Wolfgang Pauli
(1900 - 1958)
Nobel Laureate in Physics in 1945 - "The principle of exclusion"

Chapter V: CASE STUDIES ON PV-SYSTEMS

CASE STUDY 1: Feasibility study for a PV-system for Sifnos Island (Greece) and Glasgow (UK)

5.1 Introduction

In this chapter, an application of the previous sizing methodology will be used in order to size a PV-generator.
This methodology will be used for two different locations one in Greece and one in Scotland.
The first step will be to determine the available average daily insolation for each site. Then, the average power consumption and finally the size the PV-system which is just adequate to cover the desired load will be estimated.
Solar insolation data can be downloaded from the METEONORM data bank for many cites of any country; see references.

5.2 Average daily solar radiation

- **Sifnos-Greece**

The available solar energy impinging on the PV-panels will be computed according to the procedure to be described in §5.6. Some of the parameters that are needed are the site's latitude and the clearness index $\mathbf{K_t}$. These parameters are shown in § 5.6 along with the complete set of solar insolation calculations for the Sifnos Island-Greece.
Finally, the results of the average daily radiation in Wh/m^2 on an inclined surface are shown in Table 5.1, and in fig. 5.1, below.

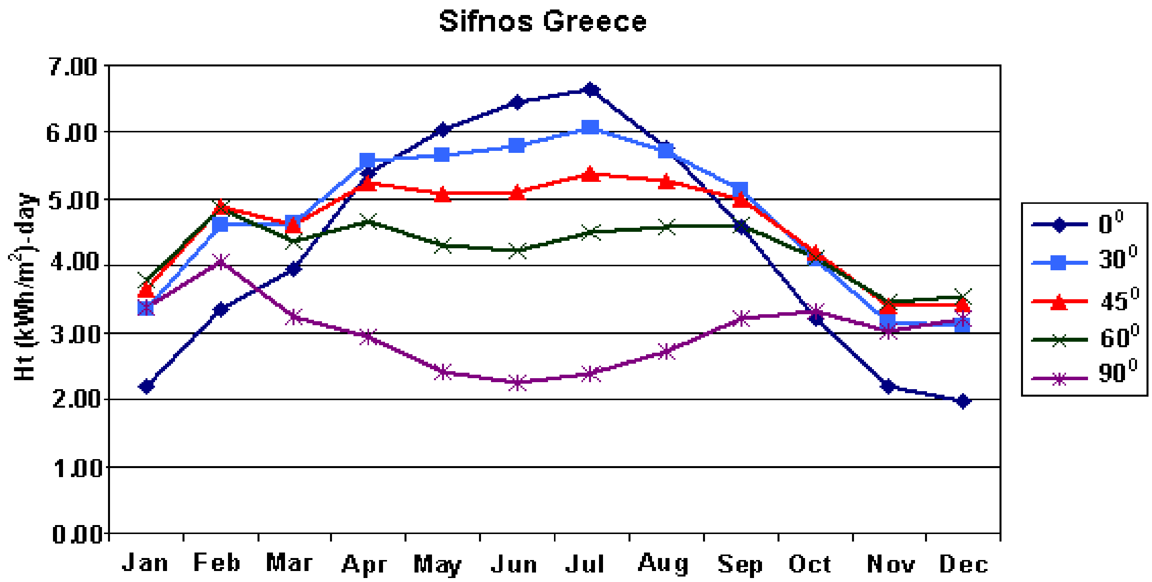

Figure 5.1: *Shows the average daily radiation for different inclination of PV-panels , in Sifnos island.*

Table 5.1: *Daily irradiation in Sifnos (in kWh/m² per day) for a typical day every month as a function of the panel inclination in degrees.*

Panel Tilt, Degrees	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual KWh/m²
0	2.20	3.36	3.96	5.39	6.03	6.46	6.63	5.77	4.58	3.20	2.20	1.98	**4.31**
5	2.43	3.63	4.13	5.50	6.04	6.42	6.61	5.84	4.74	3.40	2.40	2.21	**4.44**
10	2.64	3.87	4.28	5.57	6.02	6.36	6.56	5.88	4.87	3.58	2.58	2.42	**4.55**
15	2.85	4.10	4.41	5.62	5.97	6.26	6.48	5.88	4.98	3.73	2.75	2.61	**4.64**
20	3.03	4.30	4.51	5.63	5.89	6.14	6.37	5.86	5.05	3.87	2.90	2.79	**4.70**
25	3.20	4.47	4.59	5.61	5.79	5.98	6.23	5.80	5.10	3.99	3.04	2.96	**4.73**
30	3.35	4.61	4.64	5.57	5.65	5.80	6.06	5.71	5.12	4.08	3.16	3.10	**4.74**
35	3.47	4.73	4.66	5.49	5.49	5.60	5.86	5.60	5.11	4.15	3.26	3.23	**4.72**
40	3.58	4.82	4.65	5.38	5.30	5.37	5.63	5.45	5.06	4.19	3.34	3.34	**4.68**
45	3.66	4.88	4.62	5.24	5.09	5.11	5.38	5.27	4.99	4.21	3.40	3.43	**4.61**
50	3.72	4.90	4.57	5.07	4.85	4.84	5.10	5.07	4.89	4.21	3.44	3.49	**4.51**
55	3.76	4.90	4.48	4.88	4.59	4.54	4.80	4.84	4.77	4.18	3.46	3.53	**4.39**
60	3.78	4.87	4.37	4.66	4.31	4.23	4.49	4.59	4.61	4.12	3.45	3.55	**4.25**
65	3.77	4.80	4.24	4.42	4.02	3.91	4.15	4.32	4.44	4.04	3.43	3.55	**4.09**
70	3.73	4.71	4.08	4.16	3.71	3.58	3.81	4.03	4.23	3.94	3.39	3.53	**3.91**
75	3.68	4.59	3.90	3.87	3.39	3.24	3.45	3.72	4.01	3.81	3.32	3.48	**3.71**
80	3.60	4.44	3.70	3.57	3.06	2.90	3.09	3.40	3.76	3.66	3.24	3.41	**3.49**
85	3.49	4.26	3.48	3.26	2.74	2.56	2.74	3.07	3.49	3.50	3.13	3.32	**3.25**
90	3.37	4.06	3.24	2.93	2.41	2.24	2.39	2.73	3.21	3.31	3.01	3.21	**3.01**

Notice*: the numbers above provide the PSH values, too.*

- **Glasgow-Scotland**

Using the same procedure, one obtain the data for Glasgow, as presented in the appropriate Table 5.26 in § 5.6.

These data on the average daily solar radiation falling on an inclined surface in Glasgow are given by Table 5.2, and fig 5.2, below.

Table 5.2: *Daily irradiation in Glasgow (in kWh/m² per day) for a typical day every month as a function of the panel inclination in degrees.*

Panel Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	Annual KWh/m²
0	0.65	0.93	1.91	3.33	4.48	4.22	4.12	3.30	2.45	1.33	0.55	0.34	**2.30**
5	0.82	1.03	2.04	3.44	4.54	4.23	4.14	3.38	2.58	1.47	0.63	0.41	**2.39**
10	0.98	1.12	2.16	3.54	4.58	4.23	4.16	3.44	2.71	1.60	0.70	0.47	**2.48**
15	1.14	1.21	2.27	3.63	4.61	4.22	4.16	3.48	2.81	1.72	0.78	0.54	**2.55**
20	1.29	1.29	2.36	3.69	4.61	4.20	4.15	3.51	2.90	1.83	0.84	0.60	**2.61**
25	1.44	1.37	2.45	3.74	4.60	4.15	4.12	3.53	2.98	1.93	0.91	0.65	**2.66**
30	1.57	1.43	2.52	3.77	4.56	4.10	4.07	3.52	3.04	2.02	0.97	0.71	**2.69**
35	1.70	1.49	2.57	3.77	4.51	4.02	4.00	3.50	3.08	2.10	1.02	0.75	**2.71**
40	1.81	1.54	2.61	3.76	4.43	3.93	3.92	3.47	3.11	2.17	1.07	0.80	**2.72**
45	1.91	1.58	2.64	3.73	4.33	3.82	3.82	3.41	3.12	2.22	1.11	0.84	**2.71**
50	2.00	1.62	2.65	3.68	4.22	3.70	3.71	3.34	3.11	2.26	1.14	0.87	**2.69**
55	2.07	1.64	2.65	3.61	4.08	3.56	3.58	3.25	3.08	2.29	1.17	0.90	**2.66**
60	2.13	1.65	2.63	3.52	3.92	3.41	3.43	3.15	3.04	2.30	1.19	0.92	**2.61**
65	2.18	1.65	2.60	3.41	3.75	3.24	3.27	3.04	2.98	2.30	1.20	0.94	**2.55**
70	2.21	1.65	2.55	3.28	3.56	3.07	3.10	2.91	2.91	2.28	1.21	0.95	**2.47**
75	2.23	1.63	2.49	3.14	3.36	2.89	2.92	2.77	2.81	2.25	1.21	0.95	**2.39**
80	2.23	1.61	2.41	2.98	3.15	2.69	2.73	2.61	2.71	2.21	1.20	0.95	**2.29**
85	2.21	1.57	2.32	2.81	2.92	2.49	2.54	2.45	2.59	2.16	1.18	0.94	**2.18**
90	2.18	1.53	2.22	2.62	2.69	2.29	2.33	2.28	2.45	2.09	1.15	0.93	**2.06**

Note: *Comparing data in Tables 5.1 and 5.2 one understands that as PSH values for Glasgow are quite shorter than the corresponding ones for Sifnos island, energy delivered by the PV-generator is much bigger for Sifnos.*

In addition to that loads differ as natural lighting is richer for Sifnos.

If air-conditioning is to be taken into account, Sifnos has some disadvantage due to higher ambient temperature compared to Glasgow.

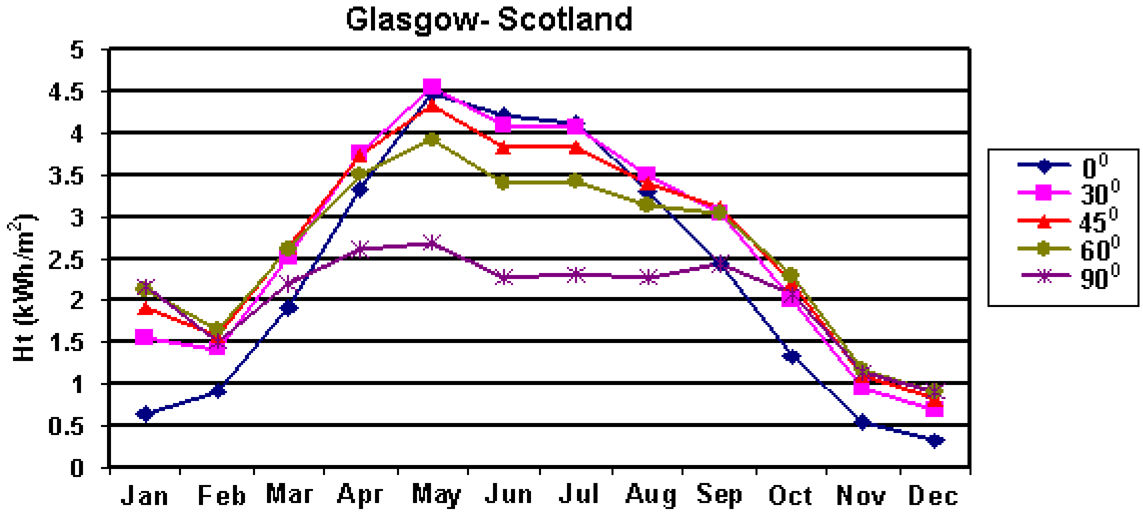

Figure 5.2: *Average daily radiation for different inclination angles in Glasgow*

5.3 Load demand

A table showing the most common appliances used in a household is given in the next page. They are described by their nominal power and the time they are used during the day.

These two numbers have to be multiplied in order to find the total energy; in Wh, consumed during a typical day, see also § 4.1.3 .

Four seasons are included in the load profile study, with different utilization times for the appliances. These values, as estimated for each season, are used to determine the average daily annual consumption on a seasonal basis. These are just estimates, and they can vary according to the place, time of season or residential customs.

The percentage of the average daily electric load for winter is shown in fig. 5.3.

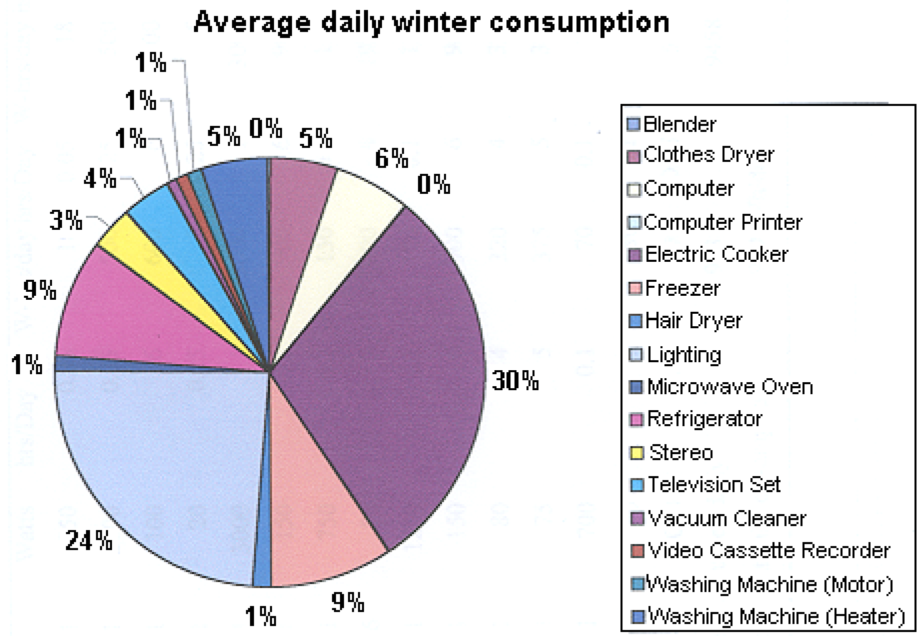

Figure 5.3: *Percentage of average daily electric load in winter time*

5.4 Sizing of the PV-system; determination of important settings.

a. The optimum tilt angle (**β**) for both PV-systems in the two locations must be determined.
b. The operating voltage of the PV-system is set equal to 12 V. The voltage of the PV-system should be equal to the storage subsystem: battery bank usually 12 V or if in series 24 V-48 V etc., see § 2.2. However, these are low $\mathbf{V_{DC}}$ values which imply high losses due to Joule effect, see § 4.1.4.
c. The PV-panels chosen for the sizing procedure is KC120, which has a relative high conversion efficiency (13%).

Note: *This choice to keep operating voltage low, 12 or 24 Volts, is not the best one. In Case study 2 we will analyze two scenario for 24 and 48 Volts operating voltage. The higher the voltage, the lower the Joule effect (*$\boldsymbol{i^2R}$*) is, and hence losses are kept low.*

Some available PV-panel types, which can be used in the PV systems are shown in Table 5.3 and in Appendix III.
A different choice of PV-panels may affect the number of PV-modules required, according to their efficiency, power and electrical characteristics.

Table 5.3: *Various PV- panel types with their electrical characteristics*

Module Name	Peak Power (W_p)	Voltage (V)	Current (i)	Length (m)	Width (m)	Total Area (m^2)	Efficiency %	Price €
MSX120	120	17.7	7	1.12	0.99	1.11	0.12	560
MSX83	83	17.1	4.85	1.12	0.66	0.74	0.11	419
MSX77	77	16.9	4.56	1.12	0.66	0.74	0.10	389
VLX80	80	17.1	4.71	1.12	0.66	0.74	0.11	420
KC120	120	16.9	7.1	1.43	0.65	0.93	0.13	573
KC80	80	16.9	4.73	0.98	0.65	0.64	0.13	382
SR100	100	17	6	1.5	0.6	0.90	0.11	505
SR90	90	17	5.4	1.5	0.6	0.90	0.10	460
SP75	75	17	4.4	1.2	0.53	0.64	0.12	405

The complete calculations for sizing of the PV-system for this case study are presented in detail in § 5.7.

As we will see in § 5.4.2. The optimum tilt angle, at which the system covers the energy needs with the minimum costs, is not the same for both sites. Table 5.5 gives the total number of PV-panels and batteries for different tilt angles in the two sites: Sifnos and Glasgow .

Calculations are made using the same type of PV-panels and the same load requirements for comparison.

5.4.1Storage subsystem

The energy balance of the system and the energy independence period, **d** days, play an important role upon the size of the storage subsystem, since the two charge deficits $\mathbf{Q_{Yd}}$ and $\mathbf{Q_d}$ depend upon these factors.

The monthly energy balance of the system will be equal to the energy input from the PV-generator, $\mathbf{E_{PV}}$, minus the energy needed by the load $\mathbf{E_L}$**;** $\mathbf{(E_{PV} - E_L)}$ for every month.

The complete sizing procedure for the storage subsystem is presented in § 5.7.

The same type of batteries is chosen for both site calculations (Sifnos and Glasgow) and the same number **d** days for energy independence. Let, **d**=5.

Attention:

However, this is not right, as for Sifnos, **d** might be (according to 4.8a and 4.8b) equal to d=3 days or even 2 days, which reduces the final cost of the PV-system considerably.

Other available battery types for sizing of the storage subsystem are given in Table 5.4.
As mentioned earlier, the number of batteries required to meet the energy scenario, as set above for different tilt angles is shown in Table 5.5.

Table 5.4: *Various types of batteries to be used in PV power storage systems.*

Battery Name	***Voltage (V)***	***Capacity (Ah)***	***Price-€ ****
6-50A-07	12	180	212
6-50A-09	12	210	251
6-50A-11	12	265	285
6-50A-13	12	320	320
6-50A-15	12	370	354
6-90A-07	12	265	266
6-90A-09	12	350	311
6-90A-11	12	440	366
6-90A-13	12	530	428
3-90A-17	6	700	557
3-90A-19	6	790	603

***** Prices for year 2001-2002.

5.4.2 Optimum tilt angle

Table 5.5 shows the required number of PV-panels and batteries for various tilt angles, if we follow the sizing steps already studied in Chapter IV, to be concretized for this case in § 5.7. The results are also plotted in two different graphs for Sifnos and Glasgow in figures 5.4 and 5.5.
From these Tables and figures, it is shown that the best tilt angle for Sifnos is between 40^o and 55^o, since there is a balance between the number of PV-panels and batteries.
This issue can, also, be clarified from the **total capital cost** of the system, plotted in figure 5.6.

The fact that a system has low capital cost does not mean that its total lifetime cost will be low, too. Maintenance and replacement costs might increase the overall system cost over the time, as the analysis in § 5.5.4 proves. For a tilt 15^0 to 45^o the required number of PV-panels and batteries remains the same as shown in fig. 5.4. For Sifnos the tilt angle is chosen to be 55^o, **as for this angle optimum values of PV-panels and batteries occur;** see Table 5.5.

Examining the results obtained for Glasgow, it is shown that the optimum tilt angle for the system is 75 to 85^o, where the number of the batteries and panels is balanced, see fig. 5.5. For lower values of tilt angles the number of panels is decreasing, but the number of batteries is substantially high. This could result to very high maintenance and replacement costs (for the batteries). The tilt is chosen to be 80^o for Glasgow.

Table 5.5: *Number of PV-panels and batteries and capital costs for different tilt angles*

Sfinos				*Glasgow*			
Tilt	***Panels***	***Batteries***	***Cost-€***	***Tilt***	***Panels***	***Batteries***	***Cost-€***
0	27	10	19738	0	51	51	51056
5	26	11	19594	5	49	55	51626
10	26	11	19594	10	47	60	52625
15	25	14	20308	15	46	63	53338
20	25	14	20308	20	45	66	54052
25	25	14	20308	25	44	68	54337
30	25	14	20308	30	43	71	55050
35	25	14	20308	35	43	71	55050
40	25	14	20308	40	43	71	55050
45	26	11	19594	45	43	71	55050
50	26	11	19594	50	43	71	55050
55	27	10	19738	55	44	68	54337
60	28	10	20309	60	45	66	54052
65	29	10	20882	65	46	63	53338
70	31	10	22027	70	47	60	52625
75	32	10	22599	75	49	55	51626
80	34	10	23744	80	51	51	51056
85	37	10	25460	85	53	48	50916
90	40	10	27185	90	56	44	50917

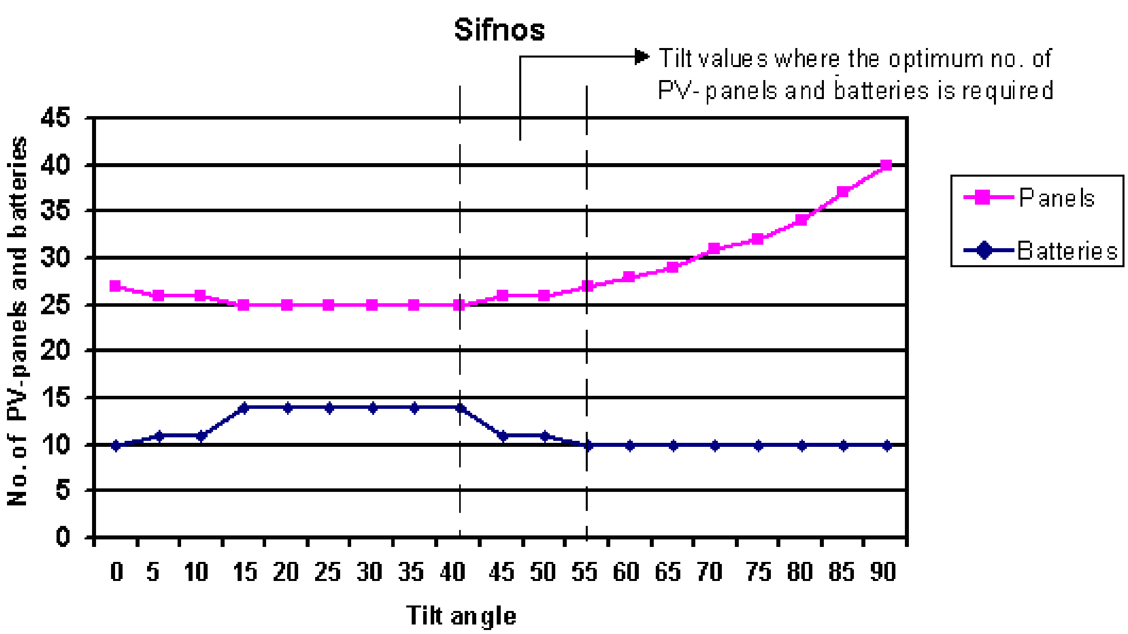

Figure 5.4: *Number of panels and batteries for different tilt angles in Sifnos island.*

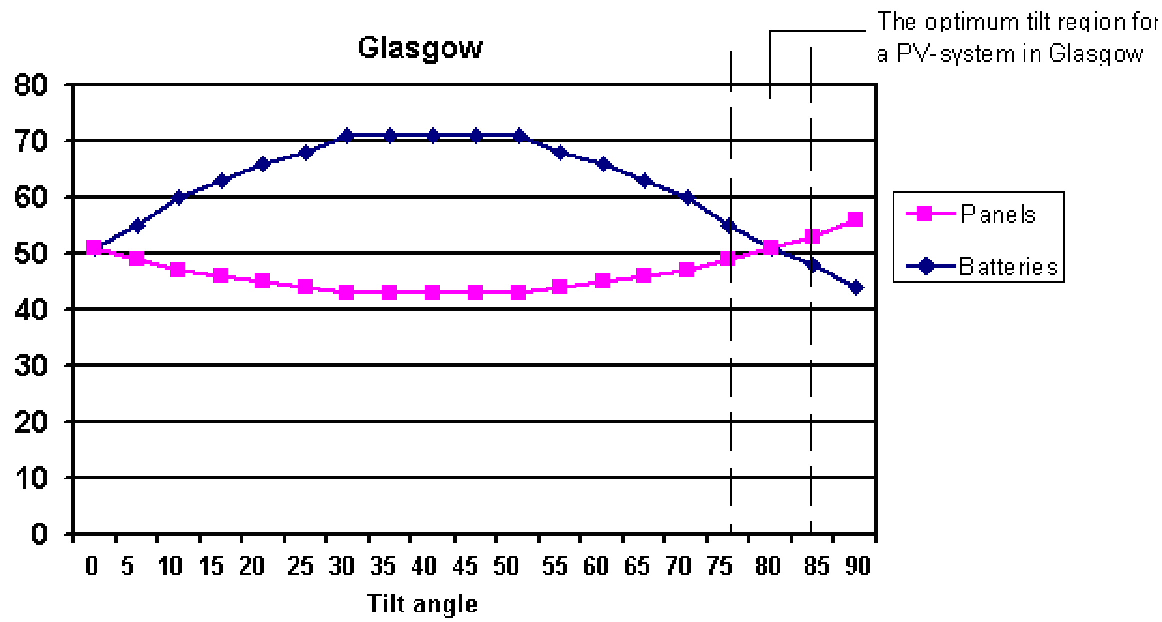

Figure 5.5: *Number of panels and batteries for different tilt angles in Glasgow.*

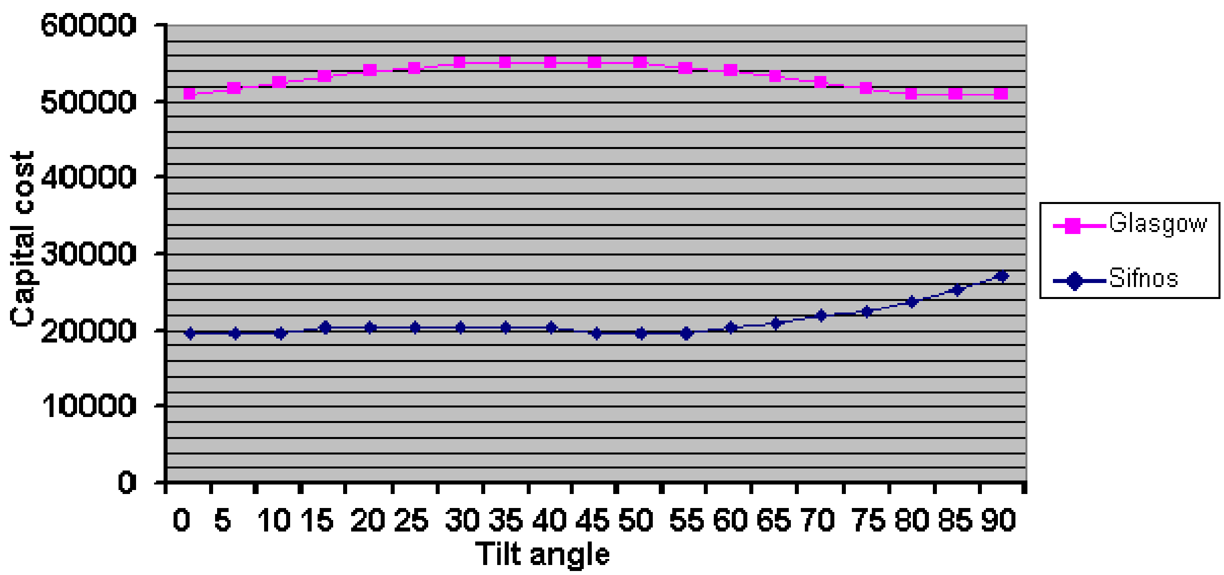

Figure 5.6: *Capital cost as a function of tilt angle*

Finally, the chosen angle, along with the number of panels and batteries is presented in Table 5.6.

Table 5.6: *Final values for Sifnos and Glasgow*

	Tilt	*PV-panels*	*Batteries*
Sfinos	55^0	27	10
Glasgow	80^0	51	51

One may realize the big difference or the advantage of Sifnos (South) against Glasgow (North) for the PV-system.

Conclusion:

The technical part of the sizing procedure included: the PV-generator (panels) and the batteries. So, it integrated both methodological approaches as developed in Chapter III for the PV-generator and for the storage system. The optimum of the solution was determined from the combination of the number of PV-panels and batteries, too. So, that cost on a **life cycle basis** is kept at minimum.

5.5 Economic considerations

5.5.1 Economic issues for PV energy systems

The price of power generated from PV-systems, depends upon two factors:

a. the system's capital cost and

b. the running cost.

Capital cost is considered to be:

a. the cost of PV-panels,

b. the **b**alance **o**f **s**ystem cost (**BOS**) –which includes the power conditioning, the wirings, support structures etc – and finally

c. the cost of the storage subsystem.

In this Chapter, the economic data for the PV-systems in both sites will be calculated, so that it can be compared with other alternative methods of power generation (grid connection, Diesel etc).

Even though the capital cost for a PV-system is substantially high, the running costs are low compared with other renewable or non-renewable systems, since it consumes no fuel nor has any moving parts (except if a tracking system is included). Maintenance of the system becomes more demanding if battery storage is included. In this case, special attention is required for the proper maintenance of batteries. Also, the batteries need to be replaced in regular periods of time, as the analysis in § 5.9.4 and in § 3.3.3 makes it clear.

5.5.2 Life **C**ycle **C**osting (**LCC**)

The two PV-systems described in § 5.4, will be evaluated using a **L**ife **C**ycle **C**ost **A**nalysis. Doing a life cycle analysis (**LCC**), the total cost of the PV-system including all expenses incurred over the life of the system is estimated.
There are two reasons to do a **LCC** analysis:

1. to compare different power options, and
2. to determine the most cost-effective system design.

If PV power is the only option, **L**ife-**C**ycle **C**ost (**LCC**) analysis can be helpful for comparing costs of different designs and/or determining **whether a hybrid system would be a cost-effective option.**

An **LCC** analysis allows the designer to study the effect of using different components with different reliabilities and lifetimes. Some might want to compare the cost of power supply options such as photovoltaic, fuelled generators, or extending utility power lines. The initial costs of these options will be different, as will the costs of the operations, maintenance, and repair or replacements be.
An **LCC** analysis can help compare the power supply options.
The **LCC** analysis consists of the estimation of the **Present Worth** (**PW**) of any expenses expected to occur over the reasonable life of the system. The **PW** methodology is briefed in § 5.5.3, below, while it was more extended in § 3.3.3 .

• In order to make a valid comparison, all future costs have to be discounted to equivalent present values. This is called "**Present Worth**" **value** or **PW**. To find the **PW** of a future cost, this must be **multiplied by an estimated discount factor**.

The parameters that need to be established for the calculations of the **LCC** are the following:

1. **Period of analysis**. It is **based on the lifetime** of the longest lived system under comparison.
2. **Excess inflation**. The **rate of price increase** of a component **above (or below) inflation** (usually assumed **to be zero**).
3. **Discount rate** (**d**). The rate (relative to general inflation) at which money will increase in value, if invested.
4. **Capital cost**. It includes the initial capital expense for equipment, the system design, engineering and installation. This cost is always considered as a single payment occurring in the initial year of the project.
5. **Operation and maintenance**. The amount spent each year in keeping the system operational.
6. **Replacement costs**. The costs of replacing each component at the end of its lifetime, as presented in § 5.4.

5.5.3 Calculations of Present Worth, PW, or Present Value.

The **PW** of a system will be calculated by considering all the expenses (running costs, replacements etc) made in one year of operation as a single payment.
The sum of discounted values (present worth) over the lifetime of the system is the life cost cycle of the system.
The **PW** of a single payment is given by equation (5.1).

$$PW = CV \times No \quad (5.1)$$

where **No** is the cost of each unit of the PV-system in the time of the installation.
CV is the **present worth coefficient**, and it is given by the equation (5.2), where **i** is the excess inflation, **d** the discount rate and the number of years (life time) or the period of each replacement, see Problem 3.8 in § 3.3.3. Finally, **CV** is calculated by:

$$CV = \left(\frac{1+i}{1+d}\right)^n \quad (5.2)$$

5.5.4 Case study for the economic analysis issues of the PV-systems in Sifnos Island and Glasgow.

5.5.4a PV systems

The life cycle cost of both PV-systems in Sifnos (Greece) and Glasgow (Scotland) will be calculated over a lifetime period of 20 years. The system will be compared with a Diesel engine system and finally, with the utility grid.
The excess inflation is set equal to zero.
Table 5.7 gives the total required number of PV-panels and batteries. The results are obtained analytically in § 5.7. The prices are found in Tables 5.3 and 5.4, too.

Tabel 5.7

	Panels	*Price (€)*	*Batteries*	*Price (€)*
Sifnos	27	572	10	428
Glasgow	51	572	51	428

The **total capital** cost for the system will **include also the BOS costs**, which includes power conditioning, installation, wirings etc.
These costs even though represent a considerable part of the total cost, will be neglected for convenience.

The running costs are set to be equal to 31 € per year, and replacement time for the batteries is set to 7 years, assuming proper maintenance.

The complete procedure for the Life Cycle Costing is found in § 3.3.3. The results are shown in the next Table 5.8. A detailed analysis is provided in § 5.8, in Table 5.28.

Tabel 5.8: *Life cycle costs for PV-system in Sifnos and Glasgow.*

Location	***Life Cycle Cost (€)***
Sifnos	27917
Glasgow	80591

The final cost for the system in Glasgow, seems very high.

A way to reducing this cost is by increasing the **safety factor** (**SF**) of the equation (4.5). The result is that more PV-panels would be needed as this factor is increased, but at the same time less batteries would be required, and hence the replacement costs are less.

Remember: battery costs have a considerable effect to the high costs of a PV-system.

The next Table 5.9 shows the number of PV-panels and batteries required for different values of safety factors,(**S.F.**) along of the **LCC**.

Tabel 5.9: *LCC for different values of the Safety Factor (S.F.); the case of the PV-system in Glasgow.*

Safety factor	***PV-panels***	***Batteries***	***LCC (€)***
1.0	51	51	80592
1.1	56	44	76807
1.2	61	36	72070
1.3	66	29	68285
1.4	71	23	65448
1.5	76	19	64512
1.6	81	16	64524
1.7	86	13	64536

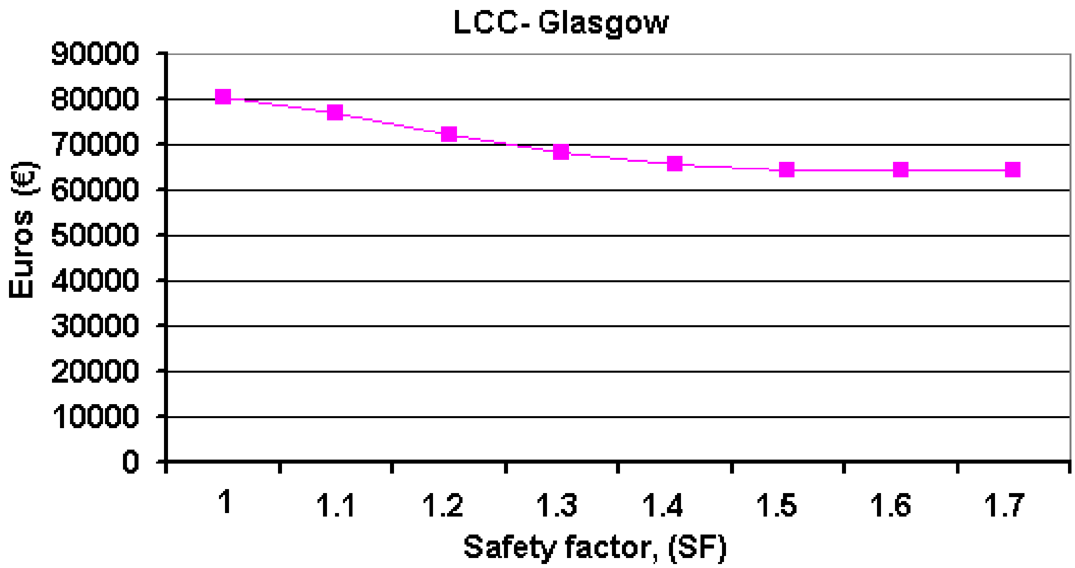

Figure 5.7: ***LCC*** *as a function of the Safety Factor (****S.F.****) for Glasgow.*

Remark:

A changing of the safety factor (**S.F.**) in Sifnos increases eventually the final **LCC**, since the number of the batteries required as determined from the analysis above is very small, indeed.

An increase in **S.F.** increases the total number of PV-panels and hence the final system cost.

5.5.4b Diesel Generator

The Diesel generator chosen for the comparison is a 12 kW generator. The specifications and data needed for the calculation of the **LCC** of the engine are shown below, in Table 5.10.

Table 5.10

Model	HD-295-12kW
Power	12kW
Fuel consumption	0.3 lt. per kW per hour
Price	4426 €

The average load that the engine needs to cover is nearly 10 kWh per day.

The fuel consumption each day will be: $\mathbf{10\frac{kWh}{day}\times 0.3\frac{l}{kWh}=3\frac{l}{day}}$.

The total fuel consumption for the whole year will be: $\mathbf{365day \times 3 \frac{l}{day} = 1090liters}$.

The price for heating diesel in Greece is roughly; 0.70 € per liter, while in UK is 0.60 € per liter. Operation and maintenance costs are set equal to 385 € per year. The above are shown in Table 5.11.

Table 5.11

Location	**Load**	**Yearly fuel Consumption**	**Price per liter**	**Total fuel cost**	**Op. & Maint. €**
Sifnos	10kW	1095lt	0.60 €	654€	385
Glasgow	10kW	1095lt	0.70 €	763 €	385

Doing an **LCC** analysis for both systems –as described in § 5.5 – yields the following results.

Table 5.12: *Life cycle cost for diesel generator*

Location	**Life cycle cost (€)**
Sifnos	12019
Glasgow	12173

5.5.4c Utility grid

An **LCC** analysis will be done also for the utility grid , in order to be compared with a PV-system. The capital costs to the grid connection vary according to the distance from the nearest power substation.
It is assumed for this analysis, that there are no significant costs occurring when connecting to the grid. The energy prices for UK and Greece are 0.14 € and 0.12 € per kWh respectively. Repeating the analysis described in § 5.5 for a 20-year period, the **LCC** for utility generated electricity is shown below.

Table 5.13: *LCC for utility generated electricity*

Location	**LCC**
Sifnos	5393 €
Glasgow	6355 €

- **Comparison of the Results**

The results obtained from the previous analysis, are shown in figures 5.8 and 5.9.

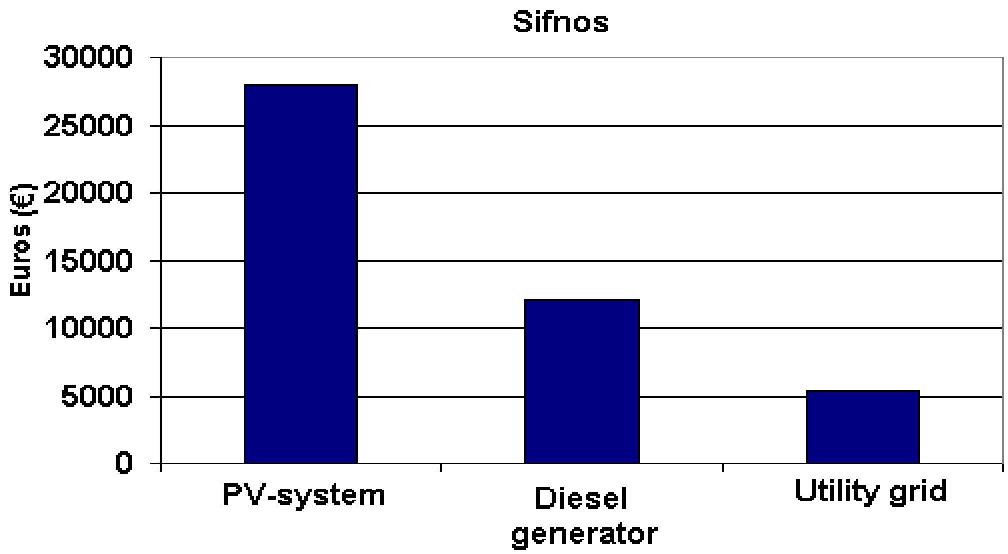

Figure 5.8: *Sifnos LCC comparison for different ways of providing electricity*

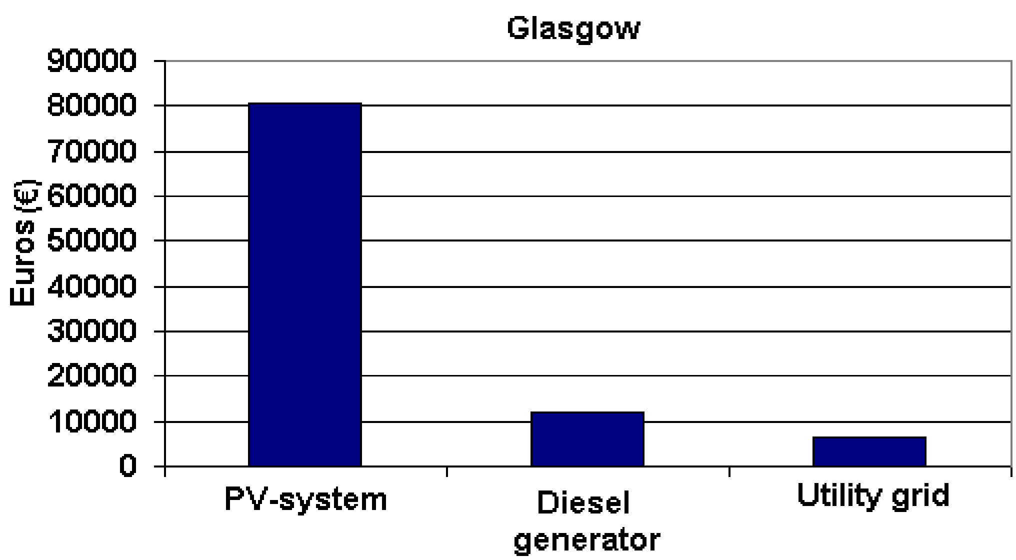

Figure 5.9: *Glasgow LCC comparison for different ways of providing electricity.*

It can be seen from both figures above, that the **LCC** is substantially higher than the other available options. Comparing the two PV-systems, Glasgow has much higher **LCC** cost than the PV-system located in Sifnos, and both systems don't seem to have an obvious advantage.

Doing various analyses with different kinds of PV-panels and batteries in order to find the most economical solution, one may optimize both systems further.

This however, will only improve the system, but not to an extent that PV-system **LCC** becomes of equal size with the other options (for the present status).
The disadvantage shown in the above figures will not be changed unless technological or other improvements are made.

5.6 Basic Formulae and Methodology to calculate Solar Radiation on inclined planes.

A. Same basic angles and basic quantities or parameters have to be studied before one proceeds to the solar radiation calculations for inclined planes. Details for these basic calculations are given in Appendix I .

B. Available solar radiation. One should study the above paragraph and especially Appendix I in order to proceed to the appropriate calculations in this paragraph.

Case 1: Sifnos-Greece: Latitude 36.6^o
Let us determine the Clearness Index , $\mathbf{K_t}$, for Sifnos

Definition:
Clearness Index $\mathbf{K_t}$; has to be determined for every month.
$\mathbf{K_t}$ is the ratio of the monthly solar energy at horizontal, $\overline{\mathbf{H}}$, in a site, over the solar energy at extra-terrestrial $\mathbf{H_{ext}}$ for the latitude of the site:

$$K_t = \overline{H}/H_{ext} \tag{5.3}$$

Extra-terrestrial Radiation is given in Table 5.19 and in the relevant table in Appendix IV .
The $\overline{\mathbf{H}}$ values for Sifnos are given by the data in Table 5.20, also in the relevant Table in Appendix IV .
Table 5.15 gives the $\mathbf{K_t}$ values for Sifnos, as calculated by dividing the corresponding values of Table 5.20 and Table 5.19.

Tabel 5.15: *Values for K_t in Sifnos*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_t	0.466	0.543	0.496	0.551	0.548	0.563	0.591	0.564	0.532	0.477	0.432	0.453

The reflectivity, **r**, of the area of Sifnos is 0.2, while for sites with more green and snow takes up higher values:
r : 0.2 - 0.7

• The sun's declination angle, δ, is given by the equation:

$$\mathbf{\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right)} \quad (5.4)$$

where **n** is the number of the day, of the year. Starting date is the point 1st January: **n=1**.

δ values are given in Table 5.16. These values are the same for both, Sifnos and Glasgow or any other place. δ values depend only on the typical (mean) day of the each month; usually taken as the 16th –17th day of the month. For February we take the 14th

Tabel 5.16: *Solar declination (It does not depend on the site; it is dependent only in the day of the year).*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
n	15	47	75	105	135	162	198	228	258	288	318	344
δ	-21.3	-13.0	-2.4	9.4	18.8	23.1	21.2	13.5	2.2	-9.6	-18.9	-23.0

Note: *The figure 75 for March is obtained by: 31(January)+28(February)+16(March)=75.*

• The sunset hour angle, ω_s, on a horizontal surface for a typical day of each month is given by the equation:

$\omega_s = \cos^{-1}(-\tan\varphi \tan\delta)$, where φ is the site's latitude 36.6^0, for Sifnos.

• ω_s values for Sifnos are calculated and given in Table 5.17.

Tabel 5.17: *Sun's hour angle for Sifnos.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
n	15	47	75	105	135	162	198	228	258	288	318	344
ω_s	73.2	80.2	88.2	97.1	104.6	108.4	106.7	100.2	91.6	82.8	75.3	71.6

• The ratio $\frac{\overline{H}_d}{\overline{\overline{H}}}$ i.e. the diffuse solar radiation over the total (global) one is given by (5.5). It is related with the clearness index $\mathbf{K_t}$, according to the equation:

$$\frac{\overline{H}_d}{\overline{\overline{H}}} = 1.39 - 4.03K_t + 5.53K^2{}_t - 3.11K^3{}_t \quad (5.5)$$

$\frac{\overline{H}_d}{\overline{\overline{H}}}$: mean monthly diffuse solar radiation on horizontal global.

Tabel 5.18: *Ratio* $\overline{H}_d / \overline{H}$ *as calculated by (5.5) using data from Table 5.15*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\frac{\overline{H}_d}{\overline{H}}$	0.40	0.33	0.37	0.33	0.33	0.32	0.30	0.32	0.34	0.39	0.43	0.41

- In order to estimate the monthly average daily total radiation on a horizontal surface **H**, the extraterrestrial insolation **(H_{ext})** on a horizontal surface must be calculated first.

H_{ext}, is the integral (global) **daily extraterrestrial radiation** on horizontal surface, determined as follows:

$$H_{ext} = \frac{24 \times 3600 \times I_{sc}}{\pi}\left(1 + 0.033\cos\left(\frac{n}{365} \times 360\right)\right) \times (\cos\varphi\cos\delta\cos\omega_s + \frac{\pi \times \omega_s}{180}\sin\varphi\sin\delta)$$

where I_{sc} is the solar insolation constant , I_{sc} = 1353 (W/m^2)

Table 5.19

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H_{ext} (kWh/m^2) per day	4.71	6.19	7.98	9.78	11.00	11.48	11.22	10.23	8.62	6.71	5.10	4.38

- The values of **H** on horizontal can be calculated using the formula:

$$\overline{H} = \overline{K}_t \times \overline{H}_{ext} \qquad (5.7)$$

where **K_t** is usually tabulated**.** If not it has to be calculated as shown above.

Table 5.20: *Average total (global) radiation per month on horizontal surface for Sifnos.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (kW/m^2)day	2.20	3.36	3.39	5.39	6.03	6.46	6.63	5.77	4.58	3.20	2.20	1.98

- The next step is to calculate **R_b** i.e. the conversion coefficient of the beam solar insolation from the horizontal to the inclined panel.

$$R_b = \frac{I_{b,n}}{I_{b,h}} = \frac{\text{solar beam (direct) on a tilted plane}}{\text{solar beam (direct) on horizontal}} \qquad (5.8)$$

$\Rightarrow$ **$I_{b,n} = R_b \times I_{b,h}$** , while (5.9)

$\overline{R}_b$ is the mean monthly value of $\mathbf{R_b}$, as the simulation in our case is on monthly basis.

$\overline{R}_b$ is function of the site's latitude, $\boldsymbol{\varphi}$, the panel's slope, $\boldsymbol{\beta}$, and the sunset hour angle, ω'_s, on a tilted surface, according to:

$$\overline{R}_b = \frac{\cos(\varphi-\beta)\cos(\delta)\sin(\omega'_s)+\left(\pi/180\right)\omega'_s\sin(\varphi-\beta)\sin(\delta)}{\cos(\varphi)\cos(\delta)\sin(\omega_s)+\left(\pi/180\right)\sin(\varphi)\sin(\delta)} \quad (5.10)$$

The sunset hour angle $\boldsymbol{\omega'_s}$ to the inclined plane is given by the equation:

$$\omega'_s = \min\left[\cos^{-1}(-\tan\varphi\tan\delta), \cos^{-1}(-\tan(\varphi-\beta)\tan\delta)\right] \quad (5.11)$$

That is: $\boldsymbol{\omega'_s}$ is the lower value of the above two angles :

$\boldsymbol{\omega_s}$ and $\mathbf{\cos^{-1}(-\tan(\phi-\beta)\tan\delta)}$.

$\boldsymbol{\omega'_s}$ values for any surface tilted with angle β in Sifnos are given in Table 5.21.

Tabel 5.21: *Sunset hour angle on a tilted surface*

Panel Tilt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	73.2	80.2	88.2	97.1	104.6	108.4	106.7	100.2	91.6	82.8	75.3	71.6
5	73.2	80.2	88.2	95.9	102.1	105.2	103.8	98.5	91.4	82.8	75.3	71.6
10	73.2	80.2	88.2	94.8	99.8	102.3	101.2	96.9	91.1	82.8	75.3	71.6
15	73.2	80.2	88.2	93.8	97.7	99.7	98.8	95.4	90.9	82.8	75.3	71.6
20	73.2	80.2	88.2	92.8	95.8	97.3	96.6	94.1	90.7	82.8	75.3	71.6
25	73.2	80.2	88.2	91.9	94.0	95.0	94.6	92.8	90.5	82.8	75.3	71.6
30	73.2	80.2	88.2	91.1	62.3	92.8	92.6	91.6	90.3	82.8	75.3	71.6
35	73.2	80.2	88.2	90.3	90.5	90.7	90.6	90.4	90.1	82.8	75.3	71.6
40	73.2	80.2	88.2	89.4	88.8	88.5	88.7	89.2	89.9	82.8	75.3	71.6
45	73.2	80.2	88.2	88.6	87.1	86.4	86.7	88.0	89.7	82.8	75.3	71.6
50	73.2	80.2	88.2	87.7	85.3	84.2	84.7	86.7	89.5	82.8	75.3	71.6
55	73.2	80.2	88.2	86.8	83.5	81.8	82.6	85.4	89.3	82.8	75.3	71.6
60	73.2	80.2	88.2	85.9	81.5	79.4	80.3	84.1	89.0	82.8	75.3	71.6
65	73.2	80.2	88.2	84.9	79.4	76.7	77.9	82.6	88.8	82.8	75.3	71.6
70	73.2	80.2	88.2	83.7	77.0	73.7	75.2	80.9	88.5	82.8	75.3	71.6
75	73.2	80.2	88.2	82.4	74.3	70.2	72.1	79.1	88.2	82.8	75.3	71.6
80	73.2	80.2	88.2	81.0	71.2	66.2	68.5	76.9	87.9	82.8	75.3	71.6
85	73.2	80.2	88.2	79.2	67.5	61.3	64.1	74.4	87.5	82.8	75.3	71.6
90	73.2	80.2	88.2	77.1	62.7	55.0	58.5	71.2	87.0	82.8	75.3	71.6

So, $\mathbf{R_b}$, values for Sifnos are given in Table 5.22, below, as calculated from (5.8).

Tabel 5.22: *Ratio R_b, for Sifnos during the year for various slopes*

Panel Tilt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.18	1.12	1.07	1.03	1.00	0.99	1.00	1.02	1.05	1.10	1.16	1.19
10	1.34	1.23	1.13	1.05	1.00	0.98	0.99	1.03	1.10	1.19	1.31	1.37
15	1.50	1.33	1.19	1.07	0.99	0.96	0.97	1.03	1.13	1.28	1.44	1.54
20	1.64	1.42	1.23	1.07	0.97	0.93	0.95	1.03	1.16	1.35	1.57	1.70
25	1.77	1.50	1.26	1.07	0.95	0.90	0.92	1.02	1.18	1.42	1.69	1.85
30	1.89	1.57	1.29	1.06	0.92	0.86	0.89	1.00	1.19	1.47	1.79	1.98
35	2.00	1.63	1.31	1.04	0.88	0.82	0.85	0.97	1.19	1.51	1.88	2.10
40	2.09	1.67	1.31	1.02	0.84	0.77	0.80	0.94	1.18	1.54	1.95	2.20
45	2.16	1.71	1.31	0.99	0.80	0.72	0.75	0.90	1.17	1.56	2.01	2.28
50	2.22	1.72	1.29	0.95	0.74	0.66	0.70	0.85	1.14	1.57	2.06	2.35
55	2.26	1.73	1.27	0.90	0.69	0.60	0.64	0.80	1.11	1.56	2.09	2.40
60	2.28	1.72	1.23	0.85	0.62	0.54	0.57	0.74	1.06	1.55	2.10	2.43
65	2.28	1.70	1.19	0.79	0.56	0.47	0.51	0.68	1.01	1.52	2.09	2.44
70	2.27	1.67	1.14	0.72	0.49	0.40	0.44	0.61	0.95	1.48	2.08	2.44
75	2.24	1.62	1.08	0.65	0.42	0.33	0.37	0.54	0.89	1.43	2.04	2.41
80	2.20	1.56	1.01	0.58	0.35	0.26	0.30	0.47	0.82	1.37	1.99	2.37
85	2.13	1.49	0.93	0.50	0.27	0.19	0.23	0.39	0.74	1.29	1.93	2.31
90	2.05	1.41	0.85	0.42	0.20	0.13	0.16	0.31	0.65	1.21	1.85	2.23

The ratio, $\overline{\mathbf{R}}$ of the monthly average daily total radiation on a tilted surface, $\boldsymbol{\beta}$, over that on a horizontal surface is determined by equation:

$$\overline{\mathbf{R}} = \frac{\overline{\mathbf{H}}_T}{\mathbf{H}} = \left(\mathbf{1} - \frac{\overline{\mathbf{H}}_d}{\mathbf{H}}\right)\overline{\mathbf{R}}_\mathbf{b} + \frac{\overline{\mathbf{H}}_\mathbf{d}}{\mathbf{H}}\left(\frac{\mathbf{1}+\cos\boldsymbol{\beta}}{\mathbf{2}}\right) + \mathbf{r}\left(\frac{\mathbf{1}-\cos\boldsymbol{\beta}}{\mathbf{2}}\right) \quad (5.12)$$

Tabel 5.23: *Ratio* $\overline{\mathbf{R}}$ *. Conversion coefficient. (mean monthly value) to convert global solar irradiation from the horizontal to a tilted surface. These values hold for Sifnos.*

Panel Tilt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.11	1.08	1.04	1.02	1.00	0.99	1.00	1.01	1.03	1.06	1.09	1.11
10	1.20	1.15	1.08	1.03	1.00	0.98	0.99	1.02	1.06	1.12	1.17	1.22
15	1.30	1.22	1.11	1.04	0.99	0.97	0.98	1.02	1.09	1.17	1.25	1.32
20	1.38	1.28	1.14	1.04	0.98	0.95	0.96	1.02.	1.10	1.21	1.32	1.41
25	1.46	1.33	1.16	1.04	0.96	0.93	0.94	1.01	1.11	1.25	1.38	1.49
30	1.52	1.37	1.17	1.03	0.94	0.90	0.91	0.99	1.12	1.28	1.43	1.56
35	1.58	1.41	1.18	1.02	0.91	0.87	0.88	0.97	1.11	1.30	1.48	1.63
40	1.63	1.43	1.18	1.00	0.88	0.83	0.85	0.94	1.10	1.31	1.52	1.68
45	1.67	1.45	1.17	0.97	0.84	0.79	0.81	0.91	1.09	1.32	1.54	1.73
50	1.70	1.46	1.15	0.94	0.80	0.75	0.77	0.88	1.07	1.31	1.56	1.76
55	1.71	1.46	1.13	0.91	0.76	0.70	0.72	0.84	1.04	1.31	1.57	1.78
60	1.72	1.45	1.10	0.87	0.72	0.65	0.68	0.80	1.01	1.29	1.57	1.79
65	1.72	1.43	1.07	0.82	0.67	0.60	0.63	0.75	0.97	1.26	1.56	1.79
70	1.70	1.40	1.03	0.77	0.62	0.55	0.57	0.70	0.92	1.23	1.54	1.78
75	1.67	1.36	0.99	0.72	0.56	0.50	0.52	0.64	0.87	1.19	1.51	1.76
80	1.64	1.32	0.93	0.66	0.51	0.45	0.47	0.59	0.82	1.15	1.47	1.72
85	1.59	1.27	0.88	0.60	0.45	0.40	0.41	0.53	0.76	1.09	1.42	1.68
90	1.54	1.21	0.82	0.54	0.40	0.35	0.36	0.47	0.70	1.03	1.37	1.62

Finally, the average daily total radiation on a sloped surface, is equal to:

$$\overline{\mathbf{H}}_{\mathbf{T}} = \overline{\mathbf{H}} \times \overline{\mathbf{R}} \qquad (5.13)$$

Table 5.24: *Daily **irradiation** in Sifnos (in **kWh/m^2 per day**) for a typical day in every month as a function of the panel inclination in degrees*

Panel Tilt	Jan *	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual kWh/m^2 per day **
0	2.20	3.36	3.39	5.39	6.03	6.46	6.63	5.77	4.58	3.20	2.20	1.98	4.31
5	2.43	3.63	4.13	5.50	6.04	6.42	6.61	5.84	4.74	3.40	2.40	2.21	4.44
10	2.64	3.87	4.28	5.57	6.02	6.36	6.56	5.88	4.87	3.58	2.58	2.42	4.55
15	2.85	4.10	4.41	5.62	5.97	6.26	6.48	5.88	4.98	3.73	2.75	2.61	4.64
20	3.03	4.30	4.51	5.63	5.89	6.14	6.37	5.86	5.05	3.87	2.90	2.79	4.70
25	3.20	4.47	4.59	5.61	5.79	5.98	6.23	5.80	5.10	3.99	3.04	2.96	4.73
30	3.35	4.61	4.64	5.57	5.65	5.80	6.06	5.71	5.12	4.08	3.16	3.10	4.74
35	3.47	4.73	4.66	5.49	5.49	5.60	5.86	5.60	5.11	4.15	3.26	3.23	4.72
40	3.58	4.82	4.65	5.38	5.30	5.37	5.63	5.45	5.06	4.19	3.34	3.34	4.68
45	3.66	4.88	4.62	5.24	5.09	5.11	5.38	5.27	4.99	4.21	3.40	3.43	4.61
50	3.72	4.90	4.57	5.07	4.85	4.84	5.10	5.07	4.89	4.21	3.44	3.49	4.51
55	3.76	4.90	4.48	4.88	4.59	4.54	4.80	4.84	4.77	4.18	3.46	3.53	4.39
60	3.78	4.87	4.37	4.66	4.31	4.23	4.49	4.59	4.61	4.12	3.45	3.55	4.25
65	3.77	4.80	4.24	4.42	4.02	3.91	4.15	4.32	4.44	4.04	3.43	3.55	4.09
70	3.73	4.71	4.08	4.16	3.71	3.58	3.81	4.03	4.23	3.94	3.39	3.53	3.91
75	3.68	4.59	3.90	3.87	3.39	3.24	3.45	3.72	4.01	3.81	3.32	3.48	3.71
80	3.60	4.44	3.70	3.57	3.06	2.90	3.09	3.40	3.76	3.66	3.24	3.41	3.49
85	3.49	4.26	3.48	3.26	2.74	2.56	2.74	3.07	3.49	3.50	3.13	3.32	3.25
90	3.37	4.06	3.24	2.93	2.41	2.24	2.39	2.73	3.21	3.31	3.01	3.21	3.01

Remark:

* The values in the column provide the **PSH** values for each month for any inclination of the PV-panel.

** These values also represent **PSH** values on a mean annual basis.

Case 2:Glasgow- Scotland

- Latitude 55.3^0. The Clearness Index, $\mathbf{K_t}$ for Glasgow. Here, the same method as for Sifnos is followed in order to calculate $\mathbf{K_t}$.

$\mathbf{K_t}$ values for Glasgow are given below:

Table 5.25

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\mathbf{K_t}$	0.406	0.297	0.355	0.410	0.433	0.371	0.379	0.368	0.385	0.352	0.275	0.264

Using the same approach described in the previous section, the monthly average daily radiation on a slope surface is found to be:

Table 5.26: *Daily irradiation in Glasgow (in kWh/m^2 per day) for a typical day in every month as a function of the panel inclination in degrees*

Panel Tilt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
0	0.65	0.93	1.91	3.33	4.48	4.22	4.12	3.30	2.45	1.33	0.55	0.34	2.30
5	0.82	1.03	2.04	3.44	4.54	4.23	4.14	3.38	2.58	1.47	0.63	0.41	2.39
10	0.98	1.12	2.16	3.54	4.58	4.23	4.16	3.44	2.71	1.60	0.70	0.47	2.48
15	1.14	1.21	2.27	3.63	4.61	4.22	4.16	3.48	2.81	1.72	0.78	0.54	2.55
20	1.29	1.29	2.36	3.69	4.61	4.20	4.15	3.51	2.90	1.83	0.84	0.60	2.61
25	1.44	1.37	2.45	3.74	4.60	4.15	4.12	3.53	2.98	1.93	0.91	0.65	2.66
30	1.57	1.43	2.52	3.77	4.56	4.10	4.07	3.52	3.04	2.02	0.97	0.71	2.69
35	1.70	1.49	2.57	3.77	4.51	4.02	4.00	3.50	3.08	2.10	1.02	0.75	2.71
40	1.81	1.54	2.61	3.76	4.43	3.93	3.92	3.47	3.11	2.17	1.07	0.80	2.72
45	1.91	1.58	2.64	3.73	4.33	3.82	3.82	3.41	3.12	2.22	1.11	0.84	2.71
50	2.00	1.62	2.65	3.68	4.22	3.70	3.71	3.34	3.11	2.26	1.14	0.87	2.69
55	2.07	1.64	2.65	3.61	4.08	3.56	3.58	3.25	3.08	2.29	1.17	0.90	2.66
60	2.13	1.65	2.63	3.52	3.92	3.41	3.43	3.15	3.04	2.30	1.19	0.92	2.61
65	2.18	1.65	2.60	3.41	3.75	3.24	3.27	3.04	2.98	2.30	1.20	0.94	2.55
70	2.21	1.65	2.55	3.28	3.56	3.07	3.10	2.91	2.91	2.28	1.21	0.95	2.47
75	2.23	1.63	2.49	3.14	3.36	2.89	2.92	2.77	2.81	2.25	1.21	0.95	2.39
80	2.23	1.61	2.41	2.98	3.15	2.69	2.73	2.61	2.71	2.21	1.20	0.95	2.29
85	2.21	1.57	2.32	2.81	2.92	2.49	2.54	2.45	2.59	2.16	1.18	0.94	2.18
90	2.18	1.53	2.22	2.63	2.69	2.29	2.33	2.28	2.45	2.09	1.15	0.93	2.06

5.7 PV-System sizing.

Case: Sifnos Greece

a. Number of series connected modules

From Table 5.3, the PV-panel type KC 120 is chosen. The number of PV-modules connected in series will be:

$$\mathbf{N_s} = \frac{\mathbf{V_{DC}}}{\mathbf{V_m}} = \frac{12}{17.7} = 0.7 \qquad (5.12)$$

The final number of modules is the nearest number above 0.7 which is 1.
Therefore N_S= 1.

Remark: As said before V_{DC}=12 Volts is not a proper value for a PV-generator. To lower losses $\mathbf{V_{DC}}$ has to be at 48 Volts.

b. Number of parallel connected modules

Equation (4.2) for the equivalent load current, $\mathbf{i_L}$, gives:

$$\mathbf{i_L} = \frac{\mathbf{E_L}}{\mathbf{24V_{DC}}} = \frac{9823Wh}{24h/day \times 12V} = 34.1A \qquad (5.13)$$

where $\mathbf{E_L}$ is the average power required by the load.

Notice: *9823 Wh is the energy per day required (Load) for a household; see Table 5.27.*

The nominal current from the PV-system, from equation (4.4), will be equal to

$$\mathbf{i_{pv}} = \frac{\mathbf{24} \times \mathbf{i_L}}{\mathbf{PSH}} = \frac{24 \times 34.1}{4.25} = 192.6A, \qquad (5.14)$$

where **PSH** is numerically equal to the calculated irradiation, in kWh/m^2 day, see Table 5.24, for a panel tilt angle of 60 degrees, in Sifnos.
The number of parallel-connected modules is given by equation (5.5).

$$\mathbf{N_p} = \frac{\mathbf{i_{pv}}}{\mathbf{i_m}} = \frac{192.6}{7.1} = 27.1 \qquad (5.15)$$

So, the final number it will be N_P=27 modules. The total number of modules will be:

$$\mathbf{N} = \mathbf{N_S} \times \mathbf{N_P} = 1 \times 27 = 27 \qquad (5.16)$$

The same procedure is repeated for Glasgow and the results are shown in Table 5.6.

c. Storage subsystem

The energy required by the load per month is 9823 Wh per day.

The energy produced by the system on a typical day is

$$\mathbf{E_{pv}} = \mathbf{Insolation} \times \mathbf{A_{pv}} \times \boldsymbol{\eta_f} = \mathbf{P_m} \times \mathbf{PSH\,(month)}$$

where η_f is the efficiency of the modules and A_{pv} is the total area of the array. We construct the Table below to obtain the monthly energy balance.

Tabel 5.27: *Monthly energy balance*

	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
E_{pv} (kWh/day)	11.72	12.10	13.44	13.26	14.78	15.02	15.95	17.23	17.10	15.06	12.64	10.37
E_L (kWh/day)	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82
E_n balance	1.90	2.28	3.61	3.44	4.96	5.20	6.12	7.41	7.28	5.23	2.82	0.55
Deficit (kWh/day)	0	0	0	0	0	0	0	0	0	0	0	0
Monthly balance	0	0	0	0	0	0	0	0	0	0	0	0

From the above table it is shown that the energy deficit **ΔE** during the year is zero, so the charge deficit Q_{Yd} will be equal to zero since $\mathbf{Q_{Yd}} = \frac{\mathbf{\Delta E}}{\mathbf{V_{DC}}} = \frac{0}{12} = 0$.

Another charge deficit has to be considered (4.8c) , $\mathbf{Q_d} = \mathbf{i_L} \times \mathbf{24} \times \mathbf{d}$). (5.17)

The chosen number of days with no energy input is chosen to be 5.

So, the value of Q_d is:

$$\mathbf{Q_d} = i_L \times 24 \times 5 = 34.1 \times 24 \times 5 = 4092\,Ah \tag{5.18}$$

The total battery capacity required is equal to:

$$\mathbf{Q_B} = \frac{\mathbf{Q_{Yd}} + \mathbf{Q_d}}{DOD} = \frac{0 + 4092}{0.8} = 5115\,Ah \tag{5.19}$$

where **DOD** is the battery max. discharge level.

The total number of battery string required is derived from:

$$\mathbf{N_{B,P}} = \frac{\mathbf{Q_B}}{\textbf{Capacity of one battery}} = \frac{5115}{440} = 11.625 \approx 12 \tag{5.20}$$

The number of the batteries in series will be equal to

$$\mathbf{N_{BS}} = \frac{\mathbf{V_{DC}}}{\mathbf{V_B}} = \frac{12}{12} = 1 \tag{5.21}$$

The total number of batteries will be:

$$\mathbf{N_B} = \mathbf{N_{BP}} \times \mathbf{N_{BS}} = 12 \times 1 = 12 \tag{5.22}$$

5.8 LCC analysis for a PV-generator.

The capital cost for Sifnos is found from Table 5.7. Total cost is given by equation (5.23). Running cost for every year is 32 € and battery replacement as mentioned in § 5.5 is done every seven (7) years. Discount rate is set equal to 0.05 for the calculation of the factor **CV**, equation (5.2).

Cost = 27 panels×573 €+10 batteries×366 €=19131 € (5.23)

A complete analysis for twenty years is shown in Table 5.28. The **PW** for costs in the 7th year of operation is calculated by adding all payments made that year. The discount factor for the 7th year will be equal to:

$$CV_7 = \left(\frac{1+0}{1+0.05}\right)^7 = 0.71$$

The final discounted value will be equal to total cost for the year, multiplied by **CV**.

Table 5.28: *Yearly cost analysis for Sifnos*

Year	Capital	Replacement	O&M	Total	Discounted
1	22582		28	22611	22610
2			28	28	25
3			28	28	25
4			28	28	23
5			28	28	22
6			28	28	20
7		4329	28	4357	3097
8			28	28	19
9			28	28	19
10			28	28	17
11			28	28	17
12			28	28	16
13			28	28	16
14		4329	28	4357	2200
15			28	28	14
16			28	28	12
17			28	28	12
18			28	28	11
19			28	28	11
20			28	28	11
				Total Discounted	**28195**

The life cycle cost for a PV-system in Sifnos will be 28195 €. The same calculations have to be made for Glasgow. The results were shown previously in Table 5.8.

CASE STUDY 2

5.9 Design and Integration of PV-configurations for a Household in Germany

This design methodology introduced the daily load profile and the load seasonal dependence . Also, load corrections due to losses and $\mathbf{P_m}$ corrections as field conditions differ from the **S.T.C.** have to be included in PV-sizing or PV feasibility study. It fallow a more complete technical approach is followed here.

5.9.1 General and Preparatory tasks

Target: Design and Integrate, possible PV-configurations for a household and determine the most cost-effective solution including all PV-elements.

Consider a case of a house in Germany. Assume or estimate the loads for that house. For this, use the values from Table 5.29 or use any data available from a proper reference material. Solar radiation data to be retrieved by a meteorological database or METEONORM.

Similarly, assume the power of each load, its demand factor and the time period the loads require energy, that is, the daily profile of the loads.

To meet the loads a PV-generator is proposed. The analysis to be outlined hereafter has to answer the following:

1. Describe the possible PV-configuration(s) which might be established and determine the most cost-effective proposed solution.
   For all the PV-elements in the configuration(s) one has to examine the costs of these. PV-elements. Also, to give details (performance, construction etc) of the PV-configurations. For the costs one may visit the web, too, to determine competitive prices.
2. Outline and estimate the size of the PV-generator to meet the load. That is:

a. To choose the PV-modules: type, characteristics etc.
b. To determine the number of PV-modules, electric connections etc.

Remark:

One may consider any possible scenario to cover, thoroughly or partially (hybrid system) the load.

3. Size a battery bank:
   For this sizing problem, we will follow both approaches: **Ah** and **Wh method,** to determine the battery bank capacity.
   Choose the type, and determine the number of batteries: **Ah**, **DOD**, no. connected in series and parallel, energy autonomy in days etc.
   Comparison of the various battery types, which meet the requirements of the problem in order to reach to the most cost-effective solution.

4. Decide on the size of any supplementary source when the proposed PV-system is hybrid

To make a proper analysis the following issues have to be covered.

1. Site conditions:

a. House orientation

b. Area: dimensions

c. Roof area

d. *Height from the ground level*

2. Load profile

a. Data sheets

3. Choosing Modules: type, number, configuration.

4. Choosing Batteries: type, number, configuration.

5. Choosing a Power Inverter

6. Conclusions and recommendations.

- To have a detailed view of the task, the following are the titles of the subtasks:

1) Description of all the required elements for the household.
2) Outline and estimation of the size of the PV-generator.
3) Sizing of the Battery bank.
4) Determination of the supplementary source if, the PV-system is a Hybrid one.

The preliminary requirements to carry out this study are:

a) House; the house is chosen in Krauthasen (Jüelich), Germany. Details are given in fig 5.11.

b) Solar irradiation data, obtained from the METEONORM package, for this site. The details of the site location are determined, too.

c) The descriptions of the respective modules, batteries, inverter, charge regulator etc, may be obtained from Internet, from various companies for better evaluation of the results.

- **Description of all the required elements for the House to be Solar House.**

Describe all possible elements of the PV-configuration for the Solar House

1) PV-Generator
2) Charger
3) Power inverter
4) Batteries
5) Diesel Generator
6) Meters, cabling, indicators etc.; see also fig. 5.10

The house structural details are:

a. House direction : N-W

b. Area : ground lot on which house is built: = 152.37m^2
total surface = 857m^2
useful roof surface = 83m^2.

c. Height from the ground level = 18.25m.

The view of the house is given in fig. 5.11.

Load Profile:

The total load for one day is considered, and the load profile is studied in detail giving some important information regarding the PV-modules selection.

The load study conclusions:

The load was divided into two segments, **winter** and **summer load**, as the difference in both will clearly provide us with valuable information on the PV-configuration to be chosen.

The details given by Table 5.29, are summarized as such:

- ✓ Winter load : 72,534Wh/day
- ✓ Summer load : 27,994Wh/day
- ✓ Common load : 29,334Wh/day: study Table 5.29 to find out the common load for the two seasons

A pre-analysis of the loads provides the following:

- An overload time lies between 12.00 -16.00 p.m., as seen in figs 5.12 & 5.13.
- A constant load of 3kW for 24h in winter, (to meet the winter load), is planned.
- The load for a winter day is split as follows:
    - during the day : 38.340Wh i.e., 53% of the total load requirement
    - during the night : 34.194Wh i.e., 47% of the total load requirement.

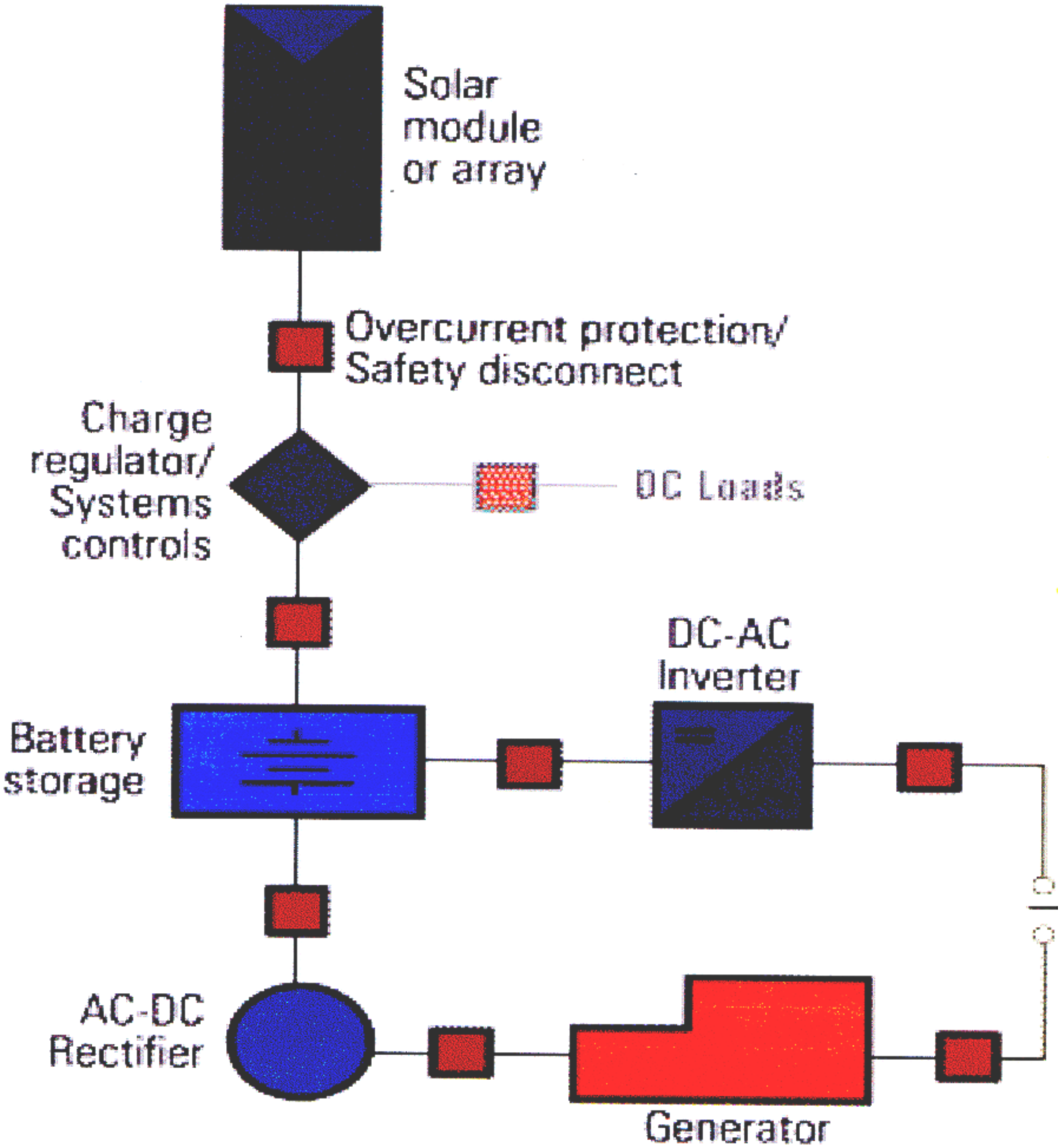

Figure 5.10: *A general lay out of PV-generator backed up by a storage system (battery bank) and a Diesel generator.*

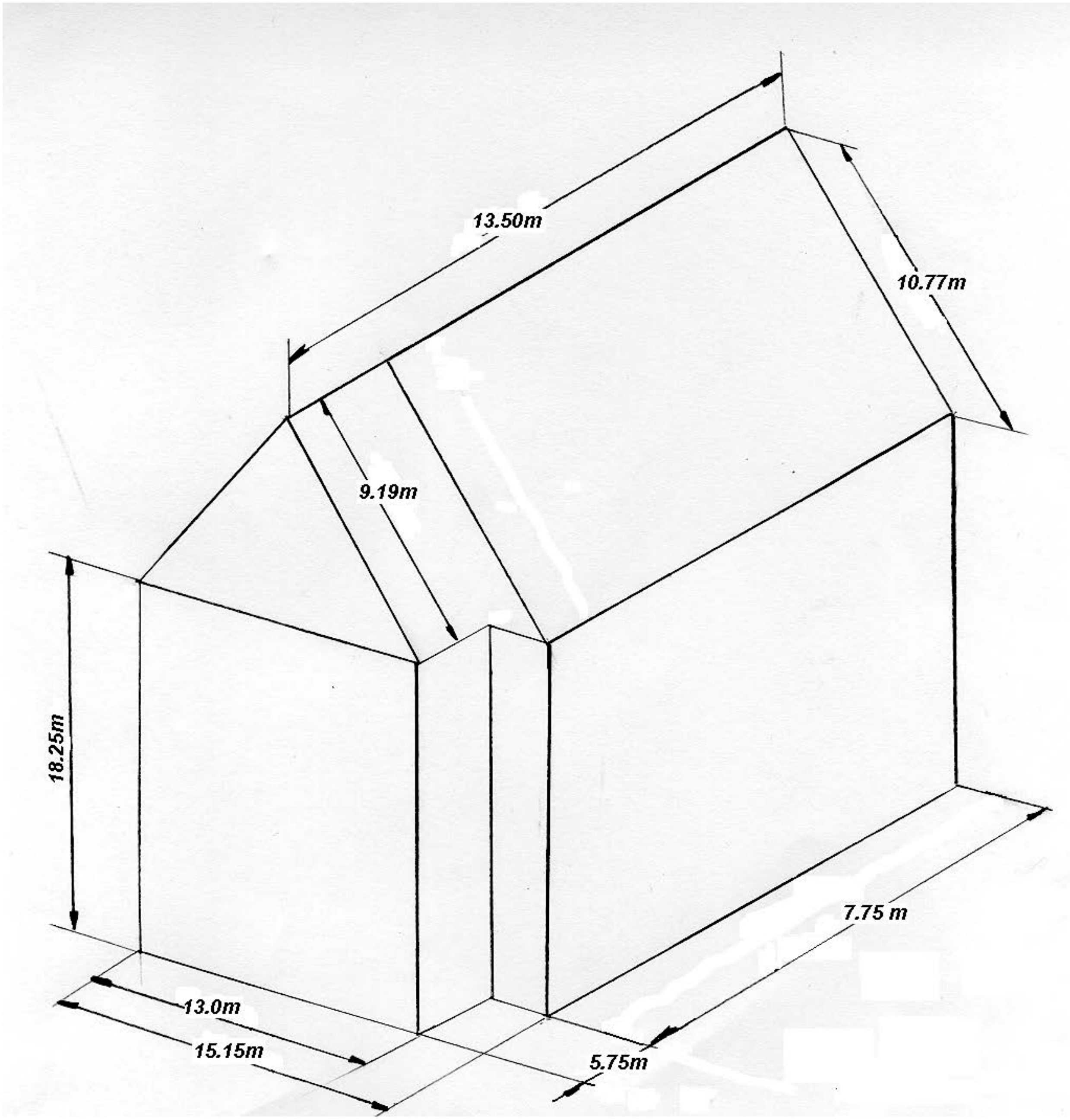

Figure 5.11: *The view of the house with dimensions and overall architecture. This is the house to be designed as a Solar House.*

Table 5.29: *Typical Loads for a household*

Load Type	Demand factor	Time (h)		Total load (Wh)	
		Winter	Summer	Winter	Summer
Lamps 2×10W	0.4	17-23	21-23	48	16
32×20W	0.4	17-23	20-24	1536	768
6×25W	0.5	18-20	21-23	150	150
2×50W	0.6	22-23	22-23	60	60
1×80W	0.6	20-21	22-23	48	48
1×300W	0.6	17-23	20-23	1080	540
Personal computer 3×180W	0.6	20-23	20-23	972	972
T.V. 2×100W	0.4	17-23	17-23	480	480
Refrigerator 2×150W	0.6	0-24	0-24	4320	4320
Wash machine with dryer 1×3600W	0.6	12-16	12-16	8640	8640
Electric oven 1×3000W	0.6	11-13 19-21	11-13 19-21	7200	7200
Dish wash machine 1×3600W	0.6	14-16	14-16	4320	4320
Heater 1×3000W	0.6	0-24	-----	43200	-----
Water heating 1×200W	0.6	19-23	19-23	480	480
Total load: 15730				**72534**	**27994**

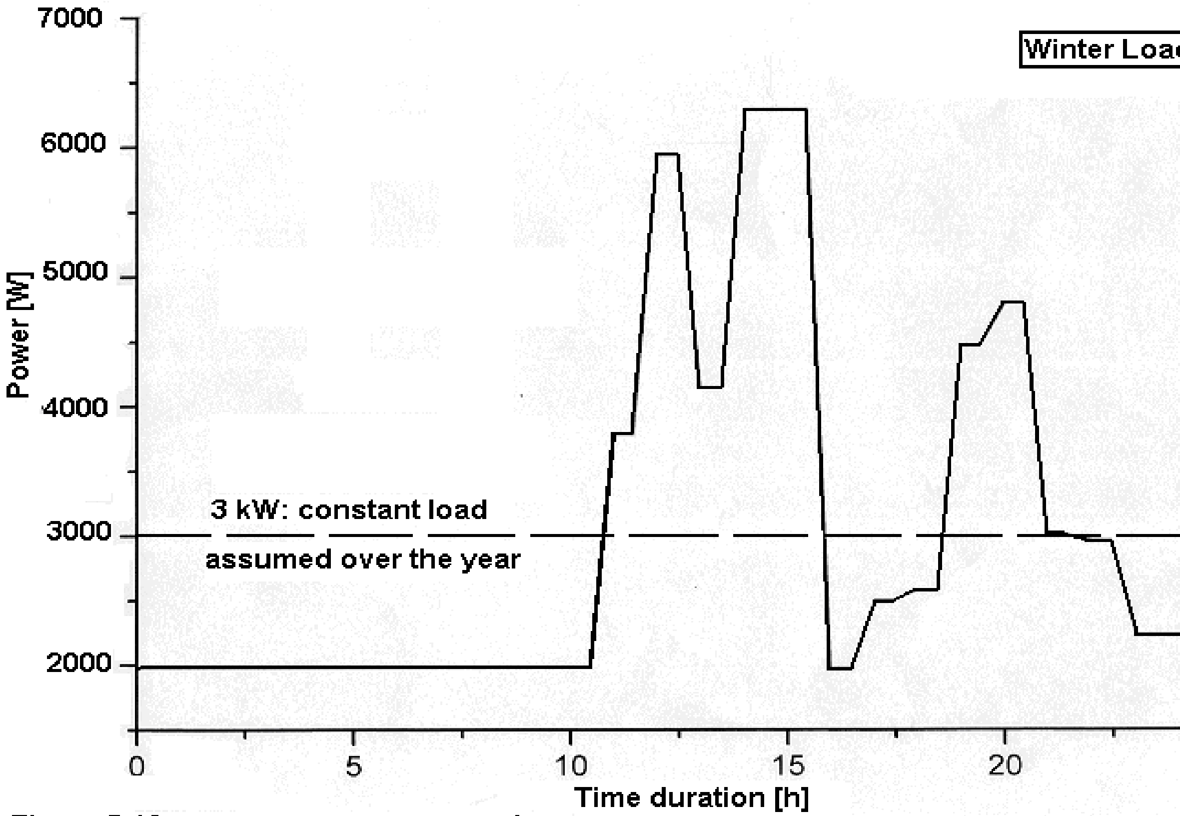

Figure 5.12: *Daily load profile according to the demand factor.*

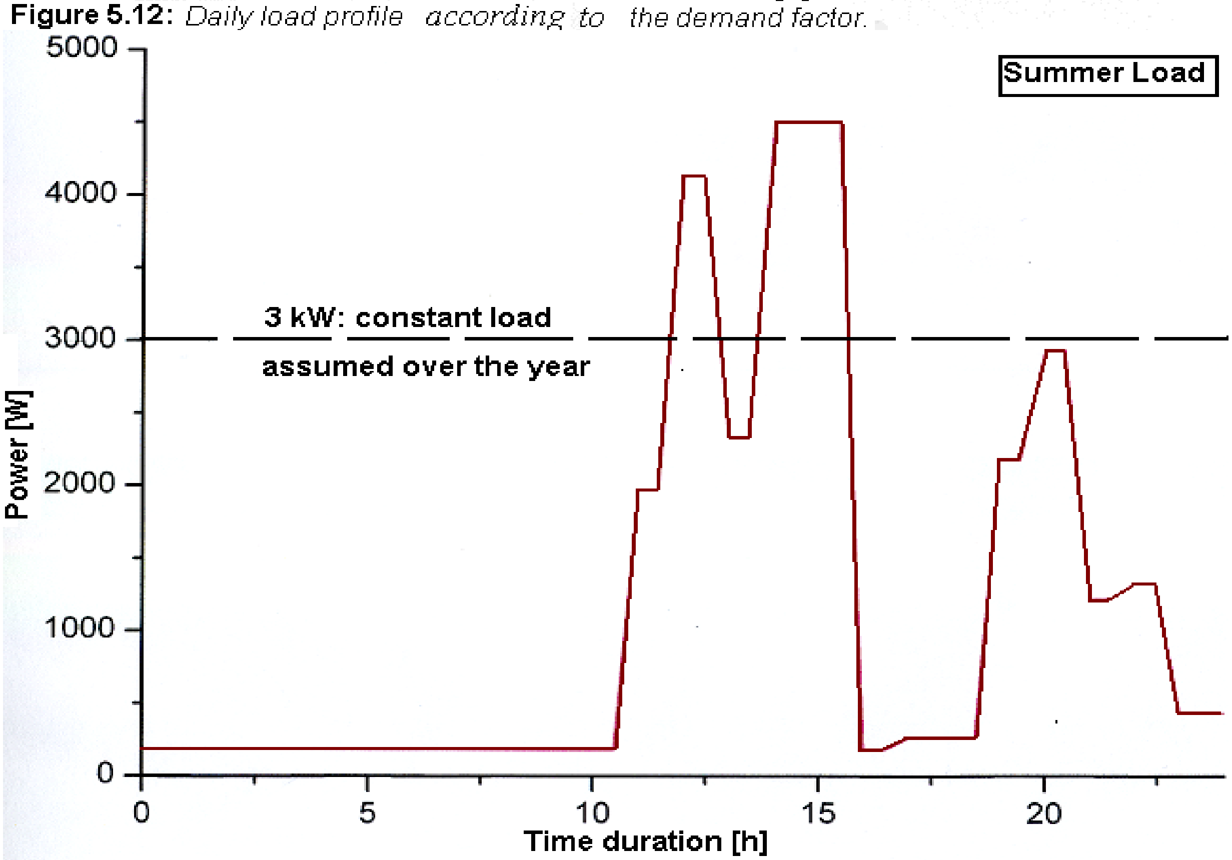

Figure 5.13: *Daily load profile according to the demand factor*

5.9.2 Outline and estimate the size of the PV-generator

This task includes: the choice of the PV-modules, the number of PV-modules required and the circuitry.

This will be answered using both methodologies:

1) Wh approach

2) Ah approach.

A detailed analysis of the whole load situation was carried out taking into consideration different PV-modules. This helped to decide which module is better or optimum for the given task.

The load is divided into three parts to make the PV-sizing analysis more effective:

a. taking the winter load
b. taking the summer load
c. a constant load of 3kW for the whole day all over the year was assumed. The assumption was based on the winter load profile, which is much higher than the summer one: see figs 5.12 & 5.13.

The PV-modules chosen for the study, keeping in mind the load requirements, are:

1. Solarex MSX - 120,

   rated peak power P_{max} =120W
   i_{sc} =7.6A, V_{oc} =21.3V, i_m =7.0A, V_m =17.1V.

2. Siemens SP 150,

   rated peak power P_{max} =150W
   i_{sc} =4.8A, V_{oc} =43.4V, i_m =4.4A, V_m =34.0V.

3. A.S.E. ASE-300-DGF/50,

   rated peak power P_{max} = 300W
   i_{sc} =6.5A, V_{oc} =60.0V, i_m =5.9A, V_m =50.0V.

4. Entech Inc. concentrating module EN-430

   rated peak power P_{max} =430W
   i_{sc} =22.9A, V_{oc} =24.5V, i_m =21.3A, V_m =20.2V.

5.9.3 Corrections in the Load due to Losses

Table 5.30	Wh method	Ah method
Cable losses & Charger losses	5%	5%
Battery efficiency losses (including cabling)	20%	0% in Ah method battery charging losses are assumed zero, see § 3.3.1
DC/AC invertor (including cabling)	15%	15%

Therefore, the corrected Load due to losses is:

- for Wh method: 1.4 × 72534Wh for winter = 101547.6Wh/day
  1.4 × 27994Wh for summer = 39191.6Wh/day
  1.4 × 29334 Wh for common = 41067.6Wh/day
- for Ah method: 1.2 × 72534Wh for winter = 87040.8Wh/day
  1.2 × 27994Wh for summer = 33592.8Wh/day
  1.2 × 29334Wh for common = 35200.8Wh/day

• **Corrections to: P_{max}, V_m, i_m for field conditions**

NOCT: Normal Operating Cell Temperature, the temperature a PV-module reaches operating under SOC.

SOC: Standard Operating Conditions, defined as :

- I_T= 800 W/m^2, T_a = 20 ^{0}C, V_m = 1 m/s.
- $\omega = 0^0$
- measured at V_{oc} conditions.

$T_c = T_a + h_w \times I_T$ where: h_w = 0.03 m$^{2\,0}$K/W. (obtained from research)

T_a = 10 ^{0}C for Jüelich, as taken from METEONORM data. Hence, from the above relationship:

T_c = 34 ^{0}C

NOCT is given equal to: 39.2 ^{0}C

I_{sc} varies very slightly with temperature. So, we consider it be independent of temperature. This does not hold for V_{oc}, see § 2.2, equation (2.8). Hence, for V_{oc} holds:

$dV_{oc}/dT = -0.0023V/^0C$ per PV-cell. Therefore, for n_s PV-cell in series in a panel the corrected V'_{oc} value is estimated by:

$$V'_{oc} = V_{oc} - 0.0023 \times n_s \times (34\text{-}10)^0C$$

✓ For Solarex PV-module:

$V'_{oc} = 21.3 - 0.0023 \times 36 \times 24^0C$

$= 19.31$ V

$FF = 120/7.6 \times 21.3 = 0.741$

$P'_{max} = i_{sc} \times V'_{oc} \times FF = 109$ W.

$V'_m = P'_{max} / i_m = 109/7.0 = 15.57$ V.

✓ For A.S.E. PV-module:

$V'_{oc} = 60.0 - 0.0023 \times 100 \times 24^0C$

$= 54.48$ V

$FF = 300/6.5 \times 60.0 = 0.769$

$P'_{max} = i_{sc} \times V'_{oc} \times FF = 272.4$ W.

$V'_m = P'_{max} / i_m = 272.4/5.9 = 46.16$ V.

✓ For Siemens PV-module:

$V'_{oc} = 43.4 - 0.0023 \times 72 \times 24^0C$

$= 39.42$ V

$FF = 150./4.8 \times 43.4 = 0.720$

$P'_{max} = i_{sc} \times V'_{oc} \times FF = 136.2$ W.

$V'_m = P'_{max} / i_m = 136.2/4.4 = 30.95$ V.

✓ For Entech. Inc. PV-module:

$V'_{oc} = 24.5 - 0.0023 \times 40 \times 24^0C$

$= 22.29$ V

$FF = 430/22.9 \times 24.5 = 0.766$

$P'_{max} = i_{sc} \times V'_{oc} \times FF = 390.9$ W.

$V'_m = P'_{max} / i_m = 390.9/21.3 = 18.35$ V.

- The annual of Peak Solar Hour (**PSH**) in Jüelich from the Meteonorm Database is equal to: PSH = 2.92 h. Detailed **PSH** monthly values are given in fig 5.14.

The voltage, **V** that power is transferred from the PV-array to the batteries, that is, the PV-system's voltage is taken to be: $V_s = 48$ V.

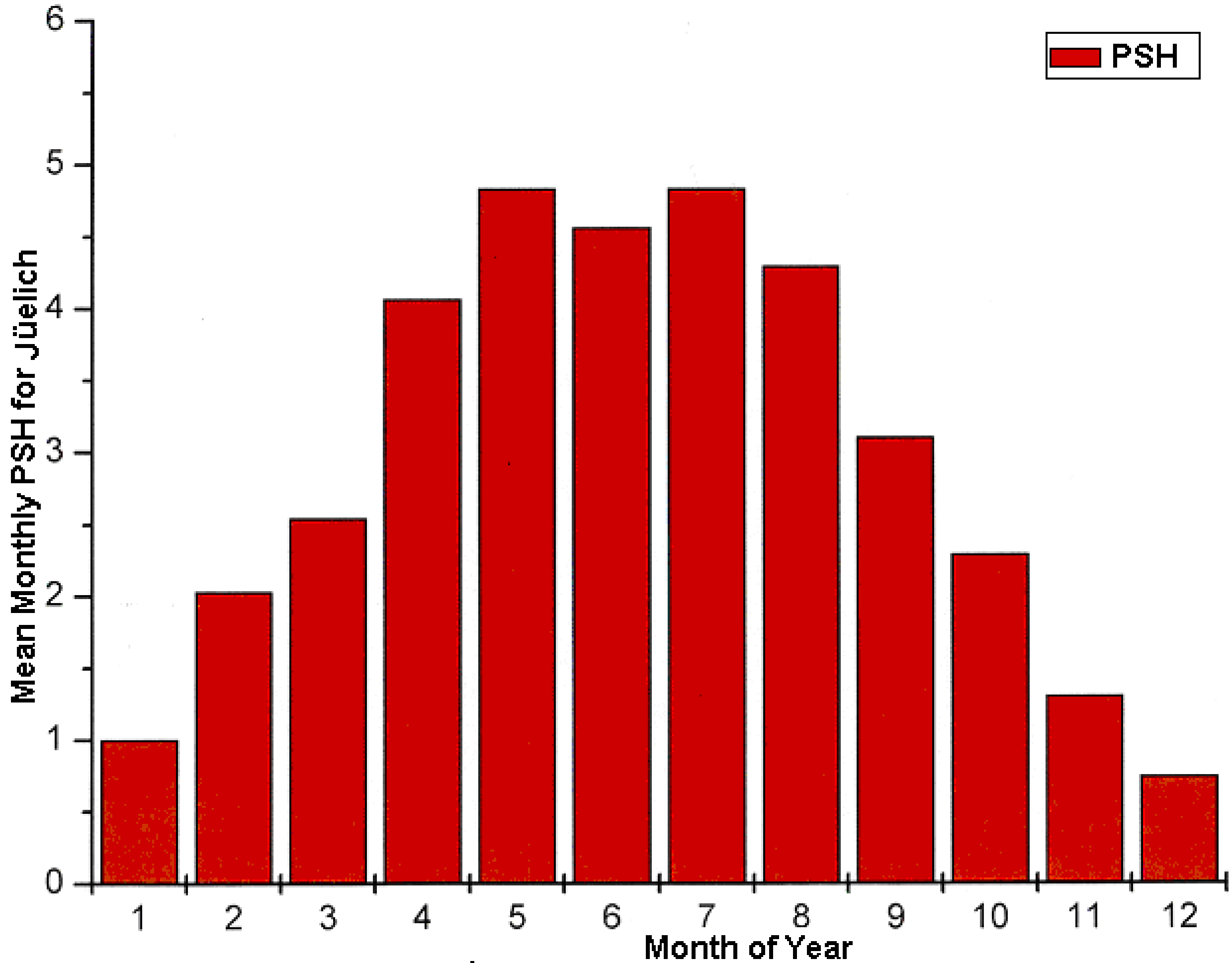

Figure 5.14: *Monthly PSH values for Jüelich, Germany*

Solutions: Scenario no. I

Taking the **winter load** into consideration and using both **Wh** and **Ah** methods, we finally get:

Wh method

1. Rough $\mathbf{P_w}$ determination: $\boldsymbol{E_L/PSH}$

   = 101547.6 [Wh/day] / 2.92 [h/day]

   = 34776.5 W

2. Number of PV- Panels required are:

   for choice 1. → 34776.5/109 = 319
   (SOLAREX)
   for choice 2. → 34776.5/136.2 = 255
   (SIEMENS)
   for choice 3. → 34776.5/272.5 = 127
   (A.S.E.)
   for choice 4. → 34776.5/390.9 = 89
   (Entech.Inc.)

3. Number of PV- Panels in series,

   $\mathbf{N_{p,s} = V_s / V'_m}$ are:

   for choice 1. → 48/17.1 =2.8 ≈ 3

   for choice 2. → 48/34.0 = 1.4 ≈ 2

   for choice 3. → 48/51.0 = 0.9 ≈ 1

   for choice 4. → 48/20.2 = 2.3 ≈ 3

4. Number of strings in parallel, $\mathbf{N_{p,p}}$ are:

   for choice 1. → 319/3 = 106.3 ≈ 107

   for choice 2. → 255/2 = 127.5 ≈ 128

   for choice 3. → 127/1 = 127

   for choice 4. → 89/3 = 29.6 ≈ 30

Ah method

1. Determination of the charge delivered daily by the PV- Generator

   = 87040.8 Wh/48 V = 1813.35 Ah

2. Determination of the mean daily current from the PV-Generator

   $\mathbf{i_L}$ = 1813.35 [Ah] / 2.92 [h] = 621 A

3. Number of strings in parallel,

   $\mathbf{N_{p,p} = i_L/i_m}$ are:

   for choice 1. → 621/7.0 = 88.7 ≈ 89

   for choice 2. → 621/4.4 = 141.1 ≈ 142

   for choice 3. → 621/5.9 = 105.2 ≈ 105

   for choice 4. → 621/21.3 = 29.1 ≈ 29

4. Number of PV- Panels in series,

   $\mathbf{N_{p,s} = V_s / V'_m}$ are:

   for choice 1. → 48/15.57 = 3.09 ≈ 3

   for choice 2. → 48/30.95 = 1.55 ≈ 2

   for choice 3. → 48/46.16 = 1.03 ≈ 1

   for choice 4. → 48/18.35 = 2.61 ≈ 3

Remark:

According to these methods one may calculate the number of strings required in parallel. These parallel strings contain the PV-panels in series. One should observe, in detail, the differences between both methods in order to avoid the oversizing of the PV-System.

Solutions: Scenario no. II

Taking the **summer load** into consideration the two approaches give the following results:

Wh method

1. Rough P_w determination:
   = 39191.6 [Wh/day] / 2.92 [h/day]
   = 13421.7 W
2. Number of PV- Panels required are:
   for choice 1. → 13421.7/109 = 123
   for choice 2. → 13421.7/136.2 = 99
   for choice 3. → 13421.7/272.5 = 50
   for choice 4. → 13421.7/390.9 = 35
3. Number of PV- Panels in series,
   $N_{p,s} = V_s / V'_m$ are:
   for choice 1. → 48/17.1 =2.8 ≈ 3
   for choice 2. → 48/34.0 = 1.4 ≈ 2
   for choice 3. → 48/51.0 = 0.9 ≈ 1
   for choice 4. → 48/20.2 = 2.3 ≈ 3
4. Number of strings in parallel, $N_{p,p}$ are:
   for choice 1. → 123/3 = 41
   for choice 2. → 99/2 = 44.5 ≈ 45
   for choice 3. → 50/1 = 50
   for choice 4. → 35/3 = 11.6 ≈ 12

Ah method

1. Determination of the charge delivered daily by the PV- Generator
   = 33592.8 Wh/48 V = 700 Ah
2. Determination of the mean daily current from the PV-Generator
   i_L = 700 [Ah] / 2.92 [h] = 239.72≈ 240 A
3. Number of strings in parallel,
   $N_{p,p} = i_L/i_m$ are:
   for choice 1. → 240/7.0 = 34.2 ≈ 35
   for choice 2. → 240/4.4 = 54.5 ≈ 55
   for choice 3. → 240/5.9 = 40.6 ≈ 41
   for choice 4. → 240/21.3 = 11.26 ≈ 12
4. Number of PV- Panels in series,
   $N_{p,s} = V_s / V'_m$ are:
   for choice 1. → 48/15.57 = 3.09 ≈ 3
   for choice 2. → 48/30.95 = 1.55 ≈ 2
   for choice 3. → 48/46.16 = 1.03 ≈ 1
   for choice 4. → 48/18.35 = 2.61 ≈ 3

Solutions: Scenario no. III

Taking the **common load** into consideration the two approaches give the following results:

Wh method

1. Rough $\mathbf{P_w}$ determination:

 = 41067.6 [Wh/day] / 2.92 [h/day]

 = 14064.24 W

2. Number of PV- Panels required are:

 for choice 1. → 14064.24/109 = 129

 for choice 2. → 14064.24/136.2 = 103

 for choice 3. → 14064.24/272.5 = 52

 for choice 4. → 14064.24/390.9 = 36

3. Number of PV- Panels in series,

$\mathbf{N_{p,s} = V_s / V'_m}$ are:

 for choice 1. → 48/17.1 =2.8 ≈ 3

 for choice 2. → 48/34.0 = 1.4 ≈ 2

 for choice 3. → 48/51.0 = 0.9 ≈ 1

 for choice 4. → 48/20.2 = 2.3 ≈ 3

4. Number of strings in parallel, $\mathbf{N_{p,p}}$ are:

 for choice 1. → 129/3 = 43

 for choice 2. → 103/2 = 51.5 ≈ 52

 for choice 3. → 52/1 = 52

 for choice 4. → 36/3 = 11.6 ≈ 12

Ah method

1. Determination of the charge delivered daily by the PV- Generator

= 32500.8 Wh/48 V = 733.35Ah

2. Determination of the mean daily current from the PV-Generator

$\mathbf{i_L}$ = 733.35 [Ah] / 2.92 [h] = 251.1≈ 251A

3. Number of strings in parallel,

$\mathbf{N_{p,p} = i_L/i_m}$ are:

 for choice 1. → 251/7.0 = 34.2 ≈ 35

 for choice 2. → 251/4.4 = 57.04 ≈ 57

 for choice 3. → 251/5.9 = 42.5 ≈ 43

 for choice 4. → 251/21.3 = 11.7 ≈ 12

4. Number of PV- Panels in series,

$\mathbf{N_{p,s} = V_s / V'_m}$ are:

 for choice 1. → 48/15.57 = 3.09 ≈ 3

 for choice 2. → 48/30.95 = 1.55 ≈ 2

 for choice 3. → 48/46.16 = 1.03 ≈ 1

 for choice 4. → 48/18.35 = 2.61 ≈ 3

Remark:

According to these methods the number of strings required in parallel, containing the panels in series, is calculated. If we observe in detail the difference between both methods it will help to avoid oversizing the PV-generator.

5.9.4 Sizing the Batteries bank for storage and energy independence.

1. Determination of number of days of autonomy **d**, given by the formula (4.8b). Let us assume that the load is not a critical one. Hence:

$d = 0.48 \times PSH + 4.58$ [days]

$= 0.48 \times 2.92 + 4.58$

= 6 days

Here, again, we will examine all the three possible scenarios for the load. i.e., we will examine different load situations in order to estimate the necessary batteries required. As estimated before:

Winter Load	: 72534 Wh/day
Summer Load	: 27994 Wh/day
Common Load	: 29334 Wh/day

2. Let's consider Winter Load: 72534 Wh/day

2.1 Determination of the load storage for d days autonomy, i.e.:

Q = 72534 Wh/day × 6 days / 48 V = 9066.7≈ 9067 Ah (Wh method),

or equivalently

Q = 1511.12 Ah/day × 6 days = 9066.7 ≈ 9067 Ah (Ah method)

2.2 Correction due to temperature, see (5.25)

$f_{b,T} = 0.01035 \times 10\ ^0C + 0.724 = 0.8275$

(10^0C is the mean ambient temperature of the site)

Remark: $f_{b,T}$ is 1 (one) for mild climates where T=25-27 ^0C

2.3 Correction due to Charge Discharge Efficiency:

Let us take $f_{b,cd}$, defind in the next Case Study in Part C, as equal to:

$f_{b,cd} = 0.85$.

This is because we estimate that battery demand for power discharge is to be faster than the recommended rate, see equation (5.26).

2.4 Depth of Discharge:

$DOD_{max} = d / (d+1)$

$= 6 / 7 = 0.85$

2.5 The corrected battery bank capacity C_{cor} is estimated as in equation (5.28), later in the next Case Study.

$C_{cor} = Q / f_{b,T} \times f_{b,cd} \times DOD_{max}$

= 15174.2Ah

2.6 Determination of the Type of Batteries:

Total capacity C_{cor} = 15174.2 Ah

2.7 Voltage across the bank = 48 V, while

DOD =0.85 as estimated before.

2.8 Let's choose three different battery types, from GNB IIP Absolyte, with different Ah and Voltages

1) GNB – 6-90A15 12V and 615Ah.
2) GNB – 3-100A33 6V and 1600Ah.
3) GNB – 1-100A99 2V and 4800Ah.

2.9 Batteries required in series: $N_{b,s}$=V/V_b

1) 4 in series 48V:12V= 4
2) 8 in series 48V: 6V= 8
3) 24 in series 48V: 2V=24

2.10 Batteries required in Parallel connection (strings):

$$\text{strings} = \frac{\text{total (corrected) battery capacity}}{\text{battery capacity (nominal)}}, \quad \mathbf{N_{b,p} = Q / C = Q_{cor}/C}$$

1) 15174.2 / 615 = 24.6 ≈ 25
2) 15174.2 / 1600 = 9.4 ≈ 10
3) 15174.2 / 4800 = 3.1 ≈ 3

2.11 Confirmation that during the Charge Discharge Process, DOD< $DOD_{spec.}$

Daily Total Discharge is equal to 1511.1 Ah ≈ 1512 Ah.

Total Capacity is $N_{b,p} \times C$:

1) 25 × 615 = 15375 Ah
2) 10 × 1600 = 16000 Ah
3) 3 × 4800 = 14400 Ah.

***Notice:** this value is smaller that the daily discharge, as we considered that the battery bank has 3 battery strings in parallel, while the calculated figure was 3.1.*
If we took 4 as the number of battery strings that would be a good overestimation which would lead to high costs (batteries is a costly element due also to their short life cycle).

Daily Discharge is:

1) 1512 / 15375 = 0.098 or 9.8% per day
2) 1512 / 16000 = 0.0945 or 9.4% per day
3) 1512 / 14400 = 0.105 or 10.5% per day

Total Available Capacity is:

1) 15375 × 0.80 = 12300Ah
2) 16000 × 0.80 = 12800Ah

3) $14400 \times 0.80 = 11520$Ah

2.12 The required amount is 1512 Ah/day × 6day = 9072Ah.

Therefore the Available Capacity is much higher than the required amount.

If the Batteries operate continuously for 6 days:

1) 9072 Ah / 15375 Ah = 0.59<0.80
2) 9072 Ah / 16000 Ah = 0.56<0.80
3) 9072 Ah / 14400 Ah = 0.63<0.80

Hence, the batteries chosen in this analysis are appropriate, but the actual selection depends on the prices, which will be discussed later on.

3. Lets consider Summer Load

Summer Load: 27994 Wh/day

We proceed similarly as in the section for the Winter Load.

3.1 Determination of the load storage for d days autonomy, i.e.:

Q = 27994 Wh/day × 6 days / 48V = 3499.25 ≈ 3500Ah (Wh method),

or equivalently

Q = 583.0 Ah/day × 6 days = 3499.25 ≈ 3500 Ah (Ah method)

3.2 Correction due to temperature:

$\mathbf{f_{b,T}} = 0.01035 \times 10\ ^{0}C + 0.724 = 0.8275$

(10^{0}C is the mean ambient temperature of the site)

3.3 **Correction due to Charge Discharge Efficiency**:

$\mathbf{f_{b,cd}} = 0.85$.

3.4 Depth of Discharge:

$\mathbf{DOD_{max} = d / (d+1)}$

= 6 / 7= 0.85

3.5 $\mathbf{C_{cor} = Q / f_{b,T} \times f_{b,cd} \times DOD_{max}}$

= 5773.98 ≈ 5774 Ah

3.6 Determination of Type of Batteries:

Total capacity $\mathbf{C_{cor}}$ = 5774 Ah

3.7 Voltage across the bank = 48 V, while DOD =0.85 as obtained above.

3.8 Lets choose three different battery types, from GNB IIP Absolyte with different Ah and Voltages

1) GNB – 6-90A15 12V and 615Ah.
2) GNB – 3-100A33 6V and 1600Ah.
3) GNB – 1-100A99 2V and 4800Ah.

3.9 Batteries needed in series:

1) 4 in series
2) 8 in series
3) 24 in series.

3.10 Batteries needed in Parallel, $N_{b,p} = Q_{cor} / C$

1) 5774 / 615 = 9.3 ≈ 10
2) 5774 / 1600 = 3.6 ≈ 4
3) 5774 / 4800 = 1.2 ≈ 2

3.11 Confirmation during the Charge Discharge Process, DOD < $DOD_{spec.}$

Daily Total Discharge is equal to 583.2 ≈ 584 Ah.

Total Capacity is $N_{b,p} \times C$:

1) 10 × 615 = 6150 Ah
2) 4 × 1600 = 6400 Ah
3) 2 × 4800 = 9600 Ah.

Daily Discharge is:

1) 584 / 6150 = 0.094 or 9.4% per day
2) 584 / 6400 = 0.0912 or 9.1% per day
3) 584 / 9600 = 0.060 or 6.05% per day

Total Available Capacity is:

1) 6150 × 0.80 = 4920Ah
2) 6400 × 0.80 = 5120Ah
3) 9600 × 0.80 =7680

3.12 The required amount is 584 × 6 = 3504Ah.

Therefore, the Available Capacity is much higher than the required amount.
If the Batteries operated continuously for 6 days; then the discharge level would be:

1) 3504 Ah / 6150 Ah = 0.569<0.80
2) 3504 Ah / 6400 Ah = 0.547<0.80
3) 3504 Ah / 9600 Ah = 0.359<0.80

Hence, the batteries chosen for the study are appropriate, but the actual selection depends on the prices, which will be discussed later, in this case study.

4. Let's consider the Common Load

The **Common Load** was estimated to be**: 29334 Wh/day**

4.1 Determination of the load storage for d days autonomy, i.e.:

Q = 29334 Wh/day × 6 days / 48 V = 3666.7 ≈ 3667 Ah (Wh method), or equivalently
Q = 611.12 Ah/day × 6 days = 3666.7 ≈ 3667 Ah (Ah method)

4.2 Correction due to temperature:

$\mathbf{f_{b,T}}$ = 0.01035 × 10 ^{0}C + 0.724 = 0.8275

(10^{0}C is the mean ambient temperature of the site)

4.3 Correction due to Charge Discharge Efficiency:

$\mathbf{f_{b,cd}}$ = 0.85.

4.4 Depth of Discharge:

DOD_{max} = d / (d+1)

= 6 / 7= 0.85

4.5 C_{cor} = Q / $f_{b,T}$ × $f_{b,cd}$ × DOD_{max}

= 6137.16 ≈ 6137 Ah

4.6 Determination of Type of Batteries:

Total capacity **Q_{cor}** = 6137 Ah

4.7 Voltage across the bank = 48 V, DOD =0.85

4.8 Lets choose three different battery types, from GNB IIP Absolyte with different Ah and Voltages

1) GNB – 6-90A15 12V and 615Ah.
2) GNB – 3-100A33 6V and 1600Ah.
3) GNB – 1-100A99 2V and 4800Ah.

4.9 Batteries needed in series:

1) 4 in series
2) 8 in series
3) 24 in series.

4.10 Batteries needed in Parallel, $N_{b,p}$ = Q_{cor} / C

1) 6137 / 615 = 9.9 ≈ 10
2) 6137 / 1600 = 3.8 ≈ 4
3) 6137 / 4800 = 1.2 ≈ 2

4.11 Confirmation that during the Charge Discharge Process, DOD < $DOD_{spec.}$

Daily Total Discharge is equal to 611.12 ≈ 611 Ah.

Total Capacity is $N_{b,p}$ × C:

1) 10 × 615 = 6150 Ah
2) 4 × 1600 = 6400 Ah
3) 2 × 4800 = 9600 Ah.

Daily Discharge is:

1) 611 / 6150 = 0.098 or 9.8% per day
2) 611 / 6400 = 0.095 or 9.5% per day

3) 611 / 9600 = 0.063 or 6.3% per day

Total Available Capacity is:

1) 6150 × 0.80 = 4920Ah
2) 6400 × 0.80 = 5120Ah
3) 9600 × 0.80 =7680

4.12 The required amount is 611 × 6 = 3666Ah.

Therefore the Available Capacity is much higher than the required amount.

If the Batteries operate continuously for 6 days:

1) 3666 Ah / 6150 Ah = 0.59<0.80
2) 3666 Ah / 6400 Ah = 0.57<0.80
3) 3666 Ah / 9600 Ah = 0.38<0.80

Hence, the batteries chosen for this study are appropriate, but the actual selection depends on the prices, which will be discussed below.

5.9.5 Selection of the Appropriate Choice

After the full analysis of the load situations presented and the required PV-modules and battery banks details for the given household, we may choose Solution III, where the common load is taken into account on a whole year basis. The additional amount of energy required may be supplied by a supplementary source like:

a. Diesel Engine
b. Wind Generator , etc.

PV-Modules chosen for this case are the A.S.E. – 300-DGF/50 300 W_p, keeping in mind that the useable area of the roof and the high value of W_p keep the price, paid per Ampere produced low.

Batteries are chosen according to the cost-effective study, which follows:

Power Inverter is from TRACE; type DR3624, 3.6 KVA, 24V DC input, 120V AC output, 60 Hz, with a built in Charger 70 amps, and additional 30 amps, transfer relay. Number of units required: 2.

5.10 Financial Issues,

An attempt is made in order to make clear what it means economics in the battery branch of a PV-generator.

Let’s start with batteries details from the above analysis:

a. The price of a 48 V battery bank giving an output of 1600 Ah(see step 4.8 in §5.9.4) is ≈11496.00 € (prices of 2002)
b. The price of a 48 V battery bank giving a output of 615 Ah is ≈7000.00 €

According to Scenario III, for a common load, the total capacity required is 6137 Ah, see step 4.5 in §5.9.4.
The number of batteries required in series, because the bank provides a voltage of 48 V, and V_s=48 is 1, i.e. only one string is required.

Batteries required in parallel:

a. $\mathbf{N_{b,p}}$ = 6137 / 1600 = 3.8 ≈ 4
while for the other type of battery:
b. $\mathbf{N_{b,p}}$ = 6137 / 615 = 9.9 ≈ 10
Let: Inflation rate = 2% (Inf.)
Interest rate = 4% (Int.)

- Let the initial amount to purchase the battery bank be $\mathbf{N_0}$

a.11496€ × 4 = 45984 €
b.7000€ × 10 = 70000 €

- This amount after **n** years, if deposited will increase, but also inflation pushes the other direction .

An estimate for **n**, is done by assuming 1 cycle per day and that the life of the batteries is around 6 years.
Present value co-efficient (**CV**):

CV = (1+Infl.) / (1+Inter.)
= 1.02 / 1.04 = 0.9807

As the lifetime of the PV – Module is estimated 25 years; therefore the number of replacements are 3.

Table 5.31

Type of Battery	1600 Ah	615 Ah
Initial Amount	4 × 11496 = 45984 €	10 × 7000 = 70000 €
1st Replacement	45984 × $(0.9807)^{6.16}$ = 40782.1 €	70000 × $(0.9807)^{6.16}$ = 62081.3 €
2nd Replacement	45984 × $(0.9807)^{12.32}$ = 36168.6 €	70000 × $(0.9807)^{12.32}$ = 55058.4 €
3rd Replacement	45984 × $(0.9807)^{18.48}$ = 32077.1 €	70000 × $(0.9807)^{18.48}$ = 48829.9 €
Total	**155011.8 €**	**235969.6 €**

So, it is clear from the analysis that the batteries with high capacity are less expensive that the ones with low capacity.
This analysis will help us to decide on the type of the battery that has to be chosen.
Further, the normal average Price per Watt, including the encapsulation, is in a range of about, 5 – 6 €/W, taking an average of 5.5 €.

The total initial cost of the various PV-modules chosen for this study is:

1) 120W × 5.5 €/W = 660 € per module

2) 150W × 5.5 €/W = 825 € per module

3) 300W × 5.5 €/W =1650 € per module.

Total Cost of the PV-generator as chosen for Scenario III is:

1) 3 × 36 =108 × 660 € = 71280 €

2) 2 × 57 =114 × 825 € = 94050 €

3) 1 × 43 = 43 × 1650 €= 70950 €.

Cost of the Inverter is equal to: 2 × 1595 € = 3190 €.

Total Cost of the PV-Solar House is:

a.	PV-Generator	:	70950 €
b.	Batteries	:	45984 €
c.	Invertor	:	3190 €
			120124.00 €

d. Diesel Generator: 1700.00 €

121824.00 €

e. Installation Charges: 12182.4 €

(an estimation of 10% of Total Cost

Total: 134006.4 €

5.11 SUMMARY: Results on the PV-configurations

Winter

1. Load Profile: 72534 Wh/day

Load Correction:

a. Wh method: 1.4 × 72534 = 101547 Wh/day

b. Ah method: 1.2 × 72534 = 87040.8 Wh/day

2. Modules Chosen

a. Solarex MSX – 120 W.

b. Siemens SP – 150 W.

c. A.S.E. 300DGF – 300 W.

3. Correction to Field Conditions

a. 109 W

b. 136.2 W

c. 272.4 W

Wh method

P_w = 34776.5 W

N_{pv}

a) 319

b) 255

c) 127

Ah method

C_d = 1813 Ah.

mean daily current = 621 A

Voltage Transfer: 48 V

$N_{p,s}$	$N_{p,p}$
a) 3	a) 88
b) 2	b) 142
c) 1	c) 105

Sizing batteries:

d = 6 days

$f_{b,T}$ = 0.827, $f_{b,cd}$=0.85, dod = 0.85

C_{cor}= 15174.28 Ah

Batteries chosen are:

1) GNB 6 – 90A15 12V 615Ah
2) GNB 3 – 100A33 6V 1600Ah
3) GNB 1 – 100A99 2V 4800Ah.

Batteries in Series, $N_{b,s}$:

1) 4
2) 8
3) 24

Batteries in Parallel, $N_{b,p}$:

1) 25
2) 10
3) 3

Daily Discharge:

a. 9.8%

b. 9.4%

c. 10.05%

If the Batteries are discharged continuously for 6 days: i) 0.59, ii) 0.56, iii) 0.63 < 0.80

Summer

1. Load Profile: 27994 Wh/day

Load Correction:

a. Wh method: 1.4 × 27994 = 39191.6 Wh/day

b. Ah method: 1.2 × 27994 = 33592.8 Wh/day

2 Modules Chosen

a. Solarex MSX – 120 W.

b. Siemens SP – 150 W.

c. A.S.E. 300DGF – 300 W.

3 Correction to Field Conditions

a. 109 W

b. 136.2 W

c. 272.4 W

Wh method

P_w = 13421.7 W

N_{pv}

a) 123

b) 99

c) 50

Ah method

C_d = 700 Ah.

mean daily current

Voltage Transfer: 48 V

$N_{p,s}$	$N_{p,p}$
a) 3	a) 35
b) 2	b) 55
c) 1	c) 41

Sizing batteries:

d = 6 days

$f_{b,T}$ = 0.827, $f_{b,cd}$=0.85, dod = 0.85

C_{cor}= 5774 Ah

Batteries chosen are:

1) GNB 6 – 90A15 12V 615Ah
2) GNB 3 – 100A33 6V 1600Ah
3) GNB 1 – 100A99 2V 4800Ah.

Batteries in Series, $N_{b,s}$:

1) 4
2) 8
3) 24

Batteries in Parallel, $N_{b,p}$:

1) 10
2) 4
3) 2

Daily Discharge:

a. 9.4%

b. 9.1%

c. 6.05%

If the Batteries are discharged continuously for 6 days: i) 0.56, ii) 0.54, iii) 0.35 < 0.8

SUMMARY: Results on the PV- configurations

Common

1. Load Profile: 29334 Wh/day

Load Correction:

a. Wh method: 1.4 × 29334 = 41067.6 Wh/day
b. Ah method: 1.2 × 29334 = 35200.8 Wh/day

2. Modules Chosen

a. Solarex MSX – 120 W.
b. Siemens SP – 150 W.
c. A.S.E. 300DGF – 300 W.

3. Correction to Field Conditions

a. 109 W
b. 136.2 W
c. 272.4 W

Wh method	**Ah method**
P_w = 14064.2 W	C_d = 733 Ah.
N_{pv}	mean daily current
1. 129	= 251A
2. 103	
3. 52	

Voltage Transfer: 48 V

$N_{p,s}$	$N_{p,p}$
a) 3	a) 36
b) 2	b) 57
c) 1	c) 43

Sizing batteries:

d = 6 days

$f_{b,T}$ = 0.827, $f_{b,cd}$=0.85, dod = 0.85

C_{cor}= 6137 Ah

Batteries chosen are:

1) GNB 6 – 90A15 12V 615Ah
2) GNB 3 – 100A33 6V 1600Ah
3) GNB 1 – 100A99 2V 4800Ah.

Batteries in Series, $N_{b,s}$:

1) 4
2) 8
3) 24

Batteries in Parallel, $N_{b,p}$:

1) 10
2) 4
3) 2

Daily Discharge:

a. 9.8%
b. 9.5%
c. 6.3%

If the Batteries are discharged continuously for
6 days: i) 0.59, ii) 0.57, iii) 0.38 < 0.80

SUMMARY: Results on the PV- configurations

Using Concentrating PV-system

Winter

1 Load Profile: 72534 Wh/day

Load Correction:

a. Wh method: 1.4 × 72534 = 101547 Wh/day

b. Ah method: 1.2 × 72534 = 87040.8 Wh/day

2. Modules Chosen

a. Entech – 430 W

3. Correction to Field Conditions

a. 389 W

Wh method	**Ah method**
P_w = 34776.5 W	C_d = 1813 Ah.
N_{pv}	mean daily current
a) 319	= 621 A

Voltage Transfer: 48 V

$N_{p,s}$	$N_{p,p}$
a) 3	a) 29

Common

1. Load Profile: 29334 Wh/day

Load Correction:

Wh method: 1.4 × 29334 = 41067.6 Wh/day

Ah method: 1.2 × 29334 = 33592.8 Wh/day

2 Modules Chosen

a. Entech – 430 W

3 Correction to Field Conditions

a) 389 W

Wh method	**Ah method**
P_w = 13421.7 W	C_d = 700 Ah.
N_{pv}	mean daily current
a) 36	= 251 Ah

Voltage Transfer: 48 V

$N_{p,s}$	$N_{p,p}$
a) 3	a) 12

5.12 Results and Comments

1. Whereas, the lifetime of the concentrating Modules are 50% less than the normal modules,
2. Whereas, the inefficiency is not yet standardized due to the influence of the series resistance, and more important
3. If we take into account that these concentrating lenses use beam radiation (and not the diffused), while the site of installation in Jüelich which has through the year more diffused radiation, compared to beam radiation.

This solution is not worthwhile for installation, even though it produces high power and occupies less area.

- **OPTIMUM LOAD MATCHING:**

The matching efficiency was defined as the ratio of the load energy to the array maximum energy delivered.

The **Quality** of **Load Mismatching** is defined by two factors:

1. The Insolation – utilization efficiency
2. Time – utilization efficiency

So, **Load Mismatching Factor**: $\mu = E_L / E_{max}$

E_{max} is the Integral from t (sunrise) to t (sunset); that is total $P_{max} \times PSH$ (5.24)

E_{max} is calculated for the months of the highest and lowest insolation.

For a case of consideration let us take a mean day; the 15 of May (a month with the highest Insolation from Meteonorm Data), to demonstrate the Load Mismatching Factor.

PSH for this month is: 4.83h. Let us consider the A.S.E. modules. Then

$P_m = V_m \times i_m \times$ No of strings, or

$P_{PV\text{-}Array}$ = 50 [V] × 5.9 [A] × 43 = 12685 [W]

From equation (5.24) we get

E_{max} = 12685 [W] × 4.83 [h] = 61269 [Wh]

Hence, μ = 41067.6 [Wh] / 61269 [Wh] = 0.67

This shows that the design of the complete system is near to a good design, as the Load Mismatching Factor will never be greater than 1, and the system which attains a value in range between 0.7 to 0.8 is a well designed system; not oversizing the PV-SYSTEM.