiles and curtain walls. This helps reduce the relative cost of the PV power system to the cost of the conventional building materials, and allows the utility and/or building owner to capture distributed generation benefits. The use of PV in the built environment is expanding with demonstration projects in industrialized countries.

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

11.Off-grid applications

Currently, PV is most competitive in isolated sites, away from the electric grid and requiring relatively small amounts of power, typically less than 10 kWp. In these off-grid applications, PV is frequently used in the charging of batteries, thus storing the electrical energy produced by the modules and providing the user with electrical energy on demand.

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

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

12. Water pumping applications

Photovoltaic water pumping is one of the most common PV applications around the world, with thousands of photovoltaic-powered 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 used for intermediate-sized pumping applications, filling the gap between small hand pumps and large engine-powered systems 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 often unnecessary. PV water pumping systems are relatively simple, require little maintenance, and provide independence from fossil fuels. They are often the system of choice for locations far from the utility grid (e.g. ranches) or for settings where the grid 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 are required).

13. Photovoltaic Project Modelling

The photovoltaic project model can be used to evaluate the energy production and financial performance of photovoltaic projects, from small-scale water pumping systems to intermediate residential off-grid systems to large grid-connected systems, anywhere in the world. There are three basic applications that can be evaluated with the PV model:

- On-grid applications, which cover both central-grid and isolated-grid systems;

- Off-grid applications, which include both stand-alone (PV-battery) systems and hybrid (PV-battery-genset) systems

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

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

This course describes the methodology used to calculate, on a month-by-month basis, the energy production of PV systems. A flowchart of the algorithms is shown in Figure 2. The basics of solar energy that are covered in the following sections describe the tilted radiation calculation algorithm which is common to all three application models (i.e. on-grid, off-grid, and water pumping applications). It is used to calculate 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 calculates PV array energy production given ambient temperature and available solar radiation.

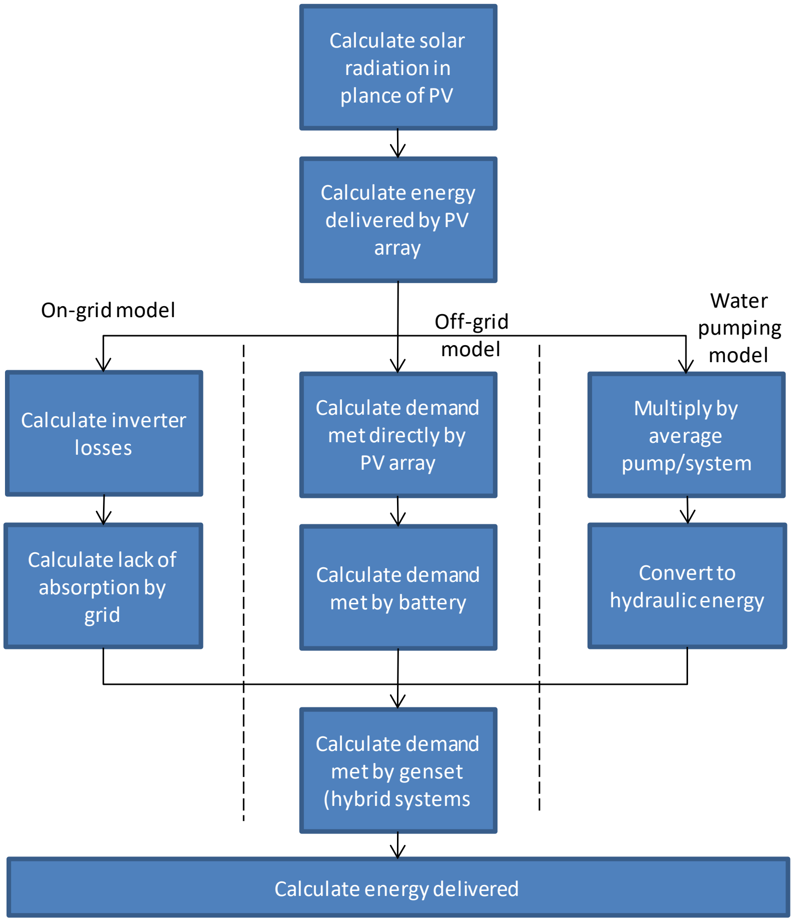

Figure 2. Photovoltaic energy model flowchart

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

Photovoltaic systems have relatively few components, but the behavior of these components is non-linear and their interactions are complex.

The presented calculation method uses simplified algorithms to minimize data input requirements and speed up the calculations 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 effects. The on-grid and water-pumping models are straightforward algorithms based on assumed average efficiencies. The off-grid model is the more complicated one. It uses the concept of daily utilisability to find out the part of the load that can be met directly by the PV array. Correlations derived from hourly computer simulations are used to determine how the battery can provide for the rest of the load. Finally, an energy balance determines the part of the load met by the genset, if there is one.

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

14.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 derived in this section will be used in several parts of the calculation methodology.

15.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:

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

where n is the day of the ear (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.

16.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, calculated through equation (1), and ψ is the latitude of the site, specified by the user.

17.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:

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

where G_{sc} is the solar constant equal to 1,367 W/m2, 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 average 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 average daily solar radiation on a horizontal surface and $\bar{H}_0$ is the monthly average extraterrestrial daily solar radiation on a horizontal surface. $\bar{K}_T$ values depend on the location and the time of year considered; they are usually between 0.3 (for very overcast climates) and 0.8 (for very sunny locations).

18.Tilted Irradiance Calculation

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.

19.Description of algorithm

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

- Calculate hourly global and diffuse irradiance on an horizontal surface for all hours of an "average day" having the same daily global radiation as the monthly average;
- Calculate 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 obtain the average daily irradiance in the plane of the PV array.

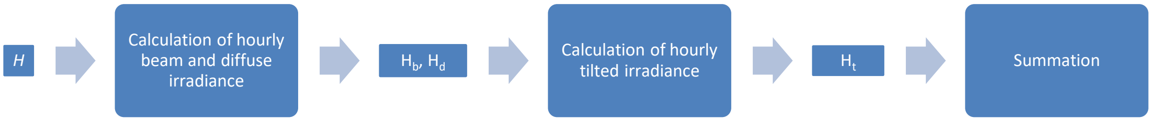

Figure 2. Flowchart for tilted irradiance calculation

20.Calculation of hourly global and diffuse irradiance

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

First, monthly average daily diffuse radiation $\bar{H}_d$ is calculated from monthly average daily global radiation $\bar{H}$:

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

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

$$\frac{\overline{H}_d}{\overline{H}} = 1.311 - 3.022\overline{K}_T + 3.427\overline{K}_T^2 - 1.821\overline{K}_T^3 \qquad (6)$$

when the sunset hour angle is greater than 81.4° (the monthly average clearness index, $\overline{K}_T$ is calculated through equation 4).

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

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

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

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

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 calculation is made, also expressed in radians; and with the formula:

$$r_d = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \qquad (10)$$

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

$$H = r_t\overline{H} \qquad (11)$$

$$H_d = r_d\overline{H}_d \qquad (12)$$

$$H_b = H - H_d \qquad (13)$$

21.Calculation of hourly irradiance in the plane of the PV array

Calculation 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 amply 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 represents the diffuse reflectance of the ground (also called ground albedo) and β represents the slope of the PV array. Ground albedo is set to 0.2 if the average monthly temperature is greater than 0°C, 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 expressed 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.

22.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.

23.PV Array Model

The PV array model is shown 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

24.Calculation of average efficiency

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

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

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:

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

where NOCT is the Nominal Operating Cell Temperature and $\overline{K}_t$ 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	η_r(%)	NOCT (°C)	β_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 characteristics 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:

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

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

25.Other corrections

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

$$E_p = S\eta_p\overline{H}_t \qquad (19)$$

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

$$E_A = E_p(1-\lambda_p)(1-\lambda_c) \qquad (20)$$

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

$$\eta_A = \frac{E_A}{S\overline{H}_t} \qquad (21)$$

26.On-Grid Model

The on-grid model is the simplest system 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 power. The energy available to the grid is what is produced by the array, reduced by inverter losses:

$$E_{grid} = E_A\eta_{inv} \qquad (22)$$

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

$$E_{dlvd} = E_{grid}\eta_{abs} \qquad (23)$$

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

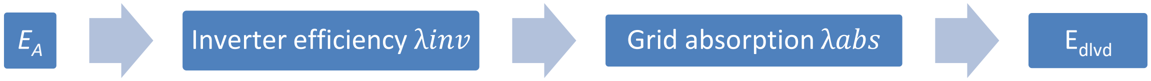

Figure 5. Flowchart for PV on-grid model

27.Off-Grid Model

The off-grid model represents stand-alone systems with a battery backup, with or without an additional genset. The conceptual framework of the model is shown in Figure 6. Energy from the PV array is either used directly by the load, or goes through the battery before being delivered to the load. The remainder of the load is provided by the genset if there is one, that is, stand-alone and hybrid systems differ only by the presence of a genset that supplies the part of the load not met directly or indirectly by photovoltaics.

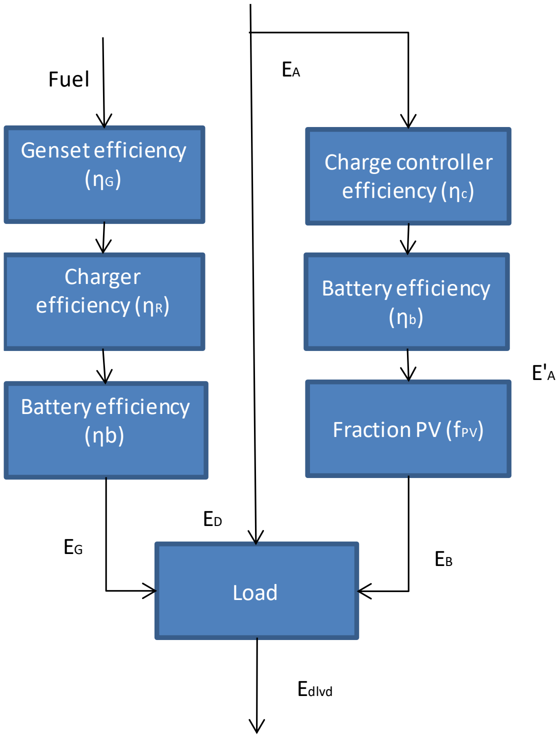

Figure 6. Flowchart for PV off-grid model

28.Equivalent DC demand

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

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

$$\mathrm{D_{DC,equ}} = \mathrm{D_{DC}} + \frac{\mathrm{D_{AC}}}{\eta_{\mathrm{inv}}} \tag{24}$$

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

29.Types of loads

In some cases, part of the energy demand can be met directly by the photovoltaic system without any energy flowing through the battery (this has some important consequences in terms of energy delivered by the system, because inefficiencies in the battery storage can then be ignored). How much of the energy demand 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 to power it (water pumping also falls into that category, although a separate model is used

- 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 systems.

- Negative. In this case all the energy flows through the battery first before being delivered to the load. This corresponds 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 calculation is a division of the DC equivalent electrical demand in three parts:

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

where:

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

- $D_{continious}$ is the part of the demand that is constant throughout the day

- $D_{battery}$ is the part of the demand 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 used to calculate this is described in the next section. It makes use of the critical PV absorption level P_{crit}, defined as the load corresponding to the constant energy demand:

$$P_{crit} = \frac{D_{continious}}{24} \qquad (26)$$

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

30.Utilisability method

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 used to perform the calculation.

31.Monthly average daily utilisability

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

$$I_{TC} = \frac{P_{crit}}{\eta_A S} \qquad (27)$$

where P_{crit} is the critical 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 average critical radiation level $\overline{X}_c$, defined as the ratio of the critical 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 average, is equal to:

$$\overline{X}_c = \frac{I_{TC}}{r_{t,n} R_n \overline{H}} \qquad (28)$$

The meaning of $r_{t,n}$ and R_n will be explained later. Finally, the monthly average 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 critical level, divided by the monthly radiation, is:

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

With

$$a = 2.943 - 9.271\overline{K}_T + 4.031\overline{K}_T^2 \qquad (30)$$

$$b = -4.345 + 8.853\overline{K}_T - 3.602\overline{K}_T^2 \qquad (31)$$

$$c = -0.17 - 0.306\overline{K}_T + 2.936\overline{K}_T^2 \qquad (32)$$

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

32.Intermediate quantities

Quantities of interest that appear in equations (28) and (29) are:

- $\overline{R}$, the monthly ratio of radiation in the plane of the array to that on a horizontal surface ($\overline{R} = \overline{H_t}/\overline{H}$);

- R_n, the ratio for the hour centred at noon of radiation on the tilted surface to that on a horizontal surface for an average 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, both for the hour centered around solar noon. This formula is computed for an "average day of month", i.e. a day with daily global radiation H equal to the monthly average daily global radiation; $H_d$is the monthly average daily diffuse radiation for that "average day" (equations 5 and 6), ρ_g is the average ground albedo, and β is the slope of the array (for tracking surfaces, the slope at noon is used);

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

33.Energy breakdown

The energy delivered directly to the continuous load is simply:

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

where E_A is the energy available from the array; and the energy delivered to the matched load is:

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

The energy delivered directly to the load is therefore:

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

and the energy delivered to the battery is:

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

34.Energy going through the battery

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

The average battery efficiency as revealed by series of study results 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 delivered to the load has to go through the battery first (night-only load), the effective energy produced by the array has to be reduced by battery inefficiencies.

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

$$\mathrm{ALR} = \frac{\mathrm{E}'_\mathrm{A}}{\mathrm{L}'} \qquad (38)$$

$$\mathrm{SLR} = \frac{\mathrm{Q}_\mathrm{U}}{\mathrm{L}'} \qquad (39)$$

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

$$\mathrm{L}' = \mathrm{L} - \mathrm{E}_\mathrm{D} \qquad (40)$$

and E'_A is the available array output reduced by the energy delivered directly to the load, and then by the charge controller efficiency η_c and battery efficiency η_b:

$$\mathrm{E}'_\mathrm{A} = (\mathrm{E}_\mathrm{A} - \mathrm{E}_\mathrm{D})\eta_\mathrm{c}\eta_\mathrm{b} \qquad (41)$$

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

$$\mathrm{Q}_\mathrm{U} = \mathrm{Q}_\mathrm{B}\mathrm{f}_\mathrm{B} \qquad (42)$$

where $\mathrm{f}_\mathrm{B}(\mathrm{T}_\mathrm{B}, \mathrm{r})$ is the usable fraction of capacity available, which depends on battery temperature T_B and on discharge rate r.

The average discharge rate is taken as 24n where n is the number of days of autonomy. Energy delivered 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 the charger efficiency.

The energy used by the genset, Q_G , expressed either in L/d or m3/d, is simply:

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

where η_G is the average genset 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 genset will be stored in the battery before reaching the load.

35.Array, battery and genset sizing

For stand-alone systems, the array is sized so that its output as defined in previous sections is greater than 1.2 times the load for all months of the year. For hybrid system, the suggested array size is 25% of that for the stand-alone system; 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 capacity available depends on battery temperature T_B and on discharge rate . If $f_B(T_B, r)$ is the usable fraction of capacity available, then the design battery capacity is:

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

This quantity is calculated on a monthly basis and the maximum over the year is taken as the suggested battery size. Finally, the suggested genset capacity is taken as the maximum of the AC demand and:

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

where η_R is the charger efficiency. This corresponds to the power required to charge the battery in 8 hours.

36. Water Pumping Model

The water pumping model is based on the simple equations found in Royer et al. and is shown schematically in Figure 7. The daily hydraulic energy demand E_{hydr}, in J, corresponding to lifting water to a height h (in m) with a daily volume Q (in m3/d) is:

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

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}:

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

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

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

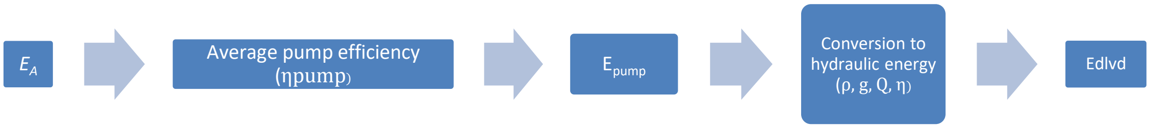

Figure 7. Flowchart for PV water pumping model

Energy delivered is simply:

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

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 daily water delivered is obtained from:

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

Suggested array size is calculated simply by inverting the above equations and is therefore equal to E_{pump}/η_A where η_A is the overall array efficiency (equation 21). This quantity is calculated 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 power. This is the only method possible since it is assumed that the pump power rating is not known (only the energy demand is known).

37.Summary

In this course calculation methodology used for photovoltaic project modelling have been shown in detail. The tilted irradiance calculation algorithm and the PV array model are common to all applications. The tilted irradiance calculation uses an hourly model extended to take into account tracking surfaces. The PV array model takes into account changes in array performance induced by ambient temperature. The On-grid model and the Water pumping model are relatively simple models based on assumed average efficiencies. The Off-grid 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.