Erwin Schrodinger
(1887 - 1961)
Nobel Laureate in Physics in 1933 - "The formalism of the quantum mechanics"

Chapter III

PV-GENERATOR SYSTEMS AND COMPONENTS

3.1 Types of PV-generators or systems

a. Autonomous – Stand Alone PV-system

A general simple block diagram for stand alone PV-system is shown below.

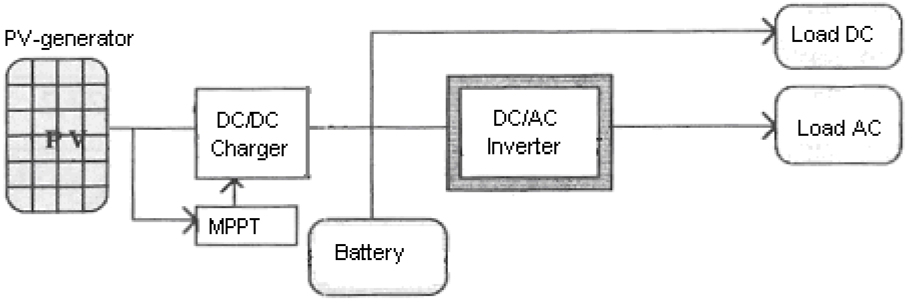


Figure 3.1.a: *Block diagram of a stand-alone PV-system to feed DC and AC loads. Energy storage (batteries) and an MPPT device are included to let for energy independence for a time period and to increase system's efficiency, respectively.*

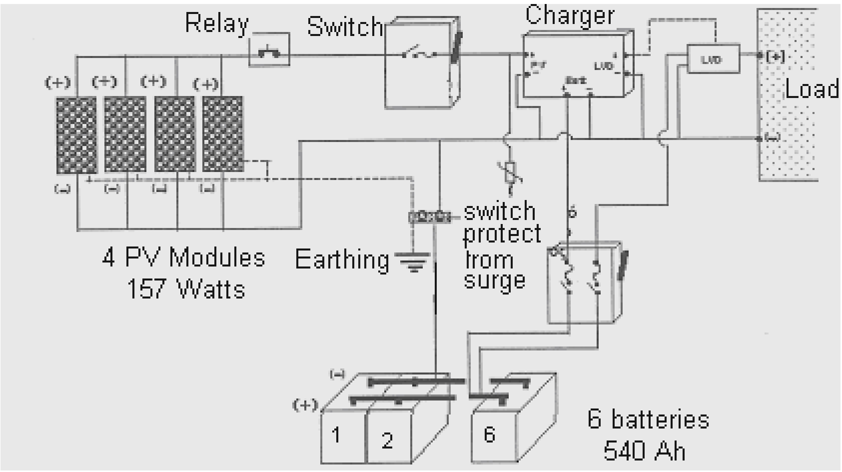


Figure 3.1.b: *4 PV-panels connected in parallel to meet load. The charge along with a protection device store energy in 6 batteries with capacity 540 Ah.*

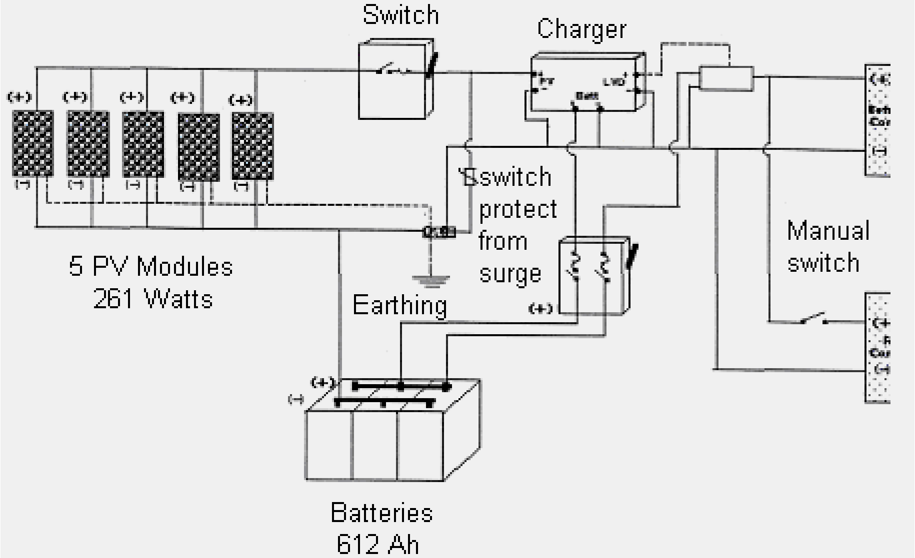


Figure 3.1.c: *5 PV-panels connected in parallel to meet* ***DC*** *load. The charge store energy in batteries with capacity 612 Ah.*

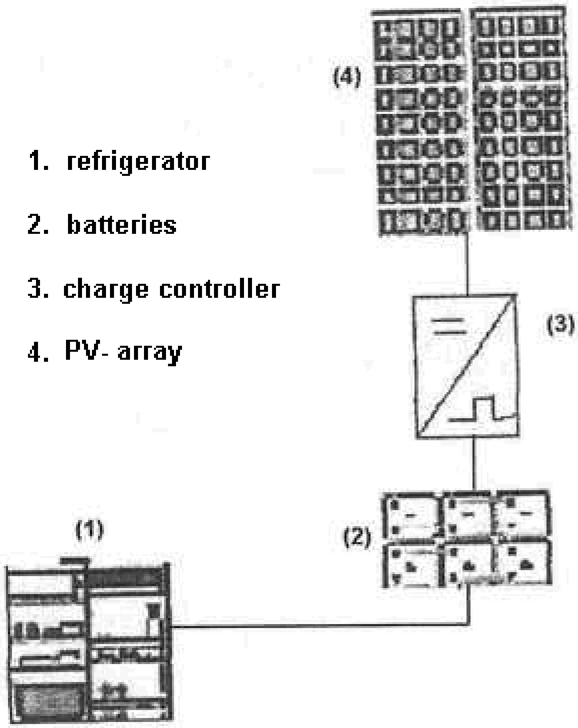


Figure 3.1d: *A bloc diagram of the PV stand alone refrigerating system, as design and construct in the solar Laboratory of T.E.I. Patras*

b. Other types: Hybrid ones and PV-systems connected to the grid

1. One may design **hybrid** systems: i.e. **PV** + **Wind** and/or **Hydro** and/or **Diesel**, see figs. 3.3 and 3.4 Similarly,
2. One might design a PV connected to the grid. A simple block diagram is shown in fig. 3.2.a, b, c, d.

Exercise: one may search the web to find many PV-system designs and applications.

Please, provide detailed configurations for PV-systems, as the above mentioned, and details concerning the elements which constitute the system; see the block diagrams in figs. 3.1-3.4 .

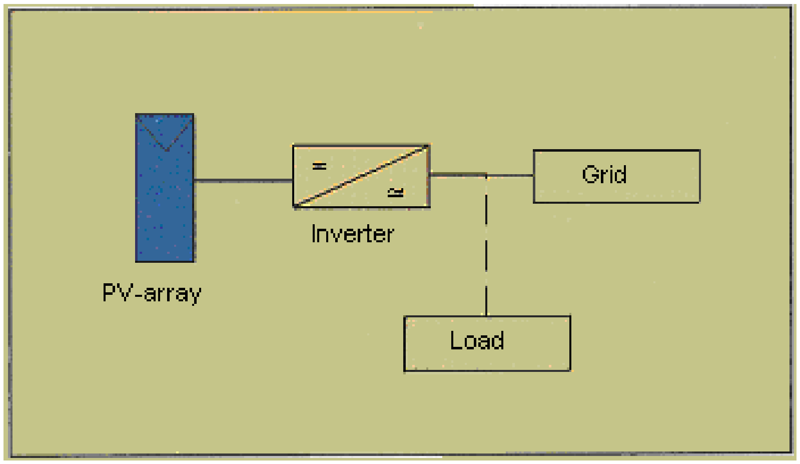


Figure 3.2a: *Simple schematic diagram of a PV generator connected to the grid. Using battery charging for partial storage is another possibility.*

Examples of PV-hybrid systems:

In general, three categories of DC/AC inverters are used in PV-systems:

a. **Variable frequency inverters**; are used for stand-alone drive/shaft power applications, almost exclusively in PV-pumping systems

b. **Self-commutating fixed frequency inverters**; able to feed an isolated distribution grid

c. **Line commutated fixed frequency inverters;** able to feed the grid, only where the grid frequency is defined by another power source connected in parallel.

In several designs, PV-systems use the grid as energy storage, instead of a battery. The latter has limited time life, as the number of cycles (charge-discharge) is limited; about 1200 cycles.

Batteries overall characteristics make the PV-system usually costy.

For medium-large PV-systems **line-commutated inverters equipped with an MPPT** are used.

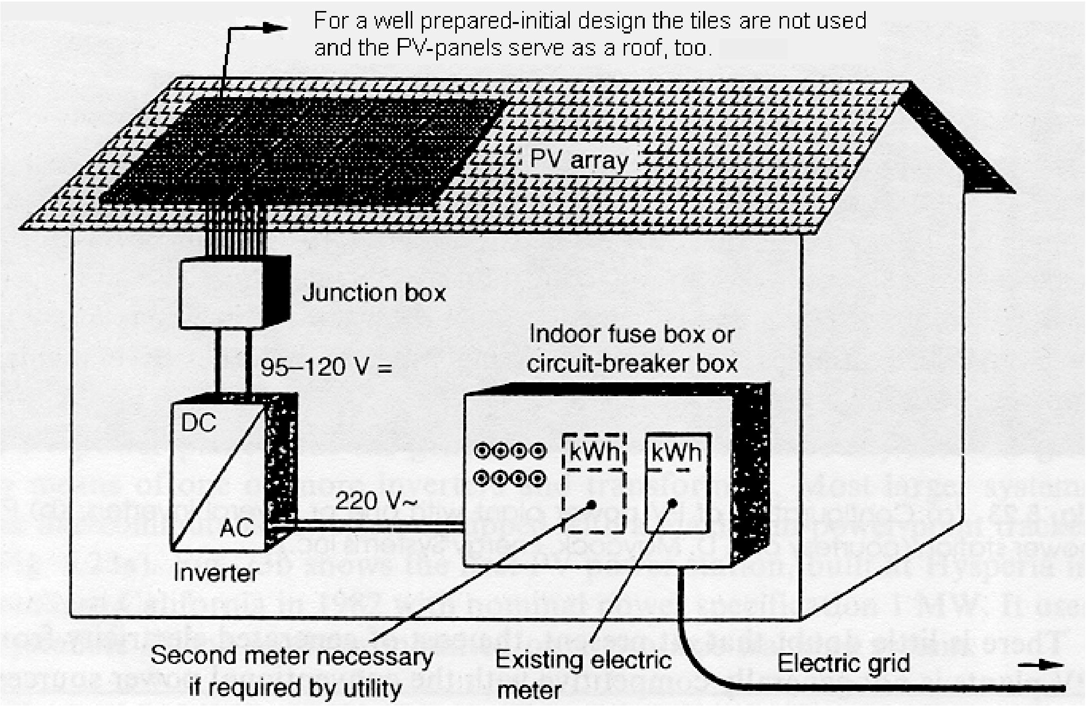


Figure 3.2b: *Roof-top grid-connected PV-system. (Solar Electricity, Tomas Markvart)*

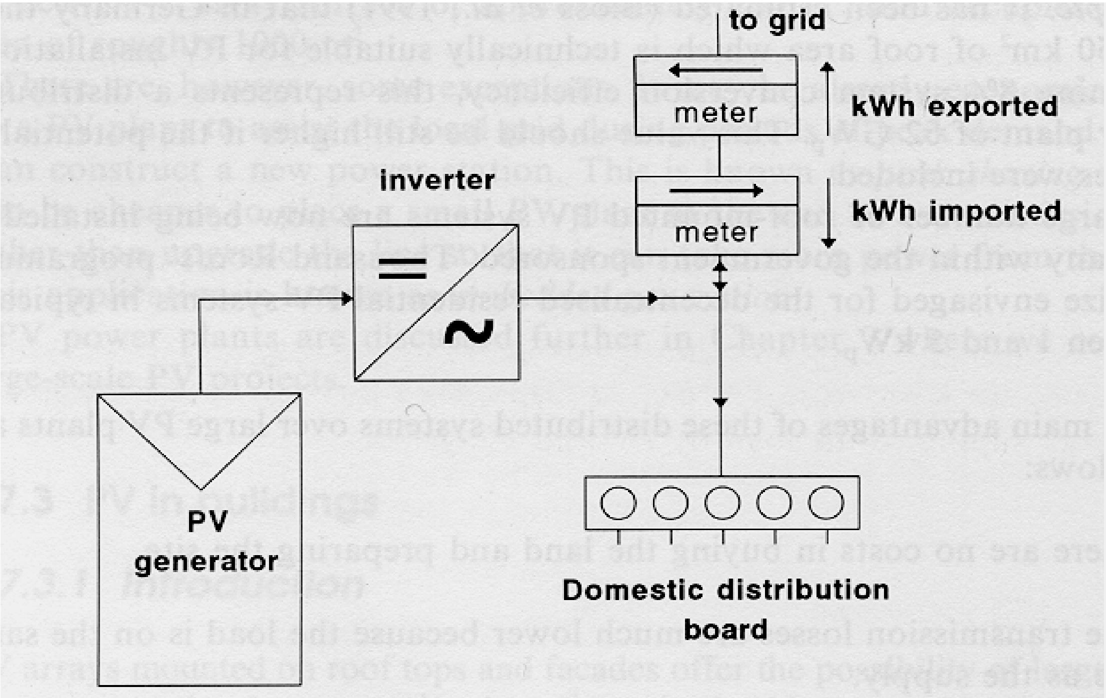
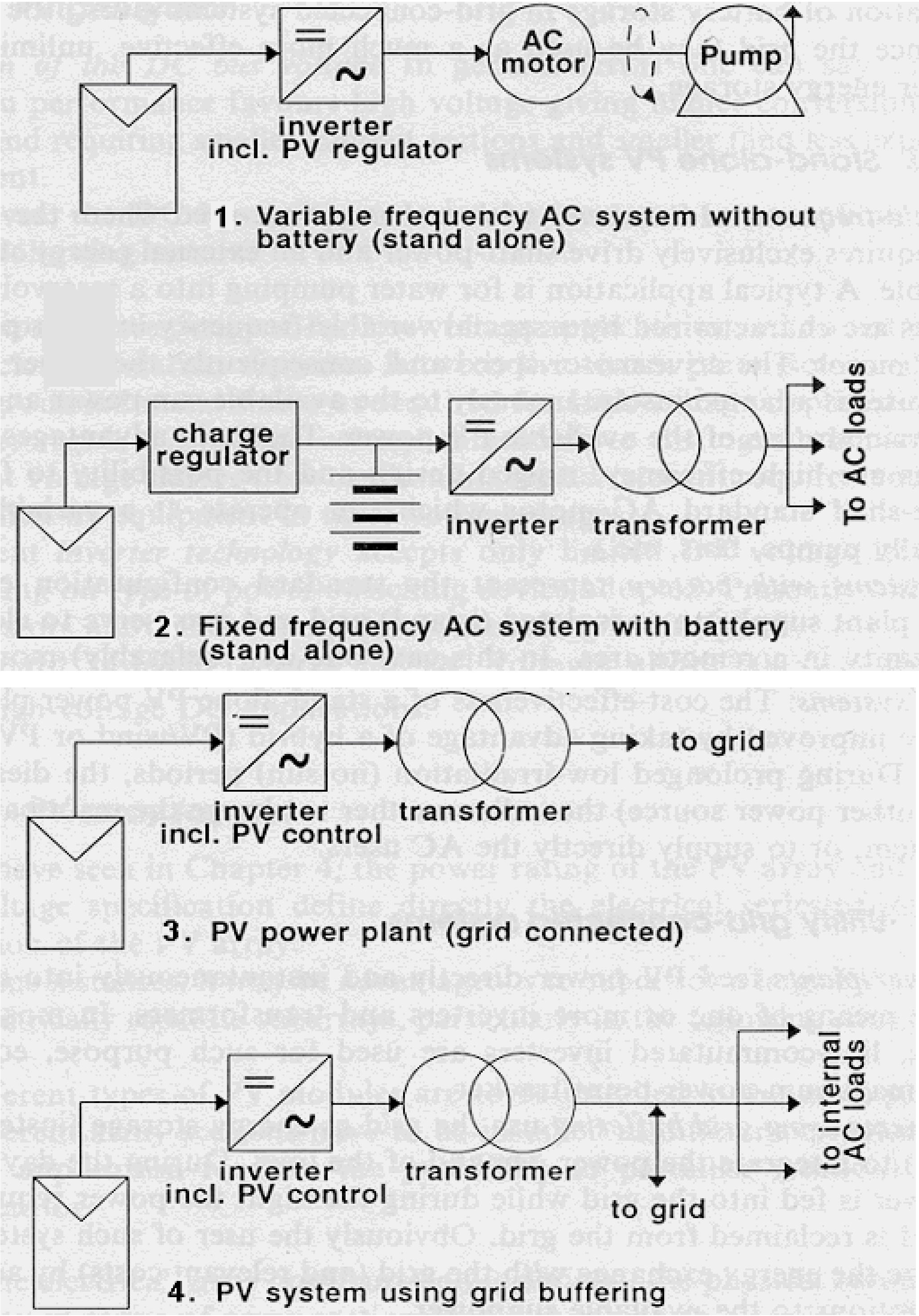


Figure 3.2c: *Configuration of a residential grid-connected system. (Solar Electricity, Tomas Markvart)*



1. Variable frequency AC system without battery (stand alone)

2. Fixed frequency AC system with battery (stand alone)

3. PV power plant (grid connected)

4. PV system using grid buffering

Figure 3.2d: *Different types of large PV-systems. (Solar Electricity, Tomas Markvart)*

- **PV – hybrid systems**

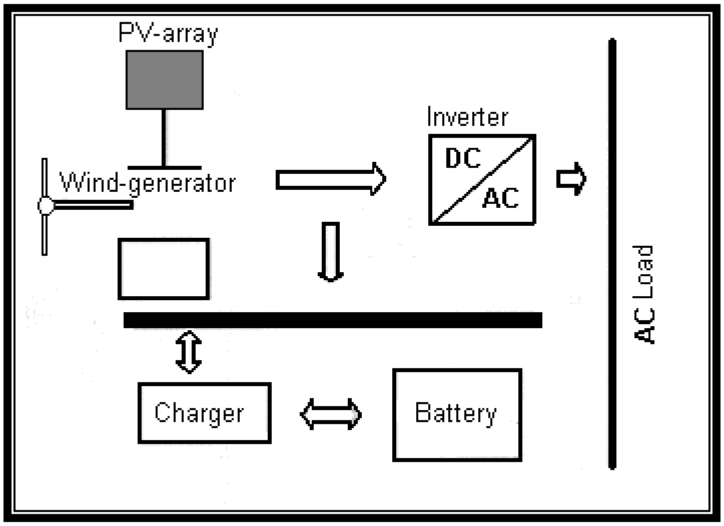


Figure 3.3: *A PV-hybrid system made up by a PV-array and a Wind generator. There is no back –up system except for the battery. In fig 3.4 below the back-up system consists of a Diesel, too.*

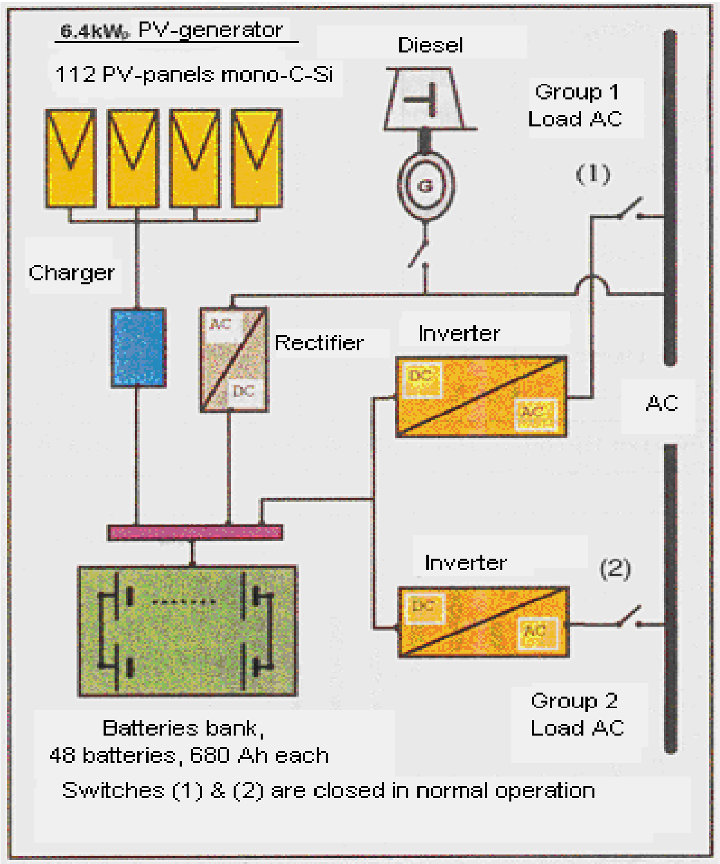


Figure 3.4: *A PV hybrid system used in a Hotel "Elounda" in Crete. The system is split in two DC/AC inverters for flexibility and effectiveness reasons. A Diesel is used to feed with power, when the PV system does not produce enough power. Then, the Diesel may charge batteries, too. For this reason a rectifier is used.*

Table 3.1: *Appliances & Loads for the Hotel Elounda in Crete, Greece*

Appliances	Power/unit. (W)	Number of units	Operation h/day	Load/day (Wh/day)
Internal Lighting	30	110	1	3300
Outside Lighting	25	30	6	4500
Refrig. in rooms	100	11	6	6600
1 Big Central Refrigerator.	400	3	11	13200
2 Big Central Refrig.	300	1	11	3300
Long waves cooker	1200	1	1	1200
Pump	750	1	2	1500
Biological cleaning	400	1	2	800
Traps for flying insects	20	15	5	1500
Others	200	22	1	4400
Total Daily Load				**40300Wh/day**

Problem 3.1

Estimate some other details for the PV-system shown in fig. 3.4. What is the Peak Power installed?

Details of the PV-system shown in fig.3.4 are given in the following:

a. In this figure a hybrid system consists of a PV-generator of 6.4 kW_p, with 112 PV-panels, mono-c-Si of 57 W_p each $\Rightarrow 112 \times 57 W_p/each = 6.4kW$.

b. The PV-inclination is $\beta=30^0$. Why such a low inclination?

The designer put two DC/AC inverters of 685 kWA each (voltage output 220 Volts, voltage input 48 Volts). So, there is a requirement of 48 Volts.

c. This 48 Volts come from the 24 batteries in series, because there are two series of batteries in parallel $\Rightarrow$ 24 batteries × 2 Volts = 48 Volts.

The typical loads for a Hotel to be taken into account, as fig.3.4 shows, are given in Table 3.1.

Remark:

Total Daily Load: 40300Wh = 40.3kWh [Energy]

PV- power installed 6.4 kW [Power]

Question: How this power was estimated?

Answer: This has to do with the quantity called Peak Solar Hour (PSH) to be studied in §3.2. If ones estimates PSH for this day of the month for the inclination of the PV-array and multiplies with the PV-power (W_p), then the product just meets the Daily Load.

⇒ Another hybrid PV-system, which consists of a PV-generator and a Diesel, with batteries as a storage system for short back up periods, is shown in fig.3.5.
The PV-system components are clearly shown and are self-explanatory.

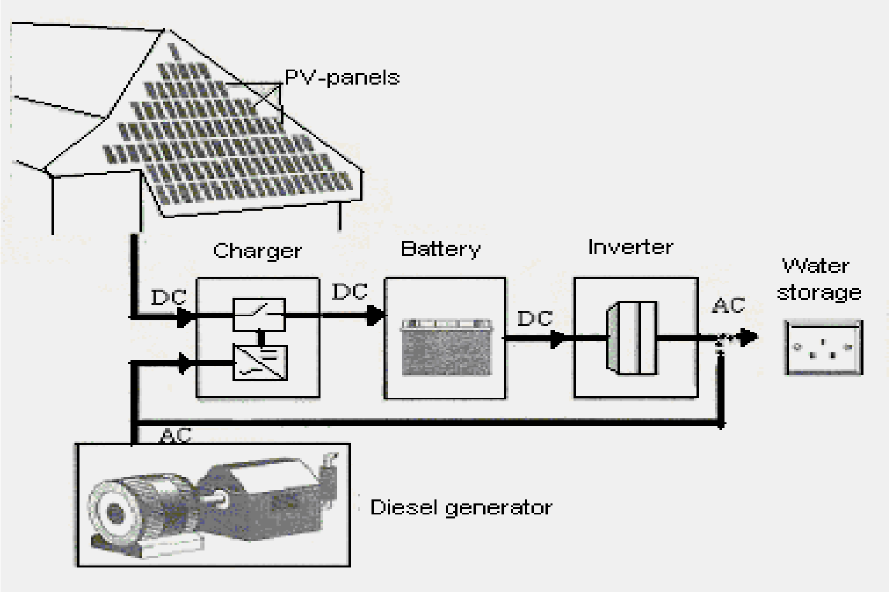


Figure 3.5: *A PV-generator of 4 kW_p at Monte-Negro (Germany) coupled to a Diesel.*

A Simple Problem 3.2, for a PV-panel power output.

Let some Si PV-panels, have $A_p = 0.4\ m^2$. Let them consist of 40 PV-cells , 100 cm^2 each.
Let, $\mathbf{i_{m(cell)}} = 2.5$ A , which is a typical value, as discussed in Chapter I, Table 1.2, with $\mathbf{V_m} = 0.5$ Volts.
Then, the power $\mathbf{P_{m,c}}$ each cell provides at its MPP , $\mathbf{P_{m,c}} = 25\times0.5 A\cdot V = 1.25$ W. Hence, the PV-panel produces , $\mathbf{P_{m,panel}} = 40\times1.25\ W = 50\ W_p$

3.2 **P**eak **S**olar **H**our (**P.S.H.**)

For convenient calculations concerning the Power and the Energy delivered during a day by a PV-generator, one defines the **P**eak **S**olar **H**our (**P.S.H.**).
To make this term understood, let us take fig.3.6, which shows the solar intensity on the horizontal in Patra, Greece during the14th of July.

One may easily notice that the intensity at horizontal is always less than 10^3 W/m^2, during that day. To estimate the efficiency and the power delivered one, should normalize the intensity to 10^3, due to the **S.T.C**. convention, see §1.2.9.

P.S.H. is defined as the time length (in hours) for a given day, under the assumption that solar insolation is constant to 10^3 W/m^2 during this time length; the **PSH** value should be such that the energy, **E**, estimated under the above assumption **[E=P×(PSH)]** is equal to the real case i.e. the one which is obtained by the integration of the area under the curve in fig.3.6.

This statement is explained graphically in fig 3.6, below.

- **Remark:**

P.S.H. is a number in hours equal to the daily energy (irradiation) in kWh/m^2

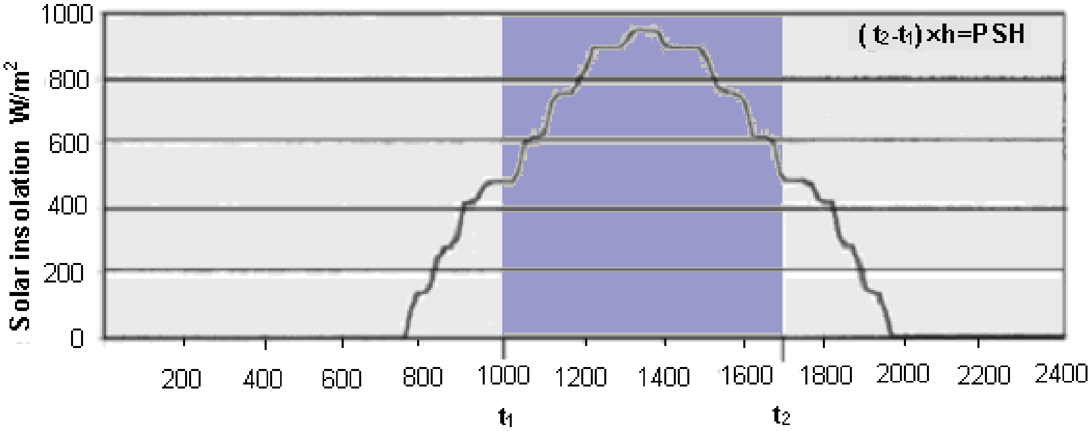


Figure3.6: *Global Solar insolation at horizontal at Patra , Greece (14.07.2001).The shadowed area : having as one side the P.S.H and height equal to 10^3w/m^2 is equivalent to the surface under the insolation curve.*

The figure in the above analysis holds for the horizontal.

However, when we analyze inclined PV-panels, then we have to convert solar insolation to the inclined plane. We do this by multiplying $\mathbf{I_h}$ (solar intensity) or $\overline{\mathbf{H}}_h$ (daily energy) at horizontal by a factor $\overline{\mathbf{R}}$.

$\overline{\mathbf{R}}$ is a conversion factor converting H_{hor} to H_T on the inclined PV-panel.

$\overline{\mathbf{R}}$ is a function of φ (latitude), inclination to horizontal (β), and the month.

More about $\overline{\mathbf{R}}$, see bibliography; also § 5.6 and Appendix IV.

Problem 3.3

From the Table 3.2 which gives the monthly global radiation at horizontal in Patra estimate the Daily global solar irradiation (kWh/m^2) on a plane at inclination of 45^0 to horizontal. Calculate the PSH per month for a PV-panel at 45^0 to horizontal.

Solution:

The procedure to convert monthly solar global irradiation values from column 3 of Table 3.2 to daily irradiation on a plane at 45^0, expressed in kWh/m^2, are self explanatory and are shown in the Table below.

The effort is to:

a. determine the conversion factor, $\overline{\mathbf{R}}$, using the proper formulae for $\overline{\mathbf{R}}$, as in § 5.6, equation (5.12). $\overline{\mathbf{R}}$ values are given in column (1). This task is left to the reader.

b. calculate the mean daily irradiance from the monthly one, by dividing the monthly value over the number of days of the month column (2).

c. multiply the above value by the convertion coefficient $\overline{\mathbf{R}}$ and divide by 3600 to convert the value to kWh/m^2.

Table 3.2: *Mean monthly and mean Daily global solar irradiation (kWh/m^2) at horizontal and on a plane at 45^0 in Patra, Greece.*

Month	$\overline{R}$ Convertion coefficient from horizontal to 45^0 (1) *see next chapter	Number of days per month (2)	Monthly global irradiation (MJ/m^2) (3)	Daily irradiation at 45^0 , in kWh/m^2, $\frac{(1)\times(3)\times 10^3}{(2)\times 3600}$ (4)	PSH (h) (5)
J	1.655	31	220	3.28	3.28
F	1.380	28	259	3.55	3.55
M	1.160	31	400	4.16	4.16
A	0.965	30	493	4.40	4.40
M	0.845	31	684	5.18	5.18
J	0.790	30	745	5.45	5.45
J	0.810	31	781	5.67	5.67
A	0.920	31	713	5.88	5.88
S	1.105	30	526	5.38	5.38
O	1.355	31	367	4.46	4.46
N	1.610	30	241	3.58	3.58
D	1.700	31	187	2.85	2.85
Average value				4.49 $\left(\frac{\mathrm{kWh}}{\mathrm{m}^2}\right)$	4.49h

Notice: *The numbers in columns (4) and (5) are the same, as explained above, but of course have a different meaning, as they represent completely different quantities.*

Remark:

The Question & Answer under the Table 3.1, is associated to PSH for the summer for Crete, for the inclination β=30^0. This PSH is a bit higher than 6 hrs for Crete. So, multiplying P_m=6.4kW with the PSH for Crete, 6h, one get a value close to 40.3 kWh which is the load to be met. This procedure outlines a simple solution to the sizing of PV- sizing systems.

Problem 3.4

Let us study a PV-system in Patra, Greece, which must provide to the load $\mathbf{R_L}$, a mean current, i_L=1.5A during all year long.

Estimate the number N of PV-panels and the configuration of the circuitry.

Solution

Let the system be inclined at $\beta=45^0$. This is a value quite effective for having a high annual average. In such cases holds: $\boldsymbol{\beta \cong \varphi}$ **(latitude).**

Let these PV-panels be connected as fig. 3.7 shows.

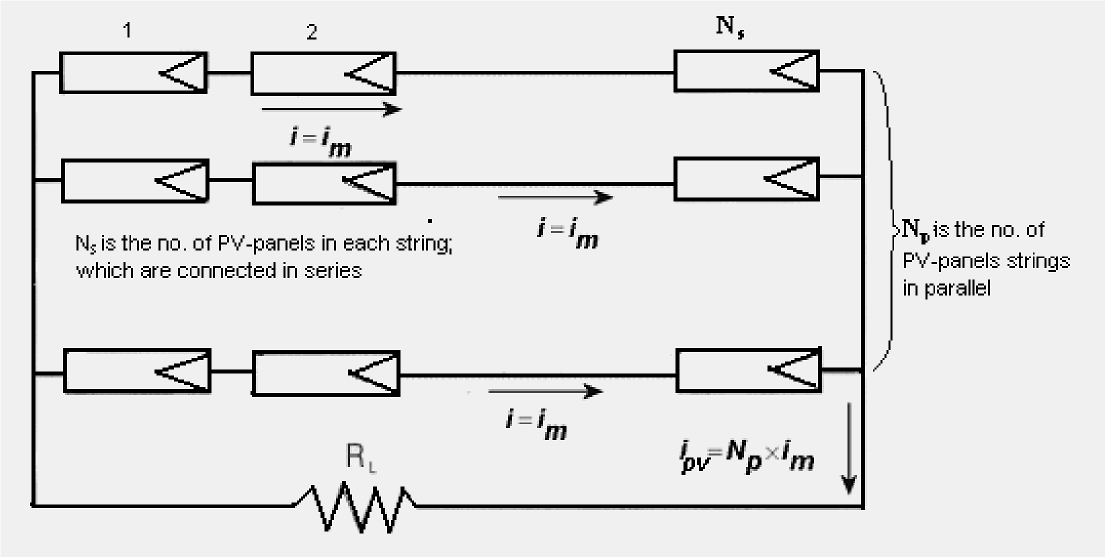


Figure 3.7: *A schematic circuitry of PV-panels, which form the PV-generator studied.*

Let $\mathbf{N_s}$ be the PV-panels in series and $\mathbf{N_p}$ is parallel.

Then, $\mathbf{N=N_s \times N_p}$

Let the solar irradiation be as Table 3.2 provides.

The energy, $\mathbf{E_L}$, for the load per day can be given by:

$$\mathbf{E_L\left(\frac{Wh}{day}\right)=PSH\times V_{DC}\times i_{pv}}, \tag{3.1}$$

where, $\mathbf{i_{pv}}$ is the current the PV-generator provides under the condition which holds for the period PSH.

Similarly, one may write for $\mathbf{E_L}$ the following expression:

$$\mathbf{E_L\left(\frac{Wh}{day}\right)=V_{DC}\times i_L\times 24\,h/day}, \tag{3.2}$$

Hence, from the above equations, one obtains:

$$\mathbf{i_{pv}} = \frac{\mathbf{24\,h/day \times i_L}}{\mathbf{PSH}}, \tag{3.3}$$

Substituting, $\mathbf{i_L}$ and **PSH** to eq.(3.3) with the value of $\mathbf{i_L}$ given above and the **PSH** as calculated before, we get:

$$i_{pv} = \frac{24\,h/day \times 1.5A}{4.49\,h/day\,(see Table 3.2)} = \mathbf{8.02A}$$

Let, now 2.1A be the $\mathbf{i_m}$ current that the PV-panels generate at MPP, at S.T.C..
Then, the number of the parallel strings of PV-panels, according to the 1st Ohm's law is :

$$N_p = \frac{i_{pv}}{i_m} = \frac{8.02A}{2.1A} = 3.81 \tag{3.4}$$

The integer number closest to 3.81 is $[N_p]$=4.
So, we set N_p=4, that is 4 parallel strings of PV-panels. However, we have not determined $\mathbf{N_s}$ i.e. the number of PV-panels in each string.
Having chosen this larger integer value for $\mathbf{N_p}$, one has to define a sizing factor, (**SF**), which equals to:

$$(SF) = [N_p] \cdot \frac{i_m}{i_{pv}} = \frac{4 \times 2.1A}{8.02A} = 1.047 \tag{3.5}$$

That is, we have oversized the system by 4.7%.

- The number of $\mathbf{N_s}$ is obtained from the Voltage required, **V**, over the $\mathbf{V_m}$ value of the PV-panel. i.e. :

$$\mathbf{N_s} = \frac{\mathbf{V}}{\mathbf{V_m}} \tag{3.6}$$

- However, as the problem does not specify what Voltage is required to be fed to the load we cannot determine $\mathbf{N_s}$.

Notice: *once again, that the design chooses as* $\mathbf{N_s}$ *the closest integer* $\mathbf{[N_s]}$ *higher to* $\mathbf{N_s}$*.*

- The values of Table 3.2, either the mean daily irradiation in kWh/m^2 per month or the PSH values per month, can be used to make the histogram, which is shown in fig3.8.

Verification:

We construct the Table 3.3 below with the $\mathbf{i_m}$ values of the PV-panels assumed at S.T.C. equal to i_m=2.1 A. As $\mathbf{N_p}$ was determined equal to 4 and PSH was estimated in Table 3.2, one can easily estimate $\mathbf{i_L}$ from eq.(3.3). The annual mean value of $\mathbf{i_L}$ should be equal to 1.5 A, as set by this exercise at the very beginning.

Table 3.3: *Monthly i_L values*

Month	$\mathbf{i_m}$ (1)	$\mathbf{N_p}$ (2)	**PSH** (3)	$\bar{\mathbf{i}}_L$ (1)×(2) ×(3)/24
January	2.1	4	3.26	1.14
February	2.1	4	3.55	1.24
March	2.1	4	4.16	1.46
April	2.1	4	4.41	1.54
May	2.1	4	5.18	1.81
June	2.1	4	5.45	1.91
July	2.1	4	5.67	1.98
August	2.1	4	5.88	2.06
September	2.1	4	5.38	1.88
October	2.1	4	4.46	1.56
November	2.1	4	3.58	1.25
December	2.1	4	2.85	1.00
Average value			4.49h	$\bar{\mathbf{i}}_L$ =1.57 A

Remarks:

1. The calculation, really, provides for i_L=1.57A.

This value 1.57 is by 4.7% higher than 1.5 A : $\left(\frac{1.57-1.5}{1.5}=0.047\right)$, which is the effect of the oversizing.

2. For more accurate calculations one should take into account the change of i_m during the year.

Figure 3.8 below provides the monthly solar irradiation in Patra and simultaneously the monthly PSH values.

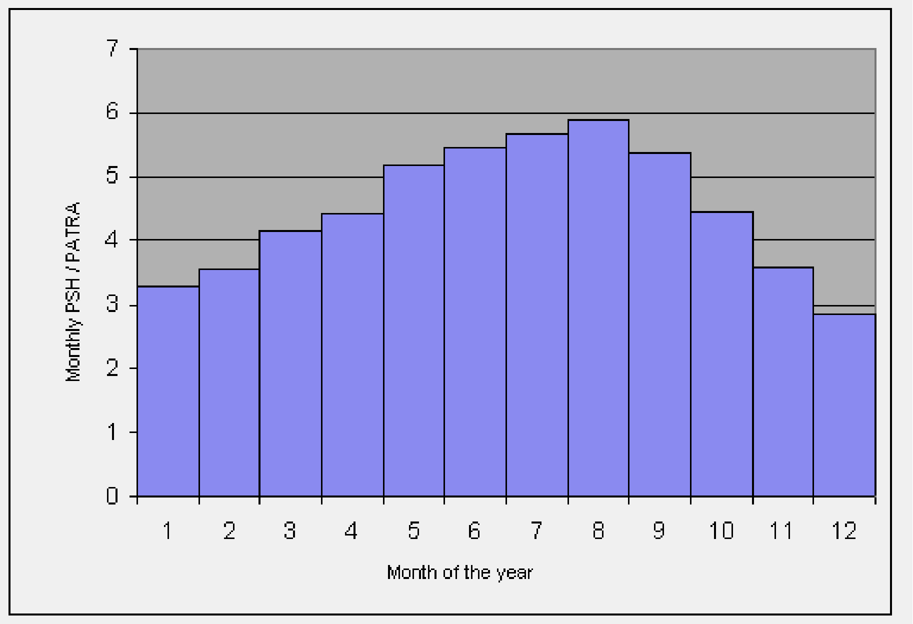


Figure 3.8: *The figure provides in this histogram the mean monthly energy (in kWh/m^2) and the P.S.H. for Patra city in Greece.*

- The $\mathbf{i_L}$ values for each month, as calculated above and given in Table 3.3, are shown by the following histogram.

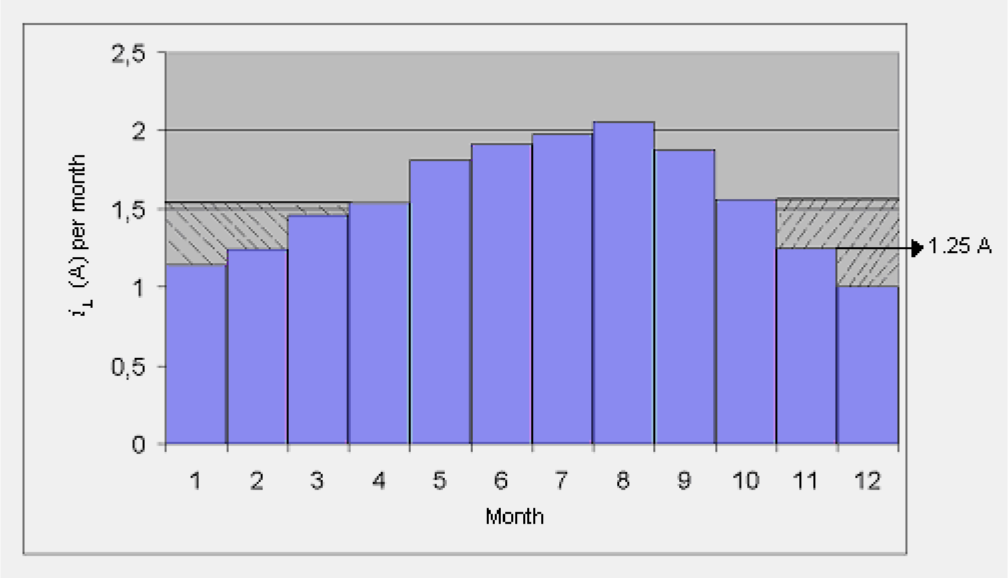


Figure 3.9: *This histogram gives the $\mathbf{i_L}$ values per month. From these $\mathbf{i_L}$ values, $\mathbf{i_{pv}}$ may be obtained, using Table 3.3 and eq. (3.3).*

- **Analysis**

From the histogram above:

1. One may distinguish the months that supplementary electric energy is required.
2. Also, if one assumes that for three days, d=3, there might be no sunshine, then the PV-system should be equipped with a conventional back-up or additional

PV-panels should be assumed in the sizing to provide more energy. This energy should be stored in batteries and be used during the period of no or inadequate sunshine.

The charge required for these **d** days is:

$$\mathbf{Q_L = d \times i_L \times 24\ h/day} \tag{3.7}$$

For example, for November the deficit is equal to:

(1.25-1.5)×24 h/day ×30 day = -180Ah (see fig 3.9) or 180 Ah are required.

The total additional charge required is the one estimated by the shadowed parts of the histogram, due to insufficient sizing.

One, then, has to add the charge required for the energy independence policy of the PV-system for **d**=3 days, that is:

$\mathbf{Q_L = d \times i_L \times 24\ h/day = 3 \times 1.57\ A \times 24\ h = 113\ Ah}$

Hence, the total additional charge required for November is equal to:

(180+113) Ah=293Ah.

Problem 3.5

Estimate the number of PV – panels, you may choose, and the configuration to make an array in Bucharest region to meet a load of 1.5 MWh per annum.

1. **Let's choose PV-panels with P_m = 45W at i_m=2.6A.**
2. **Estimate (P. S. H.)**

The annual mean **PSH** value for Bucuresti is given in the relevant Table in Appendix IV. We determine **PSH**=3.63 h.

Remember that these 45W per PV – panel are delivered at MPP when $I=10^3\ W/m^2$.

For a more detailed estimation, one should use each month's PSH value.

⇒So, each PV-panel produces:

$$\mathbf{45W \times 365Wdays \times 3.63h/day = 59.6kWh/PV - panel}$$

Then, $N_{PV} = \dfrac{1500kWh/annum}{59.6kWh/annum} = 25.2PV - panels\,of \quad 45W \cong 26$ PV-panels.

3. **Estimate N_P and N_S.**

Let, the voltage at $\mathbf{R_L}$ should be 50Volts : $V_{R_L} = 50Volts$, while.

$$E_L(kWh/day) = \frac{1500kWh/annum}{365days/annum} = 4.11kWh/day$$

We alredy know that :

$E_L = i_L \times V_{DC} \times 24h/day$, that is: $4110\dfrac{Wh}{day} = i_L(A) \times 50V \times 24\dfrac{h}{day}$

$\Rightarrow \boldsymbol{i_L} = 3.425A$

Also,

$$\boldsymbol{E_L} = \boldsymbol{i_{pv}} \times \boldsymbol{V} \times \boldsymbol{PSH} \Rightarrow 4110\frac{Wh}{day} = i_{pv}(A) \times 50V \times 3.63\frac{h}{day} \Rightarrow i_{pv} = 22.6A$$

From the above we get :

$$\mathbf{i_{pv}} = \mathbf{24h} \times \mathbf{i_L/PSH} = \frac{24 \times 3.425}{3.63} = 22.6\,.$$

Hence, $\boldsymbol{N_P} = \frac{\boldsymbol{i_{pv}}}{\boldsymbol{i_m}} \cdot \boldsymbol{(SF)} = \frac{22.6}{2.6} \cdot (SF) = 8.69 \cdot (SF) \cong 9$

$\boldsymbol{N_S} = \frac{\boldsymbol{V}}{\boldsymbol{V_m}} = \frac{\boldsymbol{50}}{\boldsymbol{V_m}}$. We determine $\mathbf{V_m}$ from: $\mathbf{P_m} = \mathbf{i_m} \times \mathbf{V_m} \Rightarrow \mathbf{V_m} = 17.3 Volts$

$\Rightarrow$ Hence, $\boldsymbol{N_s} = \frac{50}{17.3} = 2.89 \to [N_s] = 3$

- **How to determine N$_P$, in general.**

→ Let $\mathbf{i_{pv}}$ is the current delivered by the PV – generator to meet the load. This will be for the case of I=10^3W/m^2 and for the operation at MPP.

→ Let i_m the current at MPP by PV – panel used.

$\Rightarrow \boldsymbol{N_P} = \frac{\boldsymbol{i_{pv}}}{\boldsymbol{i_m}}$.

- **Analysis**

Let, Load, $\mathbf{R_L}$, requires $\mathbf{E_L}$(Wh / day), under $\mathbf{V_{DC}}$.

Let the PV – system operates all the 24 hrs of a day.

$\Rightarrow$ we define an average current $\mathbf{i_L}$ for $\mathbf{R_L}$; while the PV – generator under I_T will provide the system, as we said, with $\mathbf{i_{pv}}$ under $\mathbf{V_{DC}}$ Volts.

$$\Rightarrow \boldsymbol{i_L} = \frac{\boldsymbol{E_L (Wh/day)}}{\boldsymbol{V_{DC}} \times \boldsymbol{24(h/day)}} \quad .$$

3.3 Batteries

In PV-systems, either autonomous or hybrids, it is necessary to include in the design, a power storage system i.e. battery banks.

This stored power is to be used when the PV-generator does not operate or does not produce adequate power to meet the loads, as analyzed in the previous sub-chapter.

The most commonly used batteries in PV-systems are the ones of Pb-acid.

3.3.1 Battery characteristics:

1. **Capacity: C (Ah):** $\mathbf{C(Ah)=i_{disc}(A)\times t(h)}$ (3.8.a)

where $\mathbf{i_{disc}}$ is the current which provides a battery when discharges.

2. **Electric Energy (E.E.): EE** (Wh)=**V** (Volts)×**C** (Ah)=**V**×**C**.(Wh) (3.8.b)

Let **C=200 Ah**.

This implies that the battery provides:

100A	in	t=2 h, or
50 A	in	t=4 h, represented by C/4
25 A	in	t=8 h, represented by C/8
20 A	in	t=10 h, represented by C/10
10 A	in	t=20 h, represented by C/20

In general, the smaller the discharge, rate, the higher the available capacity is, see fig. 3.10**.**

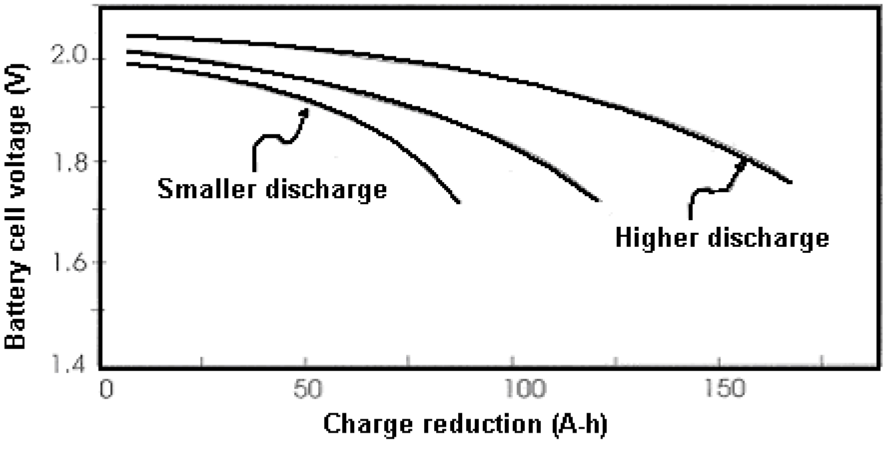


Figure 3.10: *The effect of discharge rate to the available energy or equivalently the available capacity in* ***Ah*** *for a Pb- acid battery.*

3. The capacity, **C**, depends on the temperature, **T**, too:

$$\frac{C}{C_0} = 0.00575 \times T + 0.54 \quad [\text{ T in } {}^0\text{F }], \qquad (3.9)$$

To convert **T** from **^{0}F** to **^{0}C** use the expression:

$$\frac{100 - {}^0 C}{212 - {}^0 F} = \frac{5}{9} \qquad (3.9a)$$

4. **DOD: D**epth **o**f **D**ischarge

DOD is the % of the nominal capacity of the battery that is available for use. The value is given by the manufacturer.

- For shallow Batteries: **DOD 10%-25%**
- For Deep Discharge Batteries: **DOD 80%.**

This implies, for C=200Ah, that the battery may provide during a low discharge rate: $0.8 \times 200Ah = 160Ah$, provided that: Temperature is 27 ^{0}C, and

$i_{disch} \leq C/20$ i.e. for C=200 Ah, the discharge current showld be: (3.10)

$i_{disch.} \leq 200/20 \leq 10A$.

5. **Self-Discharge:** Batteries undergo self-discharge. Typical rates are:

at	T=5^{0}C	2%	per month	self-discharge
at	T=15^{0}C	4%	per month	self-discharge
at	T=25^{0}C	10%	per month	self-discharge
at	T=40^{0}C	25%	per month	self-discharge

6. **Efficiency of battery:** It may be defined in two ways:

a. by the **Ah stored** or

b. by the **Wh stored**

$$\eta_B(Ah) = \frac{(Ah)_{disch}}{(Ah)_{ch}} \quad \text{; typical values} \quad \eta(Ah) = 0.9 \rightarrow 1. \qquad (3.11)$$

$$\eta_B(Wh) = \frac{(Wh)_{disch}}{(Wh)_{ch}} \quad \text{; typical values} \quad \eta(Wh) = 0.8 \qquad (3.12)$$

7. **SOC** (**S**TATE **O**F **C**HARGE)

SOC or **SOC(t)** provides the **Ah** stored available by the battery at time t.

Sometimes, we use **SOC** to give the **percentage of C** of a battery that is available at a given time.

The quantities: **i, V, SOC**, are inter-related.

From the above analysis, one gets:

$$\boxed{\textbf{SOC = Q(t)/C}_\textbf{b}\textbf{ = Charge (Coulomb) of battery at t/nominal capacity}} \quad (3.13)$$

Also, it can easily be proven that:
DOD = 1-SOC (3.14)

Notice: *Effective recharging takes place when* ***SOC****<0.7 and the Voltage of the battery cell is < 2.3Volts.*
The efficiency, η for ***(re)charging*** *reaches zero (0) as* ***SOC*** $\rightarrow$ ***Q_b****, where* ***Q_b*** *is the maximum charge that the battery can hold.*

- For Pb batteries with high **DOD**, holds:

$$\boxed{\textbf{Cycles} \times \textbf{DOD} \approx \textbf{1200}} \quad , \quad (3.15)$$

where : **Cycle = Charge – Discharge cycle operation.**

Problem 3.6

Let an energy scenario to meet the load demand of 83 Ah/day. Let us choose batteries of 300Ah with DOD=80%=0.8.
Try to investigate on the decision for the battery choice.

Solution

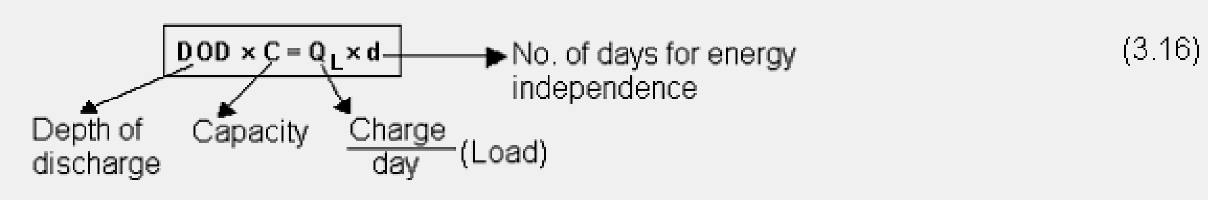
From the above, data in a day the (**DOD**) Depth Of Discharge $= \frac{83Ah}{300Ah} = 0.28$

This implies that if the load draws energy from the battery for 3 days, i.e.(d=3 days). Then, the final depth of discharge will be: $0.28 \times 3 = 0.84$ or 84%, which is very close to DOD=0.80.

Conclusion: Such a battery may surely stand an autonomy for d=3 days according to the energy scenario of 83 Ah/day, as set above.
Of course, the economic analysis based on prices and cycles to sustain will give the optimum choice.

This issue is delt in § 3.3.3 later on.

3.3.2 Generally, the following relationship holds



- The battery capacity, $\mathbf{C_N}$, to meet load $\mathbf{Q_L}$ with energy independence of **d** days is estimated by:

$$\mathbf{C_N} = \frac{\mathbf{C_L}}{\mathbf{1} - \mathbf{t_b} \times (\mathbf{C_c} + \mathbf{C_a})} \quad \textbf{,} \text{ where} \qquad (3.17)$$

$$\mathbf{C_L} = \frac{\mathbf{Q_L} \times \mathbf{d} \times \mathbf{f_c}}{\mathbf{V} \times \mathbf{DOD}} \qquad (3.18)$$

which is a more general expression of eq. (3.16).

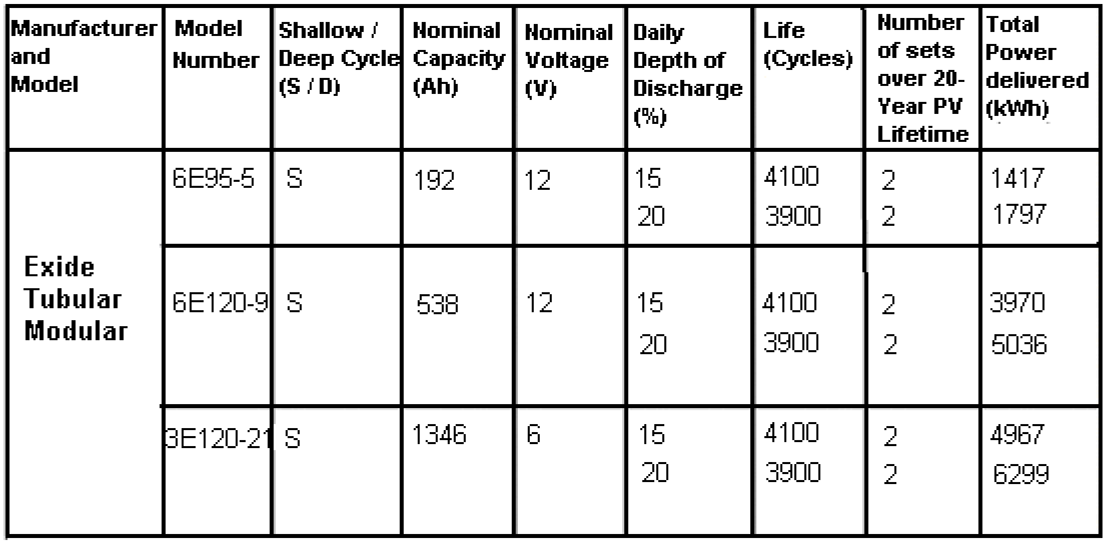
$\mathbf{t_b}$**:** no. of years that the battery will run effectively (according to specifications)
$\mathbf{Q_L}$**:** daily load (Wh/day). It depends on the external consumers or loads
$\mathbf{C_c} \approx 0.007\text{-}0.01$. it is a correction factor due to cycles / recycling
$\mathbf{C_a}$: correction due to the ageing of the battery. i.e. charging-discharging.
More specifically:
$\mathbf{C_a} \approx 0.015$ (for a battery with flow of electrolyte) and 0.020 (for conventional electrolyte)
f_c: correction due to Joule effect in battery
V: voltage across battery.

Problem 3.7
Let a stand alone PV-generator, designed to meet the load for a building in Bucharest. Let the Load be 100Ah/day. The voltage to be established due to DC/AC load requirements is V = 48Volts. The energy autonomy is assumed to be d = 3days. Determine the details of the battery bank and the type of the batteries to be used.

- **Step 1:**

Let's choose: Exide Tubular Modular of 192 Ah, see Table 3.4 below.

Table 3.4a: *Battery detailed information*



Manufacturer and Model	Model Number	Shallow / Deep Cycle (S / D)	Nominal Capacity (Ah)	Nominal Voltage (V)	Daily Depth of Discharge (%)	Life (Cycles)	Number of sets over 20-Year PV Lifetime	Total Power delivered (kWh)
Exide Tubular Modular	6E95-5	S	192	12	15 20	4100 3900	2 2	1417 1797
	6E120-9	S	538	12	15 20	4100 3900	2 2	3970 5036
	3E120-21	S	1346	6	15 20	4100 3900	2 2	4967 6299

Table 3.4b: Other types of batteries according to manufacturers.

Manufacturer and Type	**Model**	**Nominal Capacity (Ah)**	**Nominal Voltage (V)**	**DOD (%)**	**Life Cycles**	**Total to be delivered Energy (kWh)**
GNB Absolyte	638	42	6	50	1000	126
	1260	59	12	50	1000	359
	6 – 35A09	202	12	50	3000	3636
	3 – 75A25	1300	6	50	3000	1700
Exide Tubular Modular	6E120 – 5	192	12	15 20	4100 3900	1417 1797
	6E120 – 9	538	12	15 20	4100 3900	3970 5036
	3E120 – 21	1346	6	15 20	4100 3900	4967 6299
Delco – Remy Photovoltaic	2000	105	12	10 15 20	1800 1250 850	227 236 214
Global Solar Reserve gel Cell	3SSSSRC – 125G	125	6	10	2000	150
	SRC – 250C	250	2	10	2000	100
	SRC – 375G	375	2	10	2000	150
Globe	GC12 – 800-38	80 80	12 12	20 80	1500 250	288 240
GNB Absolyte	638	40	6	80	500	96
	1260	56	12	80	500	269
	6 – 35A09	185	12	80	1500	2664
	3 – 75A25	1190	6	80	1500	8568

Let the Table’s specifications for this battery type be:
DOD=0.20, C=192 Ah, V=12 Volts, Life Cycles (L.C.)=3900, 4.9 years

- Is it a successful choice? To answer we follow the analysis below:

a. Let the 100 Ah be required in 8 hours. (Assumption of the load scenario)

$\Rightarrow \quad \boldsymbol{i}_{disch.} = \dfrac{100Ah}{8h} \approx 12.5A$. This is a high discharge rate > $C/20 = \dfrac{100Ah}{20h} = 5A$.

So, it has a negative effect to the available capacity. Later on in “Case Studies” (Chapter V), we will estimate the correction to the capacity due to high discharge rate.

b. $\boldsymbol{DOD}_{day} = \dfrac{100Ah}{192Ah} = 52.08\%$, which is bigger than 20% according to the specification for DOD of this battery type.

This is , also, a big disadvantage for the case when only one battery might be used. One should look for the case in detail as more batteries would rather be connected in parallel. A detailed investigation is required. This is to be analyzed below.
The battery’s circuitry depends also on the voltage to be developed across the battery bank, also effects. This is governed by the voltage input to the DC/AC inverter or to the loads, which depends on the PV-system configuration.

c. As discharge rate is somehow high, the available capacity will be less than 192 Ah. A proper diagram is required, as the one of fig.3.11, which holds for Delco 2000 type of battery.
Let this corrected capacity be 170-180 Ah instead of 192 Ah.

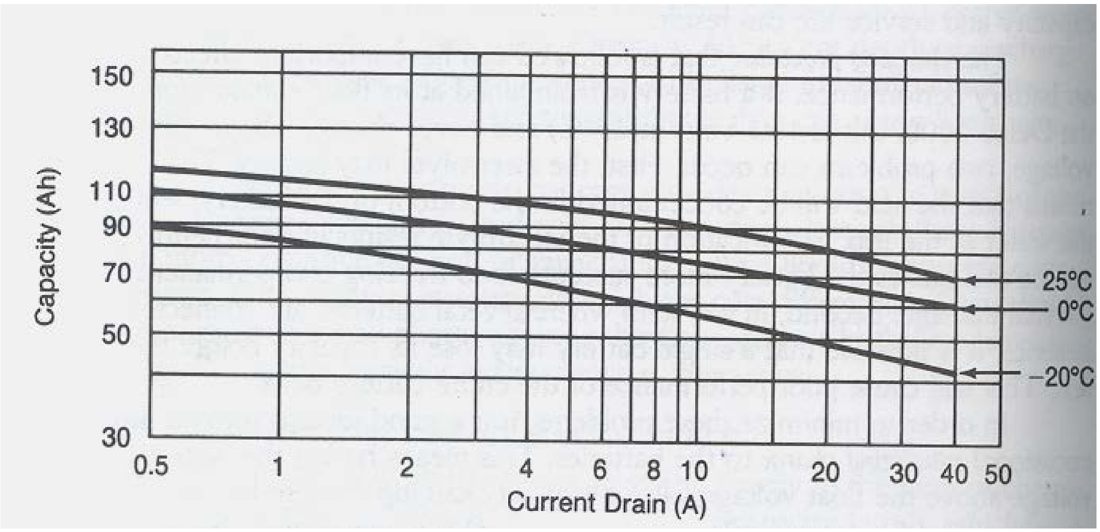


Figure 3.11: *A graph showing amp-hour capacity as a function of temperature and discharge rate for the Delco 2000 battery.*

Hence, the available capacity is

$\boldsymbol{DOD \times 180Ah = 0.20 \times 180Ah = 36Ah \ll 100Ah}$

Perhaps, bad choice, but one can never decide in such an early stage.

The answer has to be given upon the final configuration of the battery bank: i.e. how many batteries will be in series and how many in parallel; see next step.

- **Step 2:**

Let us choose **GNB Absolyte** with characteristics: **56 Ah, V=12 V, DOD=0.8**

Let's us accept that for same discharge rate the following values hold:

$i_{disch.}$=12.5 A $\Rightarrow$ C=50 Ah (T=25 ^{0}C)

Then, the:

Total Usable (or Available) Capacity =T.U.C.=$C_{i=12.5\ A}$×DOD (3.19)

=50 Ah×0.8=40 Ah

- **Step 3:**

The number of battery series in parallel, $\mathbf{N_{b,p}}$ is given by:

$$\mathbf{N_{b,p} = \frac{Q_L \times d}{DOD \times C} = \frac{100\frac{Ah}{day} \times 3days}{0.8 \times 50Ah} = \frac{300}{40} = 7.5} \qquad (3.20)$$

$\Rightarrow$ Hence, the design of the batteries bank requires 8 series of batteries in parallel.

- **Step 4:**

Check if $\mathbf{DOD_{per\ day}}$ is less than $\mathbf{DOD_{specs}}$.

As 8 series of batteries will be in parallel, then the nominal charge will be $8 \times 50Ah = 400Ah$

Hence, $\frac{100Ah(Load/day)}{400Ah(available)} = 0.25$ which is **<<0.80** so, the Life Cycles will be close to the specifications, see Table 3.4b.

- **Step 5:**

The number of batteries in series is given by:

$$\mathbf{N_{b,s}} = \frac{\mathbf{V}}{\mathbf{V_b}} = \frac{48Volts}{12Volts} = 4$$

V is the Voltage required to be developed as input to the DC/DC or DC/AC or any DC Load. This V=48 Volts were given by this exercise in the data requirements of the PV-generator.

Hence the total No. of batteries **N**:

$\mathbf{N} = \mathbf{N}_{\mathbf{b,p}} \times \mathbf{N}_{\mathbf{b,s}} = 8 \times 4 = 32$ batteries.

Remark: A more detailed analysis will be given in a next version of this book.

3.3.3 Economics of the batteries and PV-generators, in general

It is essential to examine the possible solutions for those PV & battery systems as far as it concerns the economics. The **Present Worth (P.W.)** of a system is an important factor to build this economic analysis. This notion will be explained below.

The economics of the batteries is a serious issue as these elements is the weak point of the PV-system.

Hence, the **life cycle** and the number of **charge-discharge cycles** have to be considered along with DOD and the price of the battery unit, too.

1. Let the inflation be **π%** and that
2. An asset **A_0** is required for the purchase of the battery. This asset might be deposited with an interest of **ε%**.
3. Let this unit (eg. battery) costs **No** €uros at the time of the installation.

It is evident that **A_0=No**. (3.21)

However, if the asset **A_0** is deposited, then after ***n* years** it becomes:

$$A(n) = A_0(1+\varepsilon)^n \quad , \tag{3.22}$$

On the other hand, the cost of the (this) unit if to be purchased after ***n* years**, (if this good still exists & if inflation it is the same) is given by:

$$N(n) = No(1+\pi)^n \tag{3.23}$$

That is, if someone could purchase a good, at a time, with **A_0** €uros, of **No** value, then this will not hold after ***n*** years.

Therefore:

1. One defines the **present value coefficient**, **CV** as:

$$CV = \frac{A(n)}{N(n)} = \left(\frac{1+\pi}{1+\varepsilon}\right)^n \tag{3.24}$$

This helps to determine the value of the good **in present price** in case it is to be purchased at a period of ***n*** years later. (*n* = 2,3,…..)

2. The value of the unit / good in present prices is :

$$P.W. = CV \cdot No \tag{3.25}$$

Problem 3.8

Let us consider the two possible solutions for the battery banks as analyzed in the previous problem.

1st solution :	4 batteries	50 Ah each	Life: 2.7 years
2nd solution :	1 battery	200 Ah	Life : 8 years

The Question rises:
Which is the most cost effective scenario to be adopted?
As a PV-system will live for 15-20 years let's consider a life span of 16 years.
During this period, the batteries from the 1st model will be replaced 5 times, while the battery from the 2nd model only once.

	50 Ah	200Ah
Initial purchase	$150€ \times 4 = 600€$	$1 \times 850€ = 850€$
2.7years(1st replacement)	$600€ \times CV^n = 456€$	
5.4years (2nd replacement)	$600€ \times CV^n = 399€$	
8.1years (3rd replacement)	$600€ \times CV^n = 325€$	*465€* (replacement at 8 years)
10.8years (4th replacement)	$600€ \times CV^n = 265€$	
13.5years (5th replacement)	$600€ \times CV^n = 216€$	
TOTAL	*2294€*	*1315€*

Notice: ***n*** *takes the values of: 2.7, 5.4, 8.1, 10.8, 13.5 years to estimate costs using (3.23) and (3.24).*

Remark: the following data were considered for this case

- Let π%=2% and ε%=10%

Then, $CV = \frac{(1+0.02)}{(1+0.1)} = 0.92727$

- Also n(=year of battery replacement) takes values:

n = 2.7	5.4	8.1	10.8	13.5	1st scenario
n		8			2nd scenario

Conclusions:

1. It is obvious that the purchase of one battery big capacity provided it meets the technical characteristics of a PV-generator seems to be more economically. It is also more economic from the case of four batteries and also more economic because four batteries need longer wirings.

   However, the solution with one battery takes the risk that the effect of small operational problems in one battery affects dramatically the PV insolation.
2. The above analysis is based on the assumption that the 2nd solution with one battery is feasible.

   However, even if the battery capacity meets the requirement of the storage systems for example the capacity of the battery is 200Ah, while the capacity required is 192Ah, we have to check if the other requirement with the battery capacity 192Ah.

   For example: the voltage across the battery storage needs to be 48V that is for the battery for GNB Absolyte we need four such units and not only one.

So in the analysis above has to be corrected so that four battery to be considered and not only one.

The exercise is left to the reader.