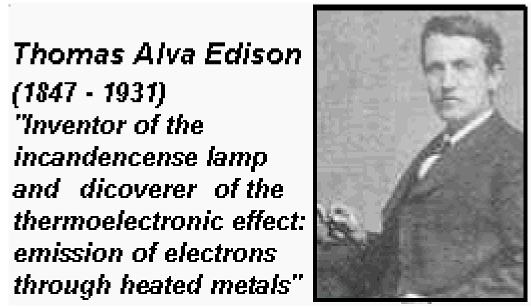

CHAPTER IV

PV-SYSTEMS ENGINEERING. THE SIZING ISSUE.

4.1 Sizing a PV system

4.1.1 Introduction

Sizing a photovoltaic system is an important task in the system's design. In the sizing process one has to consider three basic factors:

a. the solar insolation of the site

b. the daily power consumption (Wh) or the electric loads, and

c. the storage system to contribute to system's energy independence for a time period.

If the system is oversized it will have a big impact in the final cost and the price of the power produced.

If on the other hand, the system is undersized, problems might occur in meeting the power demand at any time.

The sizing should be carefully planned in order to get a cost effective system.

Three sizing case studies will be discussed in this chapter.

4.1.2 Solar radiation data

The amount of sunshine available at a given location is called "**solar resource**" or **solar insolation**.

The amount of electrical energy produced by a PV-array depends primarily on the insolation at a given location and time. Data are usually given in the form of global radiation over a horizontal surface. The procedure of solar radiation calculation on a sloped surface, is given as a case study in § 5.6.

4.1.3 Load Data

As it concerns the loads, one may get the proper information on data according to the appliances to be powered by the system.

These appliances could be domestic appliances like: TV sets, lights, refrigerator, kitchen, vacuum cleaner, washing machine, coffee machine etc.

The determination of the total daily energy consumption requires the following steps:

a. identification of all the electrical devices that will be powered by the PV-generator,

b. determination of each device's power usage (in Watts),

c. estimation of the average daily operation of each device in hours per day,

d. multiplication of **b** and **c** provides **d**: i.e. **b** (Watts)×**c** (h/day)=**d** (Wh/day)

So, one gets as result the load in Wh/day

e. summation of the watts-hours for all the devices in order to get the total daily energy requirement.

An example of such a load profile is shown below.

Table 4.1: *An example of a simplified energy profile for a household is shown in the table below.*

Type of Appliance	*No.*	*Rated Power (Watts)*	*Daily usage (hrs/day)*	*Daily Load (Wh/day)*
Cooker	1	3000	1	3000
Clothes dryer	1	2000	0.25	500
Lights	5	80	6	2400
TV	1	100	4	400
Total				6300

Note: *More detailed data about domestic loads are provided in § 5.9.*

The daily energy requirement would equal the sum of the calculated values in kWh per day. If the energy requirement varies from season to season, it must be calculated for each season or each month, provided that better accuracy on the load requirements are sought. For even more effective load management, the daily profile of each load must be studied, see fig. 4.1.

Residences tend to use more energy in winter when the days are shorter, since lights and other appliances as televisions are longer.

Of course, if air-conditioning is included, then the summertime loads are also considerable.

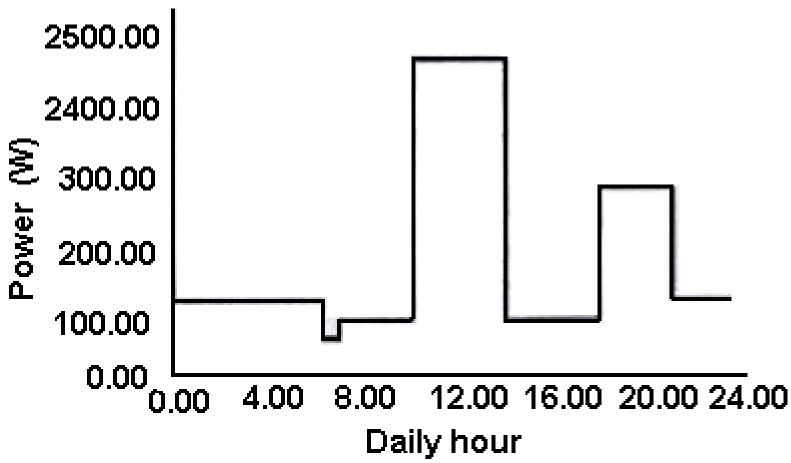

Figure 4.1: *The figure shows the daily load*

4.1.4 Sizing Procedure

The system design will be based on the yearly energy balance between the solar radiation and the load. A block diagram of the sizing procedure is shown in fig. 4.2.

- **Input data for the sizing procedure**

The available solar energy on the PV-panels for a typical day of each month and different panel inclinations can be determined from blocks 1-3, see fig. 4.2.
The load specifications are used in order to calculate the average daily load power demand for a typical day in each season (blocks 4-5).

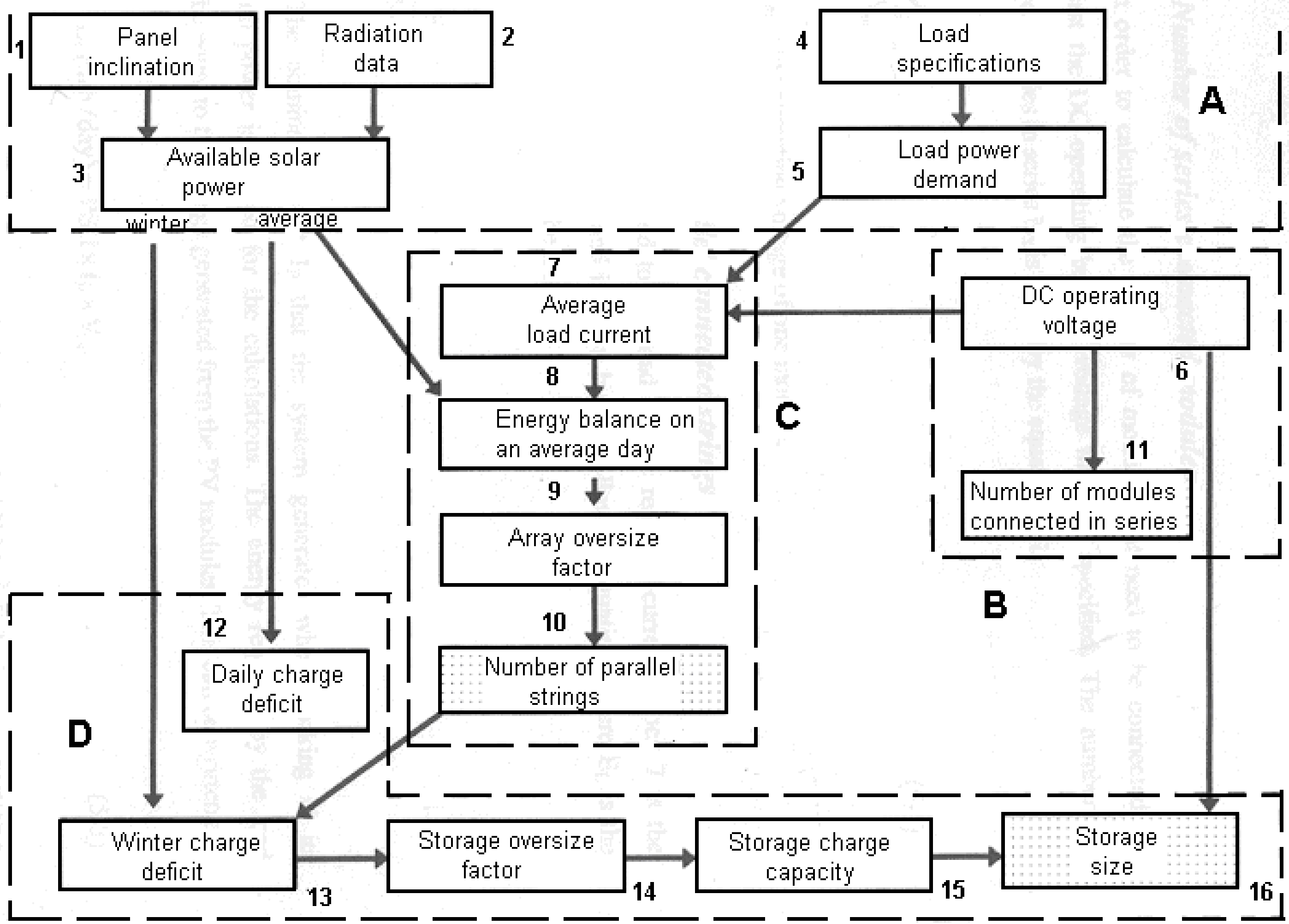

Figure 4.2: *Sizing procedure based on energy balance (from Tomas Markvart)*

- **Number of series connected modules, N_s**

In order to calculate the number of PV-modules that need to be connected in series, first the **DC** operating bus bar voltage must be specified. The number of connected modules in series, $\mathbf{N_s}$, is given by the equation (4.1).

$$\mathbf{N_s = \frac{V_{DC}}{V_m}} \tag{4.1}$$

where $\mathbf{V_m}$ is the operating voltage on the PV-modules.
The effort of the design itself and the electronic components, mainly the **MPPT**, is to set the operation voltage at $\mathbf{V_{MPP}}$.
$\mathbf{V_{DC}}$ attracts the designer's attention due to the electric losses (**Joule effect**). When $\mathbf{V_{DC}}$ is small, then **i** takes high values, so the Joule effect ($\mathbf{i^2 \times R_L}$) causes more electric energy to be converted (wasted) into heat.
$\mathbf{V_{DC}}$ should take values like 48 or 120 Volts and not 24 Volts in order to reduce current and consequently electric energy losses.

- **Number of parallel connected strings, N_p**

This number, $\mathbf{N_p}$, is related to the **energy load** and its **required current**.
In block 7, it is estimated the average current, $\mathbf{i_L}$, needed by the load and it is given by the following equation, where $\mathbf{E_L}$ is the average power required by the load.

$$\mathbf{i_L = \frac{E_L(Wh/day)}{24h/day \times V_{DC}(Volts)}\ (A)} \tag{4.2}$$

The nominal current $\mathbf{i_{pv}}$ that the PV-system generates when working at its maximum power (MPP) is needed for the calculations.
All those above issues were analyzed in § 3.2 with the problem 3.3-3.6.

Energy Balance principle:

The energy required by the load should be equal to the energy generated from the PV-modules.

This principle takes the form:

$$\mathbf{E_L\,(Wh/day) = PSH \times V_{DC} \times i_{pv}} \tag{4.3}$$

where, **PSH** is numerically equal to the irradiation on the PV-generator in $\mathbf{kWh/m^2}$.
Substituting equation (4.2) to (4.3) and solving for $\mathbf{i_{pv}}$, yields:

$$\mathbf{i_{pv} = \frac{24(h/day) \times i_L(A)}{PSH(h/day)}(A)} \tag{4.4}$$

Equation (4.4) displays that the average daily load current $\mathbf{i_L}$ multiplied by the number of hours, 24 h, should be numerically equal to the charge produced during a day which is equal to the current in **A**mps that the system produces multiplied by the number of **P**eak **S**olar **H**ours (**PSH**).

The number of modules connected in parallel, $\mathbf{N_p}$, see (blocks 9-10) is given by the following equation, where **SF** is the safety factor, or **S**izing **F**actor, introduced to oversize the current produced from the array in order to cover any loads;

$\mathbf{i_m}$ is the current generated from one PV-module.

$$\mathbf{N_p} = (\mathbf{SF})\frac{\mathbf{i_{pv}}}{\mathbf{i_m}} \tag{4.5}$$

The total number of modules needed to set up the PV-generator is:

$$\mathbf{N} = \mathbf{N_p} \times \mathbf{N_s} \tag{4.6}$$

Remark:

Corrections to $\mathbf{i_m}$, $\mathbf{V_m}$, or $\mathbf{P_m}$ due to higher temperatures than the **S.T.C.** determines have to be introduced, see § 1.2.7.

4.1.5 Sizing of the storage subsystem

An analysis of the sizing of storage systems was presented in the case of Problem 3.4.

Here, we may summarize:

1. The daily and seasonal energy deficit is calculated in the block 12. The loads during the nights and periods with very little sunshine must be net satisfactory.

2. Also, excess (unused) energy must be stored in order to be used later. Such a case was approached with Problem 3.6 followed by the economical issues of the batteries in § 3.3.3.

This sizing analysis determines the daily charge/discharge of the battery which should not exceed a certain value, as we saw in § 3.3.2.

3. The charge deficit (block 13) is a value, usually given in **Ah**, that is related to the energy balance of the year, see § 3.2. Excess energy during the summer periods has to be stored in order to cover the energy deficit during the winter.

• The charge deficit is given by the following equation, where $\mathbf{\Delta E_W}$ is the winter energy deficit.

$$\mathbf{Q_{Yd}} = \frac{\mathbf{\Delta E_w}}{\mathbf{V_{DC}}} \tag{4.7}$$

If during summer there is an excess energy $\mathbf{\Delta E_S}$ stored, the annual charge deficit is:

$$\mathbf{Q_{Yd}} = \frac{-\mathbf{\Delta E_w} + \mathbf{\Delta E_s}}{\mathbf{V_{DC}}} \tag{4.7'}$$

4. A second approach for the charge deficit was fully presented in Problem 3.4.
5. Another charge deficit (block 14) is used to allow for a certain number of days, **d**, of operation with no energy input (no sunshine, system is maintenance period etc.). This number is determined from experience and depends on the PV-system's management.
However, for more reliable data the following relationships are used to determine **d**, for the **critical** and **non-critical loads** respectively:

$$d_{cr} = -1.9 \times (PSH)_{min} + 18.3 (days) \quad (4.8a)$$

$$d_{n\text{-}cr} = -0.48 \times (PSH)_{min} + 4.58 (days) \quad (4.8b)$$

A system is considered as **critical** when for only 88 h in a year the system is allowed of no operation.
For the less **critical loads**, the relationship to be used is equation (4.8b).
The charge deficit due to this policy is given by the equation (4.8c).

$$Q_d = i_L \times 24 \times d \; (Ah) \quad (4.8c)$$

6. The nominal capacity of the battery bank Q_b in (Ah) will be given by equation 4.9 (block 15) where **(DOD)** is the battery's maximum discharge depth (**DOD**: **D**epth **o**f **D**ischarge).

$$Q_b = (Q_{Yd} + Q_d) \cdot (1/DOD) \quad (4.9)$$

7. From the operating voltage and capacity of one battery, the total number of batteries can be calculated (block 16). The same methodology was followed to determine the number of PV-panels.
8. The number of batteries in series, $N_{b,s}$, is given by equation (4.10) below, where V_B is the nominal voltage of the battery.

$$N_{b,s} = \frac{V_{DC}}{V_B} \quad (4.10)$$

9. The number of batteries in parallel, $N_{b,p}$, is given by equation (4.11) where Q_C is the nominal capacity of a single battery.

$$N_{b,p} = \frac{Q_b}{Q_C} \quad (4.11)$$

10. The total number of batteries is then calculated by:

$$N_b = N_{b,p} \times N_{b,s} \quad (4.12)$$

Table 4.2: *Notation and units of quantities in PV-sizing problems*

Symbol		**SI** ***unit***
E_L	Daily load energy requirement	Wh
i_L	Average load current	A
i_m	Module current at maximum power point	A
i_{pv}	Current generated from PV at maximum power point under standard conditions	A
N_s	Number of series connected modules	
N_p	Number of parallel strings	
$N_{b,s}$	Number of batteries connected in series	
$N_{b,p}$	Number of batteries connected in parallel	
PSH	Peak solar hours	H
Q_d	Charge deficit to compensate for loss of sunshine in a period of d days	C (Ah)
Q_{Yd}	Yearly charge deficit	C (Ah)
Q_b	Nominal battery capacity	C (Ah)
Q_c	Single battery capacity	C (Ah)
SF	Array oversize factor, **S**izing **F**actor	
V_{DC}	DC bus bar voltage	V
ΔE	Yearly energy deficit	Wh
ΔE_w	Winter (energy) deficit	Wh
ΔE_s	Summer excess energy stored	Wh
DOD	Lowest permitted state of charge	%