

# 1

## Introduction to Photovoltaic Systems and PSpice

### **Summary**

This chapter reviews some of the basic magnitudes of solar radiation and some of the basics of PSpice. A brief description of a photovoltaic system is followed by definitions of spectral irradiance, irradiance and solar radiation. Basic commands and syntax of the sentences most commonly used in this book are shortly summarized and used to write PSpice files for the AM1.5G and AM0 sun spectra, which are used to plot the values of the spectral irradiance as a function of the wavelength and compare them with a black body radiation. Solar radiation availability at the earth's surface is next addressed, and plots are shown for the monthly and yearly radiation received in inclined surfaces. Important rules, useful for system design, are described.

### **1.1 The Photovoltaic System**

A photovoltaic (PV) system generates electricity by the direct conversion of the sun's energy into electricity. This simple principle involves sophisticated technology that is used to build efficient devices, namely solar cells, which are the key components of a PV system and require semiconductor processing techniques in order to be manufactured at low cost and high efficiency. The understanding of how solar cells produce electricity from detailed device equations is beyond the scope of this book, but the proper understanding of the electrical output characteristics of solar cells is a basic foundation on which this book is built.

A photovoltaic system is a modular system because it is built out of several pieces or elements, which have to be scaled up to build larger systems or scaled down to build smaller systems. Photovoltaic systems are found in the Megawatt range and in the milliwatt range producing electricity for very different uses and applications: from a wristwatch to a communication satellite or a PV terrestrial plant, grid connected. The operational principles though remain the same, and only the conversion problems have specific constraints. Much is gained if the reader takes early notice of this fact.

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The elements and components of a PV system are the photovoltaic devices themselves, or solar cells, packaged and connected in a suitable form and the electronic equipment required to interface the system to the other system components, namely:

- a storage element in standalone systems;
- the grid in grid-connected systems;
- AC or DC loads, by suitable DC/DC or DC/AC converters.

Specific constraints must be taken into account for the design and sizing of these systems and specific models have to be developed to simulate the electrical behaviour.

### 1.2 Important Definitions: Irradiance and Solar Radiation

The radiation of the sun reaching the earth, distributed over a range of wavelengths from 300 nm to 4 micron approximately, is partly reflected by the atmosphere and partly transmitted to the earth's surface. Photovoltaic applications used for space, such as satellites or spacecrafts, have a sun radiation availability different from that of PV applications at the earth's surface. The radiation outside the atmosphere is distributed along the different wavelengths in a similar fashion to the radiation of a 'black body' following Planck's law, whereas at the surface of the earth the atmosphere selectively absorbs the radiation at certain wavelengths. It is common practice to distinguish two different sun 'spectral distributions':

- (a) AM0 spectrum outside of the atmosphere.
- (b) AM 1.5 G spectrum at sea level at certain standard conditions defined below.

Several important magnitudes can be defined: spectral irradiance, irradiance and radiation as follows:

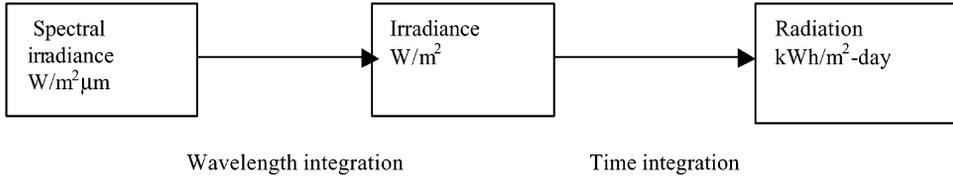
- (a) **Spectral irradiance**  $I_\lambda$  – the power received by a unit surface area in a wavelength differential  $d\lambda$ , the units are  $\text{W}/\text{m}^2\mu\text{m}$ .
- (b) **Irradiance** – the integral of the spectral irradiance extended to all wavelengths of interest. The units are  $\text{W}/\text{m}^2$ .
- (c) **Radiation** – the time integral of the irradiance extended over a given period of time, therefore radiation units are units of energy. It is common to find radiation data in  $\text{J}/\text{m}^2$ -day, if a day integration period of time is used, or most often the energy is given in  $\text{kWh}/\text{m}^2$ -day,  $\text{kWh}/\text{m}^2$ -month or  $\text{kWh}/\text{m}^2$ -year depending on the time slot used for the integration of the irradiance.

Figure 1.1 shows the relationship between these three important magnitudes.

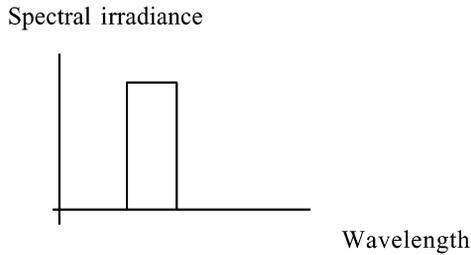
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#### Example 1.1

Imagine that we receive a light in a surface of  $0.25 \text{ m}^2$  having an spectral irradiance which can be simplified to the rectangular shape shown in Figure 1.2, having a constant value of



**Figure 1.1** Relationship between spectral irradiance, irradiance and radiation



**Figure 1.2** Spectrum for Example 1.1

1000 W/m<sup>2</sup>·μm from 0.6 μm to 0.65 μm and zero in all other wavelengths. Calculate the value of the irradiance received at the surface and of the radiation received by the same surface after 1 day.

*Solution*

The irradiance is calculated by integration of the spectral irradiance over the wavelength range (0.6 to 0.65 μm)

$$\text{Irradiance} = \int_{0.60\mu}^{0.65\mu} 1000 \, d\lambda = 0.05 \times 1000 \frac{W}{m^2} = 50 \frac{W}{m^2}$$

As the irradiance is defined by unit of area, the result is independent of the amount of area considered. The radiation received at the 0.25 m<sup>2</sup> area, comes now after integration of the irradiance over the period of time of the exercise, that is one day:

$$\text{radiation} = \text{Area} \int_0^{24h} \text{Irradiance} \cdot dt = 0.25 \, m^2 \, 24 \, h \times 50 \frac{W}{m^2} = 300 \, \text{Wh}\cdot\text{day}$$

As can be seen from Example 1.1, the calculation of the time integral involved in the calculation of the irradiance is very straightforward when the spectral irradiance is constant, and also the calculation of the radiation received at the surface reduces to a simple product when the irradiance is constant during the period of time considered.

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It is obvious that this is not the case in photovoltaics. This is because the spectral irradiance is greater in the shorter wavelengths than in the longer, and of course, the irradiance received at a given surface depends on the time of the day, day of the year, the site location at the earth's surface (longitude and latitude) and on the weather conditions. If the calculation is performed for an application outside the atmosphere, the irradiance depends on the mission, the orientation of the area towards the sun and other geometric, geographic and astronomical parameters.

It becomes clear that the calculation of accurate and reliable irradiance and irradiation data has been the subject of much research and there are many detailed computation methods. The photovoltaic system engineer requires access to this information in order to know the availability of sun radiation to properly size the PV system. In order to make things easier, standard spectra of the sun are available for space and terrestrial applications. They are named AM0 and AM1.5 G respectively and consist of the spectral irradiance at a given set of values of the wavelength as shown in Annex 1.

### 1.3 Learning Some PSpice Basics

The best way to learn about PSpice is to practise performing a PSpice simulation of a simple circuit. We have selected a circuit containing a resistor, a capacitor and a diode in order to show how to:

- describe the components.
- connect them.
- write PSpice sentences.
- perform a circuit analysis.

First, nodes have to be assigned from the schematics. If we want to simulate the electrical response of the circuit shown in Figure 1.3 following an excitation by a pulse voltage source we have to follow the steps:

#### 1. Node assignation

According to Figure 1.3 we assign

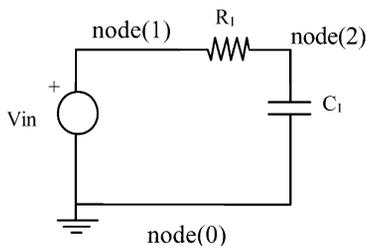


Figure 1.3 Circuit used in file learning.cir

- (0) GROUND
- (1) INPUT
- (2) OUTPUT

In Spice NODE (0) is always the reference node.

## 2. Circuit components syntax

### Resistor syntax

`rx node_a node_b value`

### Capacitor syntax

`cxx node_a node_b value`

According to the syntax and the nodes assignation we must write:

`r1 1 2 1 K;` resistor between node (1) and node (2) value 1 KOhm

`c1 2 0 1 n;` capacitor between node (2) and node (0) value 1nF

Comments can be added to the netlist either by starting a new line with a \* or by adding comments after a semicolon (;).

### Sources syntax

A voltage source is needed and the syntax for a pulsed voltage source is as follows.

### Pulse voltage source

`vxx node+ node- pulse ( initial_value pulse_value delay risetime falltime pulse_length period)`

where node+ and node- are the positive and negative legs of the source, and all other parameters are self-explanatory. In the case of the circuit in Figure 1.3, it follows:

`vin 1 0 pulse (0 5 0 1u 1u 10u 20u)`

meaning that a voltage source is connected between nodes (1) and (0) having an initial value of 0 V, a pulse value of 5 V, a rise and fall time of 1  $\mu$ s, a pulse length of 10  $\mu$ s and a period of 20  $\mu$ s.

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### 3. Analysis

Several analysis types are available in PSpice and we begin with the transient analysis, which is specified by a so-called 'dot command' because each line has to start with a dot.

*Transient analysis syntax (dot command)*

```
.tran tstep tstop tstart tmax
```

where:

first character in the line *must* be a dot

tstep: printing increment

tstop: final simulation time

tstart: (optional) start of printing time

tmax: (optional) maximum step size of the internal time step

In the circuit in Figure 1.3 this is written as:

```
.tran 0.1u 40u
```

setting a printing increment of 0.1  $\mu\text{s}$  and a final simulation time of 40  $\mu\text{s}$ .

### 4. Output (more dot commands)

Once the circuit has been specified the utility named 'probe' is a post processor, which makes available the data values resulting from the simulation for plotting and printing. This is run by a dot command:

```
.probe
```

Usually the user wants to see the results in graphic form and then wants some of the node voltages or device currents to be plotted. This can be performed directly at the probe window using the built-in menus or specifying a dot command as follows:

```
.plot tran variable_1 variable_2
```

In the case of the example shown in Figure 1.3, we are interested in comparing the input and output waveforms and then:

```
.plot tran v(1) v(2)
```

The file has to be terminated by a final dot command:

```
.end
```

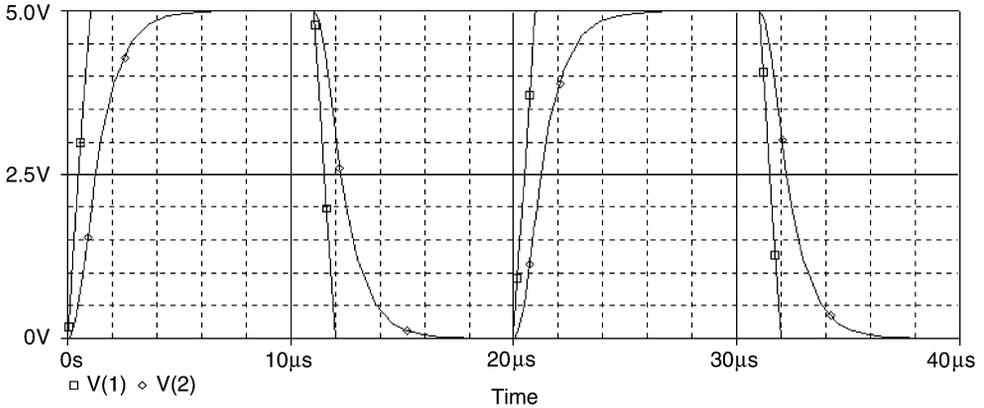


Figure 1.4 Input and output waveforms of simulation of circuit learning.cir

The file considered as a start-up example runs a simulation of the circuit shown in Figure 1.3, which is finally written as follows, using the direct application of the rules and syntax described above.

```
*learning.cir
r1 1 2 1K; resistor between node (1) and node (2) value 1 KOhm
c1 2 0 1n; capacitor between node (2) and node (0) value 1 nF
vin 1 0 pulse (0 5 0 1u 1u 10u 20u); voltage source between node (1) and node (0)
.tran 0 40 u
.probe
.plot tran v(1) v(2)
.end
```

The result is shown in Figure 1.4 where both input and output signals have been plotted as a function of time. The transient analysis generates, as a result of the simulation graphs, where the variables are plotted against time.

### 1.4 Using PSpice Subcircuits to Simplify Portability

The above example tells us about the importance of node assignation and, of course, care must be taken to avoid duplicities in complex circuits unless we want an electrical connection. In order to facilitate the portability of small circuits from one circuit to another, or to replicate the same portion of a circuit in several different parts of a larger circuit without having to renumber all the nodes every time the circuit is added to or changed, it is

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possible to define ‘subcircuits’ in PSpice. These subcircuits encapsulate the components and electrical connections by considering the node numbers for internal use only.

Imagine we want to define a subcircuit composed of the RC circuit in Figure 1.3 in order to replicate it in a more complex circuit. Then we define a subcircuit as:

### Subcircuit syntax

```
.subckt name external_node_1 external_node_2 params: parameter_1 = value_1  
parameter_2 = value_2
```

where a number of external nodes have to be specified and also a list of parameter values. The file containing the subcircuit does not require analysis sentences or sources, which will be added later on to the circuit using the subcircuit. This file can be assigned an extension .lib indicating that it is a subcircuit of a library for later use.

For the RC circuit we need two external nodes: input and output, and two parameters: the resistor value and the capacitor value to be able to change the values at the final circuit stage.

**Warning:** inside a subcircuit the node (0) is forbidden.

We will name the nodes for external connection – (11) for the input, (12) for the output and (10) for the reference.

```
* rc.lib  
.subckt rc 12 11 10 params: r = 1 c = 1  
  
r1 11 12 {r}  
c1 12 10 {c}  
.ends rc
```

Now, every time an RC circuit is to be included in a larger circuit, such as the one depicted in Figure 1.5 where two RC circuits of different component values are used, the RC circuit described in the subcircuit is used twice by means of a sentence, where a new component with first letter ‘x’ – a description given by the subcircuit name – is introduced as follows:

### Syntax for a part of a circuit described by a subcircuit file

```
x_name node_1 node_2 node_i subcircuit_name params: param_1 = value_1
```

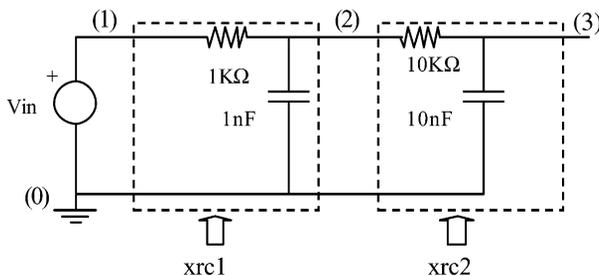


Figure 1.5 Circuit using the same RC subcircuit twice

Applying this syntax to the circuit in Figure 1.5 for the RC number 1 and number 2 it follows:

```
xrc1 2 1 0 rc params: r = 1 k c = 1 n
xrc2 3 2 0 rc params: r = 10 k c = 10 n
```

indicating that the subcircuits named xrc1 and xrc2, with the contents of the file rc.lib and the parameter values shown, are called and placed between the nodes 2, 1 and 0 for xrc1 and between 3 2 0 for xrc2. Finally the netlist has to include the file describing the model for the subcircuit and this is done by another dot command:

```
.include rc.lib
```

So the total file will now be:

```
* learning_subckt.cir
xrc1 2 1 0 rc params: r = 1 k c = 1 n
xrc2 3 2 0 rc params: r = 10 k c = 10 n
.include rc.lib
vin 1 0 pulse (0 5 0 1u 1u 10u 20u); voltage source between node (1) and node (0)

.tran 0.1u 40u
.probe
.plot tran v(1) v(2) v(3)
.end
```

### **1.5 PSpice Piecewise Linear (PWL) Sources and Controlled Voltage Sources**

In photovoltaic applications the inputs to the system are generally the values of the irradiance and temperature, which cannot be described by a pulse kind of source as the one used above. However, an easy description of arbitrarily shaped sources is available in PSpice under the denomination of piecewise linear (PWL) source.

*Syntax for piecewise linear voltage source*

```
Vxx node+ node- pwl time_1 value_1 time_2 value_2 ...
```

This is very convenient for the description of many variables in photovoltaics and the first example is shown in the next section.

A PSpice device which is very useful for any application and for photovoltaics in particular is the E-device, which is a voltage-controlled voltage source having a syntax as follows.

*Syntax for E-device*

```
e_name node+ node- control_node+ control_node- gain
```

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As can be seen this is a voltage source connected to the circuit between nodes node+ and node-, with a value given by the product of the gain by the voltage applied between control\_node+ and control\_node-.

A simplification of this device consists of assigning a value which can be mathematically expressed as follows:

$$E\_name \text{ node+ node- value} = \{expression\}$$

These definitions are used in Sections 1.6 and 1.7 below in order to plot the spectral irradiance of the sun.

**1.6 Standard AM1.5 G Spectrum of the Sun**

The name given to these standard sun spectra comes from Air Mass (AM) and from a number which is 0 for the outer-space spectrum and 1.5 for the sea-level spectrum. In general we will define a spectrum AMx with x given by:

$$x = \frac{1}{\cos \vartheta_z} \tag{1.1}$$

where  $\vartheta_z$  is the zenith angle of the sun. When the sun is located at the zenith of the receiving area  $x = 1$ , meaning that a spectrum AM1 would be spectrum received at sea level on a clear day with the sun at its zenith. It is generally accepted that a more realistic terrestrial spectrum for general use and reference is provided by a zenith angle of 48.19° (which is equivalent to  $x = 1.5$ ). The spectrum received at a surface tilted 37° and facing the sun is named a ‘global-tilt’ spectrum and these data values, usually taken from the reference [1.1] are commonly used in PV engineering.

An easy way to incorporate the standard spectrum into PSpice circuits and files is to write a subcircuit which contains all the data points in the form of a PWL source. This is achieved by using the diagram and equivalent circuit in Figure 1.6 which implements the PSpice file. The complete file is shown in Annex 1 but the first few lines are shown below:

```
* am15g.lib
.subckt am15 g 11 10
v_am15 g 11 10 pw1 0.295u 0
+ 0.305u 9.2
+ 0.315u 103.9
+ 0.325u 237.9
+ 0.335u 376
+ 0.345u 423
+ all datapoints follow here (see Annex 1 for the complete netlist)
.ends am15 g
```

It is important to notice here that the time, which is the default axis for PSpice transient analysis, has been replaced by the value of the wavelength in microns.

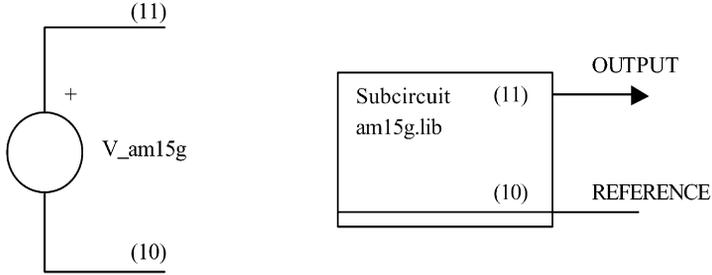


Figure 1.6 PSpice subcircuit for the spectral irradiance AM1.5 G

In order to plot a graph of the spectral irradiance we write a .cir file as follows:

```
*am15g.cir
xspectr_irrad 11 0 am15g
.include am15g.lib
e_spectr_irrad_norm 12 0 value={1000/962.5*v(11)}
.tran 0.1u 4u
.probe
.plot tran v(12)
.end
```

which calls the ‘am15g.lib’ subcircuit and runs a transient simulation where the time scale of the *x*-axis has been replaced by the wavelength scale in microns.

A plot of the values of the AM1.5 G spectral irradiance in  $W/m^2\mu m$  is shown in Figure 1.7.

Care must be taken throughout this book in noting the axis units returned by the PSpice simulation because, as is shown in the plot of the spectral irradiance in Figure 1.7, the *y*-axis returns values in volts which have to be interpreted as the values of the spectral irradiance in

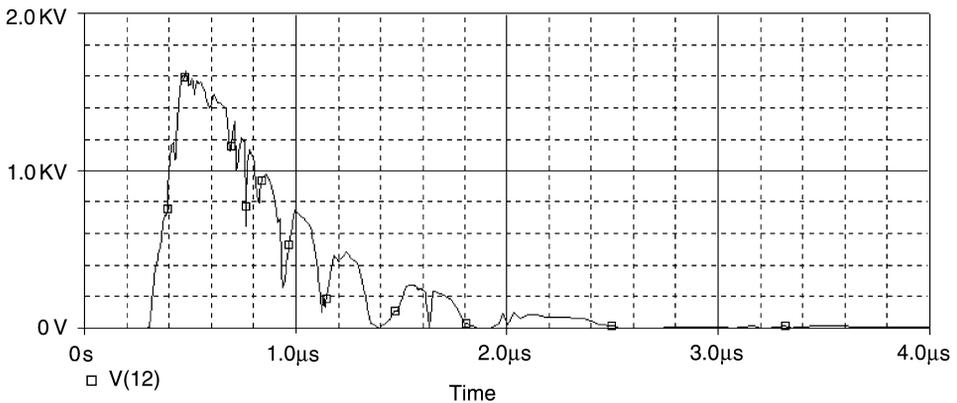


Figure 1.7 PSpice plot of AM1.5 G sun spectrum normalized to  $1\text{ kW}/m^2$  total irradiance. *Warning*, *x*-axis is the wavelength in  $\mu m$  and the *y*-axis is the spectral irradiance in  $W/m^2\mu m$

$W/m^2\mu m$ . So 1 V in the y-axis of the graph means  $1 W/m^2\mu m$ . The same happens to the x-axis:  $1 \mu s$  in the graph means in practice  $1 \mu m$  of wavelength. The difference between the internal PSpice variables and the real meaning is an important convention used in this book. In the example above, this is summarized in Table 1.1.

**Table 1.1** Internal PSpice units and real meaning

	Internal PSpice variable	Real meaning
Horizontal x-axis	Time ( $\mu s$ )	Wavelength ( $\mu m$ )
Vertical y-axis	Volts (V)	Spectral irradiance ( $W/m^2\mu m$ )

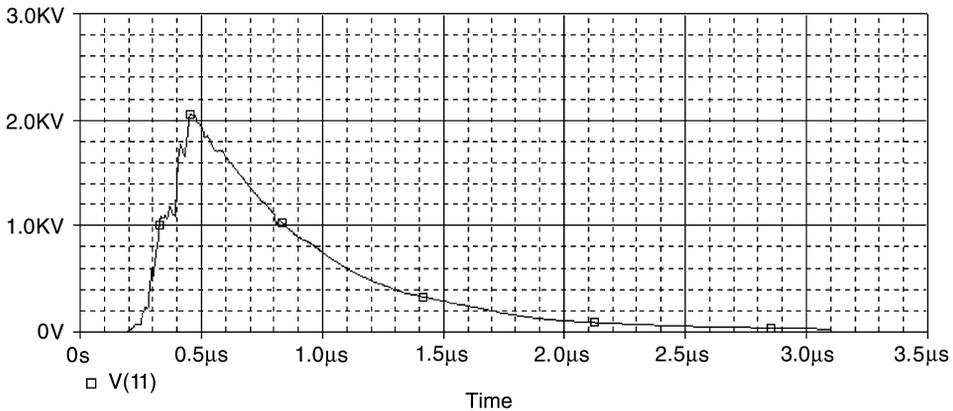
Throughout this book warnings on the real meaning of the axis in all graphs are included in figure captions to avoid misinterpretations and mistakes.

### 1.7 Standard AM0 Spectrum and Comparison to Black Body Radiation

The irradiance corresponding to the sun spectrum outside of the atmosphere, named AM0, with a total irradiance of is  $1353 W/m^2$  is usually taken from the reported values in reference [1.2]. The PSpice subcircuit corresponding to this file is entirely similar to the am15 g.lib subcircuit and is shown in Annex 1 and plotted in Figure 1.8 (files ‘am0.lib’ and ‘am0.cir’).

The total irradiance received by a square metre of a surface normal to the sun rays outside of the atmosphere at a distance equal to an astronomical unit ( $1AU = 1.496 \times 10^{11} m$ ) is called the solar constant  $S$  and hence its value is the integral of the spectral irradiance of the AM0, in our case  $1353 W/m^2$ .

The sun radiation can also be approximated by the radiation of a black body at 5900 K. Planck’s law gives the value of the spectral emissivity  $E_\lambda$ , defined as the spectral power



**Figure 1.8** PSpice plot of AM0 spectrum of the sun. *Warning*, x-axis is the wavelength in  $\mu m$  and the y-axis is the spectral irradiance in  $W/m^2\mu m$

radiated by unit of area and unit of wavelength, as

$$E_{\lambda} = \frac{2\pi h C_0^2}{\lambda^5 (e^{\frac{hc_0}{\lambda T}} - 1)} \left[ \frac{W}{m^3} \right] \quad (1.2)$$

where  $h$  is the Planck's constant ( $h = 6.63 \times 10^{-34}$  J s) and

$$\begin{aligned} 2\pi h C_0^2 &= 3.74 \times 10^{-16} \text{ Wm}^2 \\ \frac{h C_0}{k} &= 0.0143 \text{ mK} \end{aligned} \quad (1.3)$$

are the first and second radiation Planck's constants. The total energy radiated by a unit area of a black body for all values of wavelengths is given by

$$\int_0^{\infty} E_{\lambda} d\lambda = \sigma T^4 = 5.66 \times 10^{-8} T^4 \left( \frac{W}{m^2} \right) \quad (1.4)$$

with the temperature  $T$  in K°.

Assuming that the black body radiates isotropically, the spectral irradiance received from the sun at an astronomical unit of distance (1 AU) will be given by

$$I_{\lambda} = E_{\lambda} \frac{S}{\int_0^{\infty} E_{\lambda} d\lambda} \quad (1.5)$$

where  $S$  is the solar constant. Finally, from equation (1.2),  $I_{\lambda}$  can be written as:

$$I_{\lambda} = \frac{8.925 \times 10^{-12}}{\lambda^5 [e^{0.0143/\lambda T} - 1] T^4} \left( \frac{W}{m^2 \mu m} \right) \quad (1.6)$$

In order to be able to plot the spectral irradiance of a black body at a given temperature, we need to add some potentialities to the subcircuit definition made in the above sections. In fact what we want is to be able to plot the spectral irradiance for *any* value of the temperature and, moreover we need to provide the value of the wavelength. To do so, we first write a subcircuit containing the wavelength values, for example in microns as shown in Annex 1, 'wavelength.lib'.

This will be a subcircuit as

```
.subckt wavelength 11 10
```

having two pins: (11) is the value of the wavelength in metres and (10) is the reference node. Next we have to include equation (1.6) which is easily done in PSpice by assigning a value to an E-device as follows:

```
*black_body.lib

.subckt black_body 12 11 10 params:t=5900

e_black_body 11 10 value={8.925e-12/(((v(12)*1e-6)**5)*(t**4)
+*(exp(0.0143/(v(12)*1e-6*t))-1))}

.ends black_body
```

The factor  $1 \times 10^{-6}$  converts the data of the wavelength from micron to metre.  
 Once we have the subcircuit files we can proceed with a black\_body.cir file as follows:

```
*black_body.cir

.include black_body.lib

.include wavelength.lib

x_black_body 12 11 0 black_body

x_wavelength 12 0 wavelength

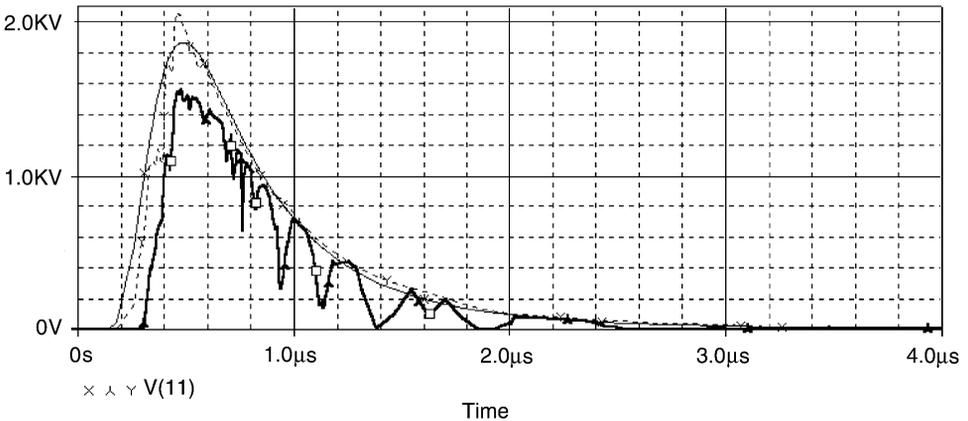
.tran 0.1u 4u

.probe

.plot tran v(11)

.end
```

where the wavelength is written in metres and the temperature  $T$  in K and  $V(11)$  is the spectral irradiance. This can also be plotted using a PSpice file. Figure 1.9 compares the black body spectral irradiance with the AM0 and AM1.5 G spectra.

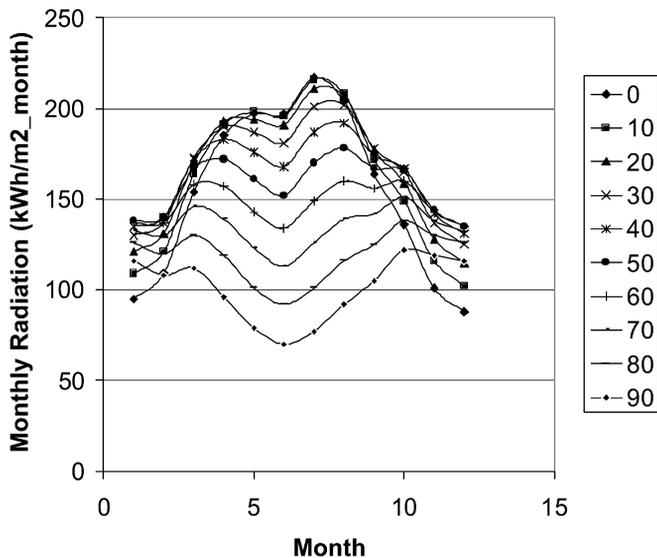


**Figure 1.9** Black body spectral irradiance at 5900 K (middle) compared with AM0 spectral irradiance (upper) and AM1.5 (lower). *Warning*, x-axis is the wavelength in  $\mu\text{m}$  and the y-axis is the spectral irradiance in  $\text{W}/\text{m}^2\mu\text{m}$

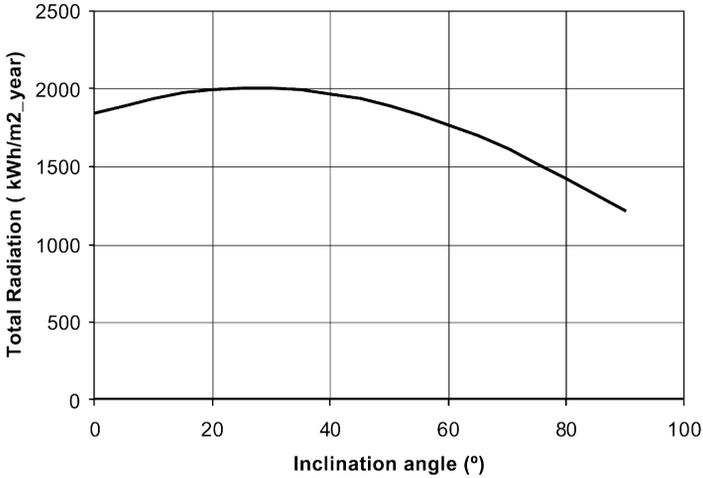
## 1.8 Energy Input to the PV System: Solar Radiation Availability

The photovoltaic engineer is concerned mainly with the radiation received from the sun at a particular location at a given inclination angle and orientation and for long periods of time. This solar radiation availability is the energy resource of the PV system and has to be known as accurately as possible. It also depends on the weather conditions among other things such as the geographic position of the system. It is obvious that the solar radiation availability is subject to uncertainty and most of the available information provides data processed using measurements of a number of years in specific locations and complex algorithms. The information is widely available for many sites worldwide and, where there is no data available for a particular location where the PV system has to be installed, the databases usually contain a location of similar radiation data which can be used (see references 1.3, 1.4, and 1.5 for example).

The solar radiation available at a given location is a strong function of the orientation and inclination angles. Orientation is usually measured relative to the south in northern latitudes and to the north in southern latitudes, and the name of the angle is the 'azimuth' angle. Inclination is measured relative to the horizontal. As an example of the radiation data available at an average location, Figure 1.10 shows the radiation data for San Diego (CA), USA, which has a latitude angle of  $33.05^{\circ}$  N. These data have been obtained using Meteonorm 4.0 software [1.5]. As can be seen the yearly profile of the monthly radiation values strongly depends on the inclination for an azimuth zero, that is for a surface facing south. It can be seen that a horizontal surface receives the largest radiation value in summer. This means that if a system has to work only in summer time the inclination should be chosen to be as horizontal as possible. Looking at the curve corresponding to  $90^{\circ}$  of



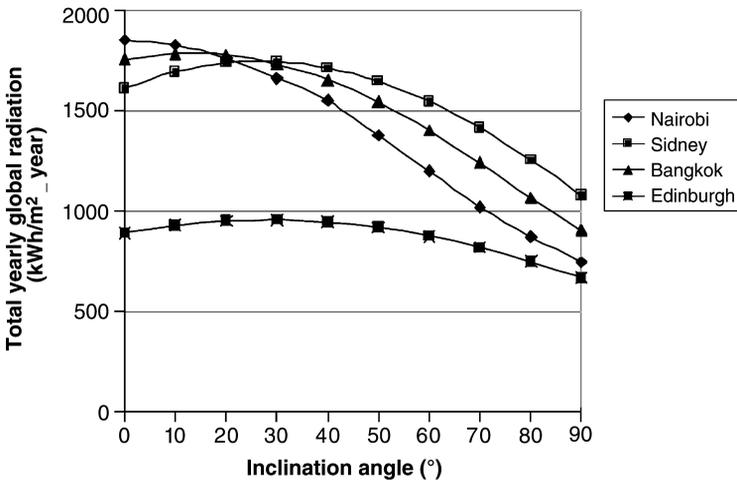
**Figure 1.10** Monthly radiation data for San Diego. Data adapted from results obtained using Meteonorm 4.0 [1.5] as a function of the month of the year and of the inclination angle



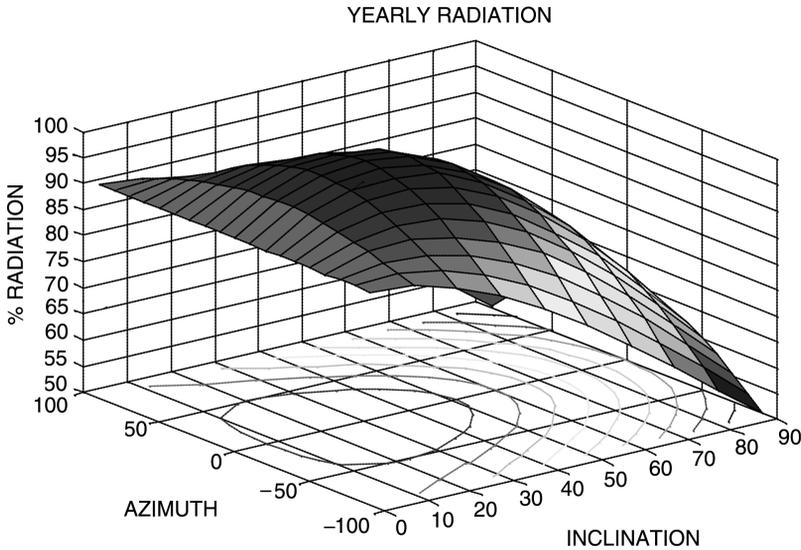
**Figure 1.11** Total radiation at an inclined surface in San Diego, for a surface facing south, as a function of the inclination angle

inclination at the vertical surface (bottom graph) it can be seen that this surface receives the smallest radiation of all angles in most of the year except in winter time.

Most PV applications are designed in such a way that the surface receives the greatest radiation value integrated over the whole year. This is seen in Figure 1.11 where the yearly radiation values received in San Diego are plotted as a function of the inclination angle for a surface facing south. As can be seen, there is a maximum value for an inclination angle of approximately 30°, which is very close to the latitude angle of the site.



**Figure 1.12** Total radiation received at an inclined surface for four sites in the world (Nairobi, 1.2° S, Sidney 33.45° S, Bangkok 13.5° N and Edinburgh 55.47° N. North hemisphere sites facing south and south hemisphere facing north



**Figure 1.13** Plot of the yearly radiation in Agoncillo, Logroño, Spain for arbitrary values of inclination and azimuth angles. Expressed in % of the maximum. The bottom projection are iso-ratio curves from 95% to 50%. Data values elaborated from Meteonorm 4.0 results

It can be concluded, as a general rule, that an inclination angle close to the value of the latitude maximizes the total radiation received in one year. This can also be seen in Figure 1.12 where the total yearly radiation received at inclined surfaces at four different sites in the world are shown, namely, Nairobi, 1.2° S, Sidney 33.45° S, Bangkok 13.5° N and Edinburgh 55.47° N, north hemisphere sites facing south and south hemisphere facing north. As can be seen the latitude rule is experimentally seen to hold approximately in different latitudes. Moreover, as the plots in Figures 1.11 and 1.12 do not have a very narrow maximum, but a rather wide one, not to follow the latitude rule exactly does not penalize the system to a large extent. To quantify this result and to involve the azimuth angle in the discussion, we have plotted the values of the total yearly radiation received for arbitrary inclination and orientation angles, as shown in Figure 1.13 for a different location, this time a location in southern Europe at 40° latitude (Logroño, Spain).

The results shown have been derived for a static flat surface, this means a PV system located in a surface without concentration, and that does not move throughout the year. Concentration and sun tracking systems require different solar radiation estimations than the one directly available at the sources in References 1.3 to 1.6 and depend very much on the concentration geometry selected and on the one or two axis tracking strategy.

### 1.9 Problems

- 1.1 Draw the spectral irradiance of a black body of 4500 K by writing a PSpice file.
- 1.2 From the data values in Figure 1.11, estimate the percentage of energy available at a inclined surface of 90° related to the maximum available in that location.

- 1.3 From the data of the AM1.5 G spectrum calculate the energy contained from  $\lambda = 0$  to  $\lambda = 1.1 \mu\text{m}$ .

### **1.10 References**

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