CASE STUDY 3

5.13 PV-SIZING. THE CASE OF A SOLAR HOUSE IN BUCHAREST.

The owners of a house in Bucharest decided to cover the energy needs of a house with R.E.S. technologies.
For hot water and space heating the solution was solar collector systems; while all the electric appliances are to be supplied from a stand-alone PV-system.

- The sizing of this PV-system will be done using two methods:

a) the method of Wh
b) the method of Ah

- **PART A**

Sizing the PV generator by the Wh method

Steps:

1. Determine the loads per day

Let it be 2500 Wh/day i.e. 1000 Wh/day in DC; that is: 40% DC
1500 Wh/day in AC; that is: 60% AC

2. Site's details:

The inclination (β) to horizontal be chosen as $\beta \approx \varphi = 45^0$, the METEO data of this site, are given in Appendix IV. Such an inclination was decided in order to achiever an optimum annual performance.
PSH per month and its mean annual value are given in the same Table in Appendix IV.

3. Elaboration for the daily load profile:

DC Load:

Let the **DC** Load split in a DC day load and DC night load with 40% during the day and 60% during the off operation hours for the PV-panels.

a. 40% during the day when PV is on operation:

$0.4 \times 1000Wh = 400Wh/day$

b. 60% during the time when PV-generator is off, at night; that is:

$0.6 \times 1000Wh = 600Wh/day$

AC Load:

Similarly as above.

a. 40% during the day directly PV to load via a DC/AC inverter:

$0.4 \times 1500Wh = 600Wh/day$

b. 60% during the night PV through batteries :
$0.6 \times 1500Wh = 900Wh/day$ and then DC/AC.

4. Rough / preliminary determination of the PV-configuration.

The PV configuration to be studied according to the description made, may have the following lay-out:

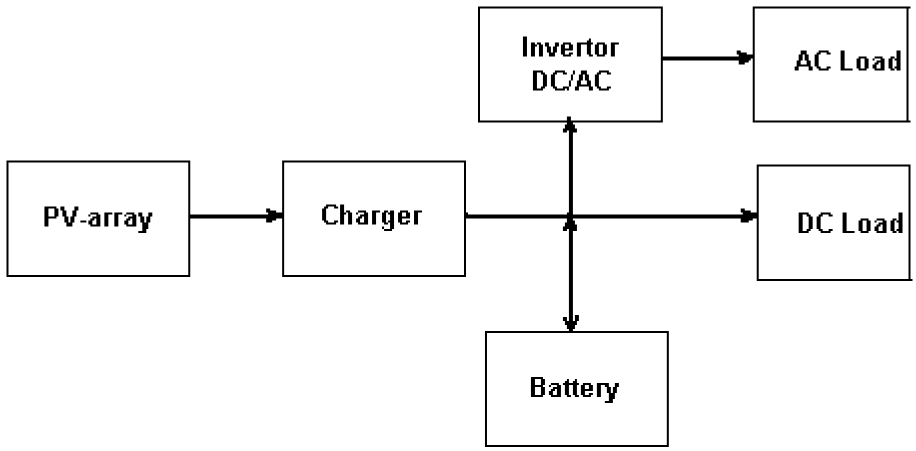

Figure 5.15: *A possible PV-lay-out to meet the loads of a Solar House*

5. Inclination to horizontal

Decide on PV-array: inclination, rotation axes etc, ground area required etc.

An investigation on various PV-inclination/rotation configurations has to be carried out for any inclination, in order to determine the most effective solution for the values of the parameters, e.g. when $\beta = \varphi$.

A detailed investigation was followed in Case Study no.1 in this Chapter.

6. Days of autonomy

Decide on days of energy autonomy of the system **d**.

Discuss on the Critical and non-Critical loads to determine **d**. Use the formulae below to estimate **d**.

Then re-discuss the PV-system-configuration to be adopted; fig.5.16.

$$d_{n\text{-}cr} = -1.9 \times (PSH)_{min} + 18.3(days)$$

$$d_{n\text{-}cr} = -0.48 \times (PSH)_{min} + 4.58(days)$$

For Bucharest (PSH) average is 3.63 while minimum is 1. So, **d** is to be 4. However, as seasonal storage or a supplement source may be used we keep **d=3** to decrease costs in batteries.

7. Correction in the loads due to losses

Table I

DC LOADS **AC LOADS**

Losses	%		Losses	%
Cabling PV-directly to loads	5			5%
Charger/cables (when via battery)	5			5%
Battery efficiency 80%	20	ch / disch in the Wh method		0%
DC/AC invertor	15	invertor efficiency 85%	DC/AC inverter	15%

Application of the above values of the losses to Loads in Step 3, produce Table II below.

Table II: *Correction of Loads*

Load	Route (see Figure 5.16)	Watt	Correction Factor	Final Load (correction value)
DC	1.2.3	400	1.05	400×1.05=420Wh
DC	1.2.4.3	600	1.25	600×1.25=750Wh
AC	1.2.5.6.7	600	1.20	600×1.20=720Wh
AC	1.2.4.5.6.7	900	1.40	900×1.40=1260Wh
Total				**3150Wh = 3.15kWh Total Final Load** **2500Wh = 2.50kWh Total Initial Load**

After the analysis made so far the PV-system configuration may change to the following:

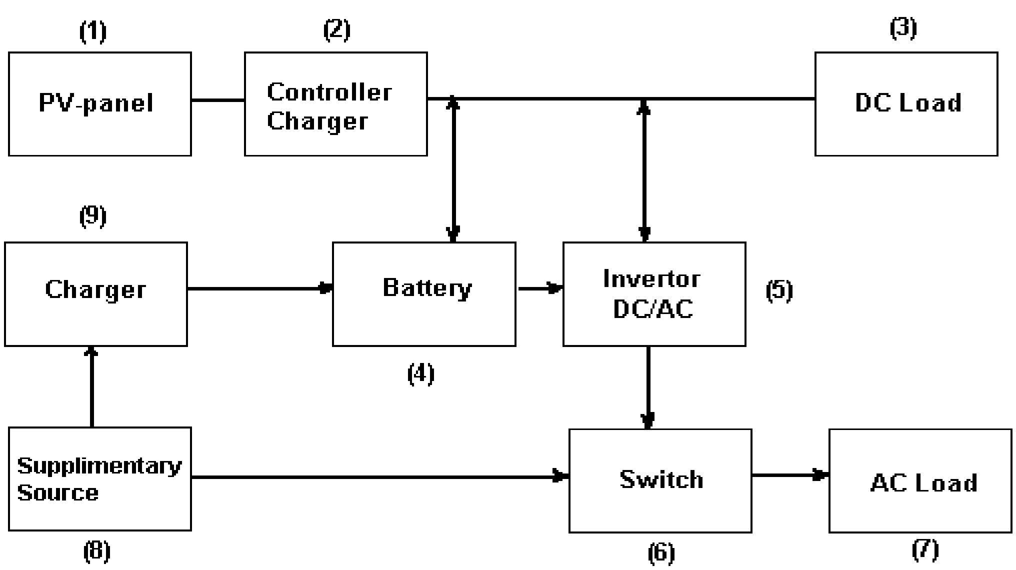

Figure 5.16: *PV-System: a Hybrid Solution*

8. **Initial / Rough W_p determination**

P_m = Load (corrected to losses): $(PSH)_{ann}$ = 3150 Wh / 5.68h = 554.6W_p

9. **Types of PV-panels to be installed.**

Decide on the PV-panels to be installed:
Let a PV type is chosen, whose characteristics are:

i_{sc} = 3.45A $\quad$ V_{sc} = 21.7Volts

i_m = 3.15A $\quad$ V_m = 17.4 Volts $\quad$ $P_m = i_m \times V_m = 54.8 \approx 55W_p$

10. **Correct P_m, V_m, i_m for the field values of the parameter, T_c.**

Lets take a PV-panel whose **NOCT** is equal to 46^{0}C.
Then, the operating temperature, $\mathbf{T_c}$, of the PV-panels is determined as follows:

$$\frac{T_c - T_a}{I_T} = \frac{NOCT - 20^0}{0.8\,kW/m^2}.$$

$\mathbf{I_T}$ should be 1kW/m^2 using **S.T.C.** as in §1.2.9.

Then, $\mathbf{T_c = T_a + \frac{46^0C - 20^0C}{0.8\,kW/m^2} \times I_T = T + \frac{26^0C}{0.8\,kW/m^2} \times 1.0\,kW/m^2 = T_a + 32.5^0C}$.

The ambient temperature for Bucharest for August is given in the relevant Table in Appendix II.

Assuming that for August the mean ambient temperature is $\overline{\mathbf{T}}_{a,Au} = 21.2^0$**C.** for Bucharest

$\mathbf{T_c}$=21.2 ^{0}C+32.5 ^{0}C=53.7^{0}C

For this temperature we evaluate $\mathbf{i_{sc}}$, $\mathbf{V_{oc}}$, **FF** and from these new conditions, we get:

a. $\mathbf{i_{sc}}$ = 3.45A ; $\mathbf{i_{sc}}$ is assumed non-dependent on temperature.
b. $\mathbf{V_{oc}}$ = 21.7Volts – 36 × 0.0023 Volts/^{0}C × (53.7 – 25)^{0}C = 19.32Volts
c. $\mathbf{FF} = \frac{55W}{3.15A \times 21.7Volts} = 0.735$.

Notice: We assume that FF does not change substantially with T_c.
Finally,

P_m (10^3W/m^2, T_c=53^{0}C) = $i_{sc} \times V_{oc} \times$FF = 3.45 × 19.32Volts × 0.735 = 49W, instead of 55 W_p under **S.T.C**.

11. **Determine the number of PV-panels, N_{pv}**

$$\mathbf{N_{pv} = \frac{P_w}{P_m} = \frac{554.6W_p}{49W_p} = 11.32PV - panels \approx 12PV - panels}$$

Notice: If we used $\mathbf{P_m}$ from the specifications (**S.T.C.**), then we would have:

$$\mathbf{N_{pv}} = \frac{\mathbf{P_w}}{\mathbf{P_m}} = \frac{\mathbf{554.6W_p}}{\mathbf{55W_p}} = \mathbf{10.1PV-panels \approx 10PV-panels}$$

12. Decide on the voltage value V_s, for Power transfer i.e. 24, 48, 120 Volts

The decision affects the PV-system elements and PV-panels electrical connections.
Consider 2 cases: V_S=48 Volts and 120 Volts
If, $\mathbf{V_S}$**=48 Volts**, then:

$$\left(\mathbf{N_{p,s}}\right)_{48V} = \frac{\mathbf{V_s}}{\mathbf{V_m}} = \frac{\mathbf{48Volts}}{\mathbf{17.4Volts}} = \mathbf{3\ PV-panels\ in\ series}$$

so, $\mathbf{N_{p,p}}$ = 12 : 3 = 4 strings of PV-panels in parallel; each string has 3 PV-panels in series.
If, $\mathbf{V_S}$**=120 Volts**, then:

$$\left(\mathbf{N_{p,s}}\right)_{120V} = \frac{\mathbf{V_s}}{\mathbf{V_m}} = \frac{\mathbf{120Volts}}{\mathbf{17.4Volts}} = \mathbf{8\,PV-panels\ in\ series}$$

so, $\mathbf{N_{p,p} = 2 \Rightarrow N_p = 16}$ **in total**

13. Confirmation

In step 11, we estimated N_p = 12 PV-panels
Hence, 12 × 49 W = 588 W_p
This has to be compared with the 554.6 W_p, estimated in step 8.

- **PART B**

Approach to the same sizing problem via the Ah methodology

Steps **1. – 6.** are the same as in the Wh method.

7′. Determination of the charge [Q(Ah)] delivered daily by the PV-generator

Assume that the power from the PV-generator is transferred at 48 Volts or 120 Volts**.**
So, then:

a. $\frac{2500Wh}{48Volts} = \frac{2500A \times V \times h}{48V} = 52.08Ah$, under 48 Volts, or

b. $\frac{2500Wh}{120Volts} == 20.83Ah$, under 120 Volts.

Let's follow both scenarios: **48 Volts** and **120 Volts**, to get analytic results**.**

A. DC Loads – directly met by the PV-generator:

1. $\frac{400Wh}{48Volts} = 8.33Ah/day$

2. $\frac{400Wh}{120Volts} = 3.33Ah/day$

Indirect coverage via batteries:

1. $\frac{600Wh}{48Volts} = 12.50Ah/day$

2. $\frac{600Wh}{120Volts} = 5.00Ah/day$

B. AC Loads – directly met by the PV-generator through the DC/AC charger:

1. $\frac{600Wh}{48Volts} = 12.50Ah/day$

2. $\frac{600Wh}{120Volts} = 5.00Ah/day$

Indirect coverage via batteries and the **DC/AC** charger:

1. $\frac{900Wh}{48Volts} = 18.75Ah/day$

2. $\frac{900Wh}{120Volts} = 7.50Ah/day$

So, the total Ah per day is: 52.08 Ah/day for DC voltage; 48 Volts.

Remark:

The same value would be obtained if we divided the load of 2500 Wh by the voltage of 48 Volts:

Q(Ah) = E : V_s = 2500Wh : 48Volts = 52.08Ah

8′. Correction to Ah due to losses in various PV-system elements

The correction is similar as in the Wh method.
The only difference is in the battery efficiency, which in this case, based on Ah, the efficiency is assumed much higher eg. near to 100%.

- **DC Loads** directly met by the PV-generator
  8.33Ah × 1.05 = 8.75Ah
- **DC Loads** via batteries
  12.50Ah × 1.05 = 13.13Ah
  (Notice: in the Wh method the correction factor was 1.25)

- **AC Loads** via inverter
  12.50Ah × 1.20 = 15Ah
- **AC Loads** via batteries and DC/AC
  18.75Ah × 1.20 = 22.5Ah

Total: 59.38Ah

9′. Determination of the mean annual current from the PV-generator, $\bar{i}_{pv}$.

Since, total daily load is 59.38Ah and $(PSH)_{ann}$ is 3.63h⇒
$\bar{i}_{pv}$ = annual mean current = 59.38Ah / 3.63h = 16.358A

10′. Determination of the PV-panels; $N_{p,p}$, $N_{p,s}$ in parallel, in series

The string in parallel **(N_p)**
N_p =16.358A / 3.15A = 5.19. Let us take **N_p=6.**

Question: How much is V_m in field conditions?

$V_m = P_m / I_m$ = 49W / 3.15A = 15.56 Volts, while in the Wh method, V_m was used equal to S.T.C. value: V_m=17.4 Volts

Remark: In the Wh method, in step 10, we estimated P_m=49Watts and V_m=15.56Volts
This leads to:
N_s= 48Volts / 15.56Volts = 3.08 ⇒ **N_s=3**

Total: $N_{pv}= N_p \times N_s = 6\times 3 = 18$

So, we result to a higher number for **N_{pv}** as **N_p** was well oversized. This approach will provide a PV-generator which generates much more energy that required. It is recommended to keep **N_s=3** so that the system has **N_{pv} = 6× 3= 18** PV-panels and not oversize **N_s=3.08 → 4** as such a decision would drastically oversize the PV-generator resulting to very high costs and unused energy production .

- **PART C**

SIZING OF THE BATTERY BANKS

1. Determine the days of autonomy, d (see Wh and Ah method).
There is no difference either method is used.
Decide on d=3 based on the formulae in step 6 in Wh method.

2. Determination of the load storage for the days of autonomy, see § 3.2.

a. **Wh method**

The load as said is 2.5kWh/day to be transferred at 48Volts.

$$\mathbf{Q(Ah)} = \frac{2500kWh/day \times 3days}{48Volts} = 156.25Ah$$

b. **Ah method**

The loads per day to be delivered by batteries are 52.08Ah, so, for 3 days there must be stored: 52.08Ah × 3days = 156.25Ah.

3. Correction in the Ah value of the batteries due to temperature

Temperature of the batteries affects their efficiency. The capacity, **C**, decreases as **T** decreases below 25 – 27 ^{0}C.
For high charge – discharge rates, **C**, changes as in figure below.

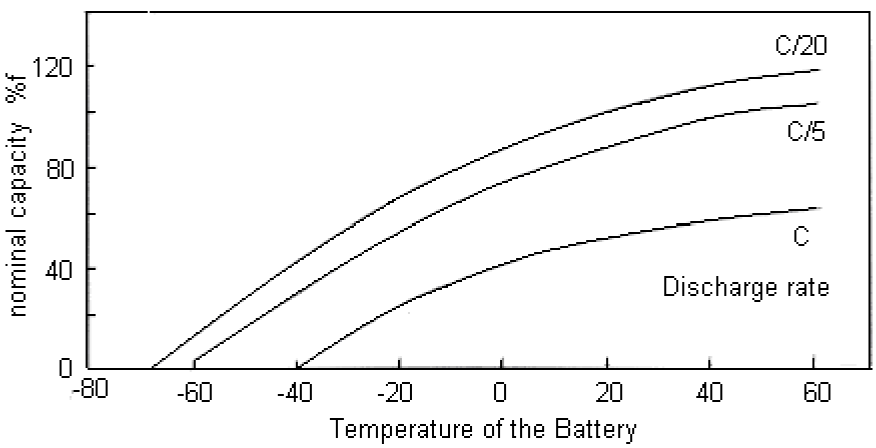

Figure 5.17: *Impact of temperature and of discharge rate to the energy delivered (come of a PV-acid battery).*

When **T** changes, **C** has to be corrected:

$$\mathbf{f_{b,T}} = \frac{\mathbf{C}}{\mathbf{C_0}} = \frac{\mathbf{C\,at\quad T^0C}}{\mathbf{C_0\,at\quad 25-27^0C}} = \mathbf{0.01035 \cdot T^0C + 0.724} \qquad (5.25)$$

Lets take $\mathbf{f_{b,T}}$ **= 1**, for the case of Bucharest. Remember that for North Germany we estimated $f_{b,T}$ =0.8275.

If **T** in $^{\mathbf{0}}$**F**, then:

$$\frac{\mathbf{C}}{\mathbf{C_o}} = \mathbf{0.00575 \times T + 0.5A \quad (T\ in\ ^0F)} \qquad (5.26)$$

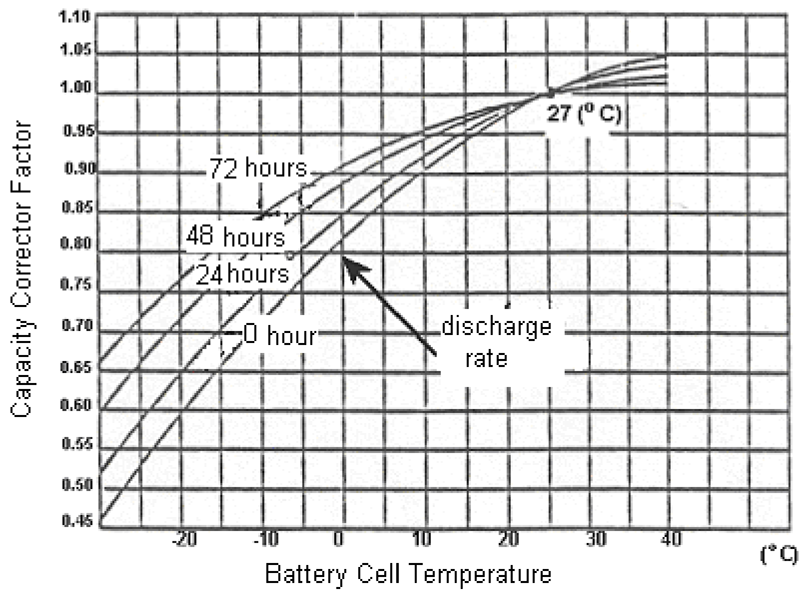

Figure 5.18: *Capacity correction factor of a Pb battery versus battery cell temperature (^{0}C).*

4. Determination of the correction coefficient due to the charge/discharge rate

A correction factor due to charge/discharge rate, $\mathbf{f_{b,cd}}$, has to be studied. $\mathbf{f_{b,cd}}$ is defined as follows:

$$\mathbf{f_{b,cd}} = \frac{\mathbf{i_{ch/disch}\ (as\ recommend)}}{\mathbf{i_{ch/disch}\ (as\ in\ the\ case)}} \tag{5.27}$$

So, the correctied capacity, $\mathbf{C_{cor}}$, is given by a formula equivalent to (3.18).

$$\mathbf{C_{cor}} = \frac{\mathbf{C(Ah/day)}}{\mathbf{f_{b,T}} \times \mathbf{f_{b,ch}} \times \mathbf{DOD}} \tag{5.28}$$

and for autonomy of **d** days

$$\mathbf{C_{cor}} = \frac{\mathbf{C(Ah/day)} \times \mathbf{d(days)}}{\mathbf{f_{b,T}} \times \mathbf{f_{b,ch}} \times \mathbf{DOD}} \tag{5.29}$$

Notice: if $\mathbf{i_{ch}}$ multiplied by **10h** i.e. $\mathbf{(i_{ch} \times 10h)Ah > C_{cor}}$ (from the above equation)

Then, $\mathbf{C_{cor} = (i_{ch} \times 10)Ah.}$

In our case:

$i = i_m \times 4$ strings = 3.15Ah × 6 = 18.9Ah

$\mathbf{(i_{ch} \times 10)Ah = 18.9A \times 10h = 189Ah}$

Compare $\mathbf{(i_{ch} \times 10)Ah}$ to $\mathbf{C_{cor}}$ where:

$$C_{cor} = \frac{52.08\frac{Ah}{day} \times 3days}{1 \times 1 \times 0.8} = 195.3Ah$$

As **C_{cor} > (i_{ch} × 10)Ah = 189Ah** ⇒ then we accept that batterie's capacity is 195.3Ah.

5. Determine the type of batteries to be used

One should choose the type of the battery to meet the requirements and the prerequisites of the problem as in the following:

a. Total capacity 195.3Ah i.e. about 200Ah

b. The voltage across batteries bank to be 48 Volts

c. The DOD value to be higher than 20%. In fact, DOD is related to **d**:

$$\frac{\mathbf{d}}{\mathbf{d}+\mathbf{1}} = \mathbf{DOD} \Rightarrow \frac{\mathbf{3}}{\mathbf{4}} = \mathbf{DOD} \Rightarrow \frac{\mathbf{d}}{\mathbf{d}+\mathbf{1}} = \mathbf{DOD_{max}}$$

$$\mathbf{DOD_{max}} = \frac{3}{7+1} = 0.75$$

d. The decision of the battery type is complex and depends not only in the above characteristics, but also on the unit price, the life cycles, duration, etc.
This has to be examined separately, as in § 3.3.3.

From the appropriate Table in Appendix III let's choose, at first, the battery type:
GNB Absolyte: C=59A, V=12Volts, DOD=0.8.

Hence, 4 batteries of this type in series are required to provide: 4 ×12Volts = 48Volts
The batteries in parallel are determined by the formula:

$$\mathbf{N_{b,p}} = \frac{\mathbf{Q_L} \times \mathbf{d}}{\mathbf{DOD} \times \mathbf{C}} = \frac{(2500Wh/48Volts) \times 3days}{0.8 \times 59Ah} = 3.13.$$

Therefore, we assume 4 strings of batteries, in parallel.

6. Confirm that during the discharge process DOD < DOD_{specs}

We decided before, in step 5, to use 4 batteries of 59Ah with DOD=0.8.
Then, in step 7' of the Ah method the daily total charge Load is equal to 52.08Ah, while total capacity is 4 × 59Ah = 236Ah.
Therefore, the daily discharge is:

$\frac{52.08Ah}{236Ah} = 0.22$ or 22% < 80% as specified of the type of the battery chosen.

As total C=236Ah, DOD=0.8,
the total available capacity is: 0.8 × 236Ah = 188.8Ah

This is higher than the 156.23Ah required for the autonomy of the 3 days.
Finally, even if batteries would operate for all 3 days, the discharge level would be:
156.25Ah / 236Ah = 0.662 or 66.2% < 80%.

7. The decision on the battery type choise, provided that this type would meat the technical requirements and the pre-requisites as presented above, should be the outcome of a financial analysis as done in the previous Case studies.