

Solar Electric Power Supply with Batteries

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11.1 INTRODUCTION

Solar electric plants shall be understood to be photovoltaic energy converters that are able to self-sufficiently satisfy a mean energy demand over a significant period of time, be it an appliance that is permanently hooked up or just for sporadic power supply of appliances. Such plants have in common that their input and output quantities fluctuate widely. They can therefore only be dimensioned on the basis of a mean value and are not able to satisfy this demand without the possibility to store energy.

The solar generator is to be dimensioned dependent on solar radiation and the demand to be encountered; the same goes for the battery. This difficult problem shall be treated first as it makes the problem definition for the energy storing device and the system on the whole clearer.

Afterward the construction of the system as whole and the most important components shall be discussed.

The demands for the energy storing devices and which system is best supplied with which battery shall be discussed with the help of some typical examples for design of such systems.

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11.2 DIMENSIONING A SOLAR ELECTRIC SYSTEM

11.2.1 Preconditions

The basic precondition is that the mean solar electric power supply must be at least equal to the mean power demand. Whenever demand and supply are exactly of the same size, the system is termed as being “critical”, whereas systems that have a certain reserve that can be called upon anytime are termed “well dimensioned”. Whenever this reserve is unnecessarily high, the reason for this can be only of economic nature (paradoxical, but most often the case) the system is termed “economically matched”.

11.2.2 Calculation of the Mean Consumption

Figures 11.1, 11.2 and 11.3 explain how the mean demand is ascertained. The load demand currents throughout a day are shown for example by Figure 11.1 for a given system-dependent voltage level. Figure 11.2 shows an example for a statement made on the Ah consumption over a period of several days (Ah balance). Finally, Figure 11.3 manifests that over a longer period of time a curve of the mean consumption can be constructed which only varies slightly from the encountered consumption.

11.2.3 Calculation of the Mean Supply

A solar cell delivers a current proportional to its surface area and the intensity of radiation at 0.5 V. The effect the cell's temperature has on its performance can be neglected here. Figure 11.4 displays the typical flow of the current delivered by the solar cell on a summer day and a winter day. Figure 11.5 shows the corresponding daily Ah balances and the resulting Ah balance curves.

Solar cells that are exposed to natural sunlight over one year show balance curves similar to the one displayed in Figure 11.6, where the sums of the Ah supply are reproduced quite exactly every year even though seasonal fluctuations are encountered.

The curve of the Ah balance mean supply is represented by the tangent line in Figure 11.7 (curve 2) to the actual Ah balance curve (curve 1). The annual observation starts at point A_1 and ends at point B_1 . In this period of time the 25 cm² silicon solar cell placed at Frankfurt/Main can at most satisfy a demand of 50 Ah per

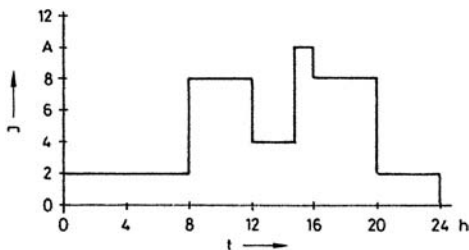


Figure 11.1 Typical profile for a day's current consumption.

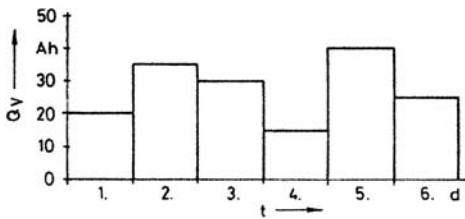


Figure 11.2 Typical Ah consumption for several days in succession.

month. If an appliance with a demand of ten times this value is to be operated, the surface area must measure ten times 25 cm^2 .

11.2.4 Calculation of the Capacity

The precondition that the supply must be at least as large as the demand is fulfilled in the points A_1 and B_1 in Figure 11.7, but just after point A_1 this is not the case anymore. Only after point C_1 up to B_1 supply is again higher than demand. The precondition can however be fulfilled by application of a storage device. This storage device must be fully charged at point A_1 and must at least have a capacity of K_1 so it will be discharged in point C_1 and again recharged in point A_2 .

11.2.5 Evaluation of the System

The system that is represented by curve 2 in Figure 11.7 having a tangent line as consumption curve to the supply curve and with a capacity of K_1 is termed “critical” as the battery will not be fully recharged if the annual supply falls short of the consumption. It is therefore more ingenious to let the supply curve rise as shown by curve 3 in Figure 11.7 so the batteries’ capacity is only demanded in point A_2 and will again be fully recharged in point B_2 .

This new design makes less use of the solar cells’ surface area and leads to smaller storage capacities (K_2). If the corresponding system should have the same power rating as the critical one, the batteries’ capacity and the surface area must be enlarged proportionally (factor: gradient of curve 2 divided by gradient of curve 3).

The advantage of this new system is the gain of the “reserve period TR”, which is the period of time between point B_2 and point A_2 , where the battery is employed

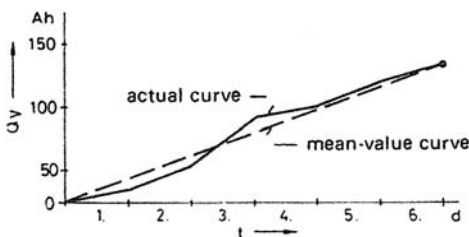


Figure 11.3 Derivation of the mean Ah consumption curve.

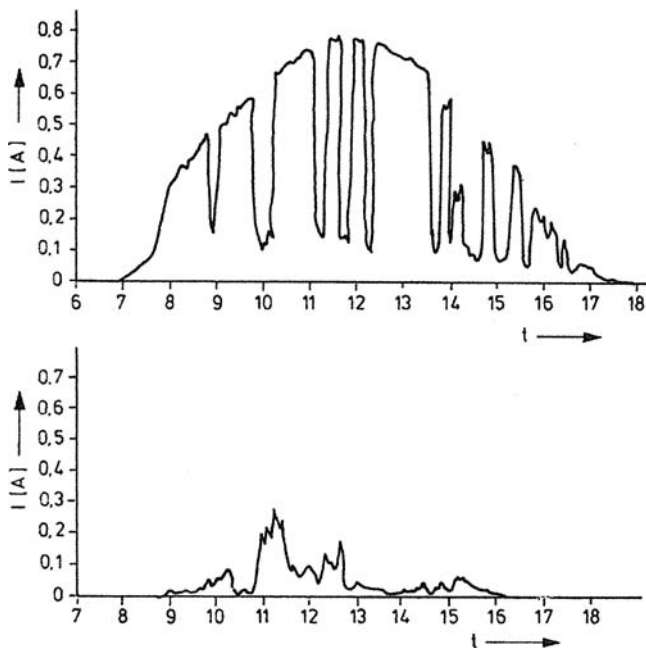


Figure 11.4 Typical profile of daily supply of current of a silicon solar cell of 25 cm^2 , in summer (top) and in winter (bottom).

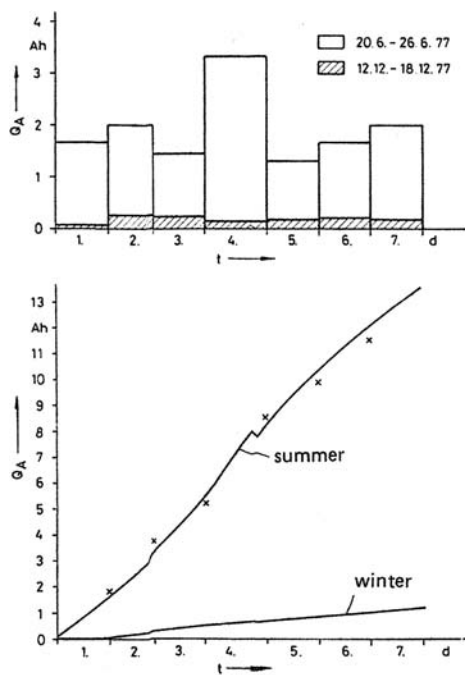


Figure 11.5 Supply of a silicon solar cell of 25 cm^2 surface area for successive days. Top: Ah balance. Bottom: Ah balance curve $Q_A(t)$.

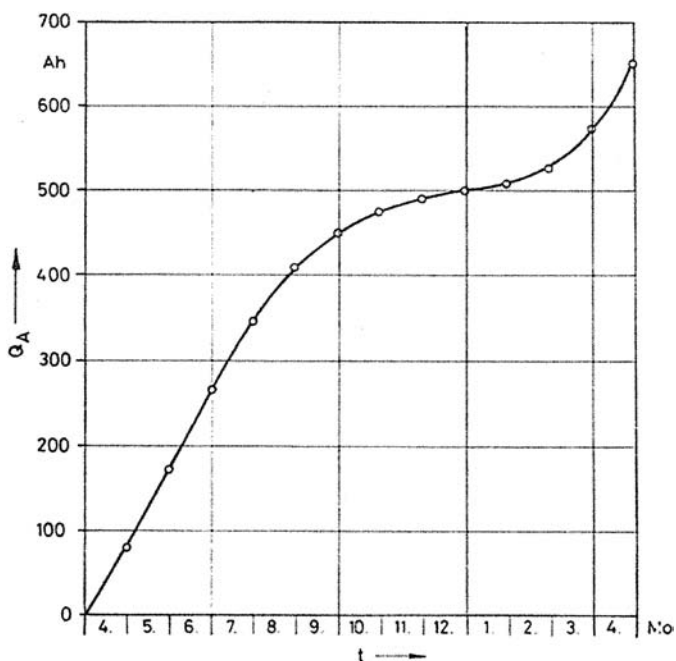


Figure 11.6 Ah balance curve $Q_A(t)$ of a 25 cm^2 silicon solar cell measured in Frankfurt/Main 1976–1977.

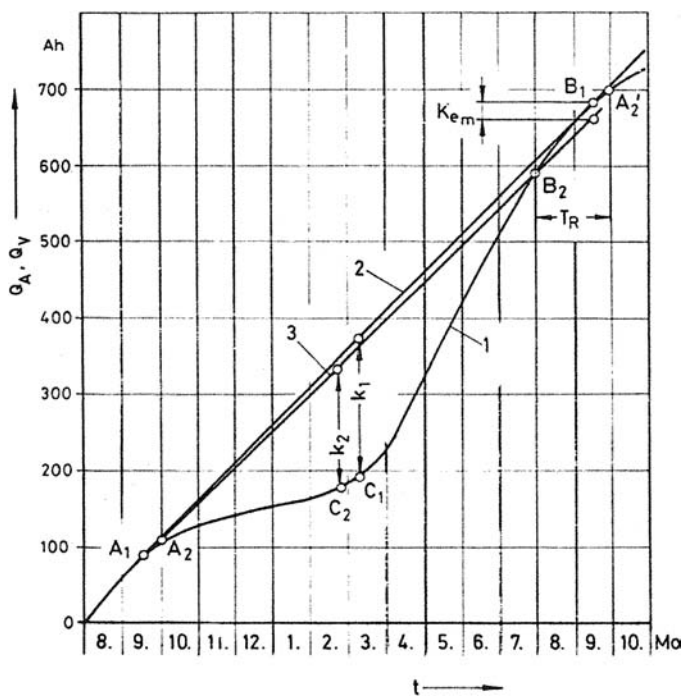


Figure 11.7 Position of the Ah balance curves of consumption at “critically matched” (2) and “well dimensioned” (3). Curve 1 represents the Ah balance curve of the supply.

once again. In this period of time an Ah reserve of up to the value Ke_m is at hand. Systems that have a “reserve period” of around 2 months can be termed “well matched”.

11.3 DESIGN OF SOLAR ELECTRIC SYSTEMS

11.3.1 The Power Source: The Solar Generator

This consists of a series connection of solar cells, mostly of the silicon type. Figure 11.8 shows a schematic cross-section and a wiring diagram of such a Si solar cell. Figure 11.9 manifests the typical characteristic diagram at different radiation intensities. If higher voltages are needed, an appropriate number of solar cells are series connected. In this way solar generator modules are formed. Commercial modules mostly consist of 32 to 36 series-connected solar cells and thereby have a voltage level that suffices to charge a 12-V accumulator.

If the ampere-hours supplied by one module are not sufficient, a corresponding number of modules in parallel connection will do the job. At present, mostly Si solar generators are employed and will probably be dominant for the next few years.

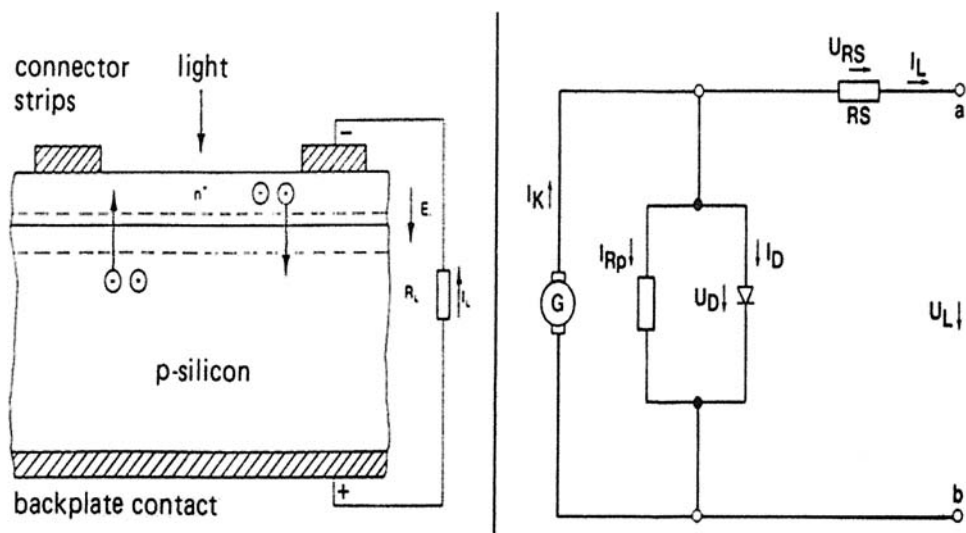


Figure 11.8 Schematic of a silicon solar cell. Left: cross-section. Right: wiring diagram.

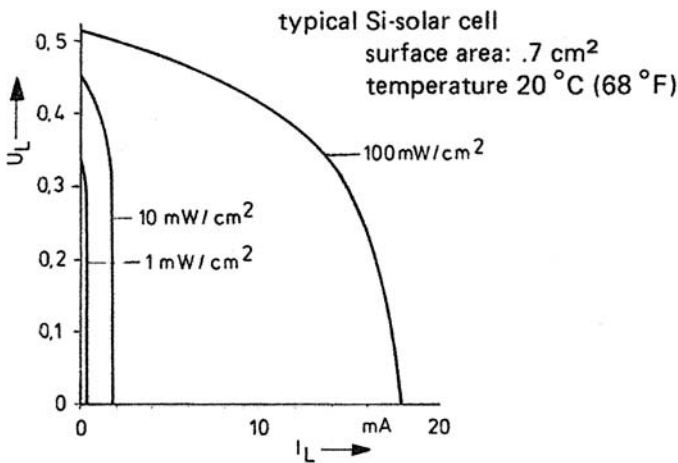


Figure 11.9 Characteristic curve of a silicon solar cell at different radiation intensities.

11.3.2 System Design

Figure 11.10 shows the principle design of a solar electric system. The solar generator is separated from the storage battery by built-in diode isolation (see Figure 11.8 on the right), which prevents discharge of the accumulator over the solar cell during low radiation periods. The consumer is usually directly connected to the battery, as only in very few cases does its input voltage range demand a processing plant.

11.3.3 The Isolating Diode

For this purpose mostly silicon power diodes are employed for various reasons. The diode should have a low conducting-state voltage as this voltage is actually subtracted from the total voltage of the solar electric generator. Schottky diodes are preferred.

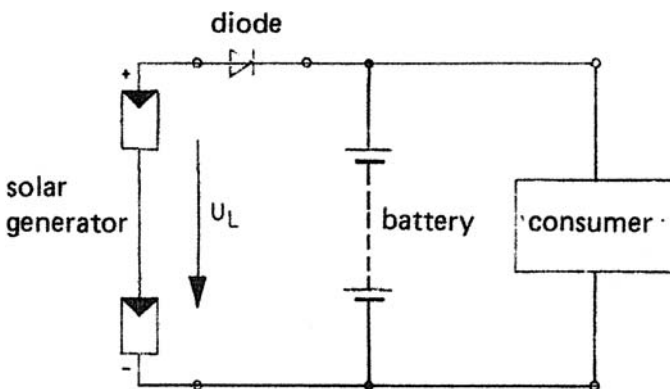


Figure 11.10 Principle design of a solar electric system.

11.3.4 The Battery

Batteries for this field of application are presently without exception electrochemical accumulators. As the demand situation differs with varying solar electric systems, it is advisable to analyze the demands closely before choosing a battery system. These subjects are explicitly treated in two separate chapters.

11.3.5 The Operating System

Solar electric power supply plants cannot be designed in such a simple manner as suggested by [Figure 10.10](#), as the battery would have to be dimensioned large enough so it would never reach the fully charged state because overcharge operation would lead to shorter servicing intervals or for some battery types even to lasting damage. Therefore current limitations as shown in [Figure 11.11](#) are indispensable and for larger plants the operating system will also have to take over other tasks such as prevention of exhaustive discharges.

11.4 ASPECTS FOR THE CHOICE OF THE BATTERY

11.4.1 Power Rating

[Table 11.1](#) lists the power ratings of different solar electric power supply systems. This listing also shows the typical load ranges for the accumulators of [Table 11.2](#).

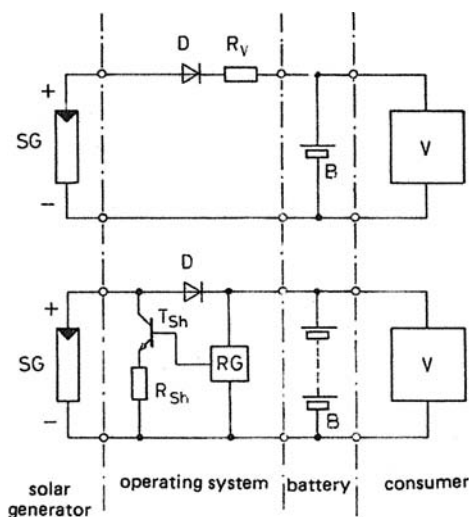


Figure 11.11 Examples for solar electric systems. Top: system with a gas-tight NiCd accumulator. Bottom: system with lead-acid accumulator, e.g. OPzS.

Table 11.1 Power ratings for solar electric power supply systems.

Power rating of the system	Typical consumer	Examples
μW	Appliances with integrated circuits and minimized energy consumption	Solar powered watches and calculators
mW	Appliances with low mean power consumption, e.g. due to occasional use	Portable radio equipment, automated ticket and lemonade machines, automatic fire and burglar alarms
W	Appliances and plants for communications and measuring purposes as well as low duty consumers	Sea markers and buoys, television convertors, radio relays, meteorologic and environmental measuring stations, power supply on boats and weekend homes, power supply for heat pumps
kW	Self-supporting networks for appliances and plants	Remote settlements, military applications

11.4.2 Feasible Battery Types

Whenever a system is dimensioned by the method introduced in Section 11.2, then the demanded capacity can be estimated and a feasible system for the accumulator can be found. The correlation between accumulator type and power rating according to [Figure 11.12](#) is shown in Table 11.2.

Table 11.2 Typical operating conditions for accumulators of different power ratings of solar electric systems.

Power rating	Discharge depth (%)		Service intervals	Service life demand
	Daily	Yearly		
μW	1–5	1 $\times$ ca. 80	Maintenance-free	About 10 years for max. 100 full cycles (80% discharge)
mW	1–5	1 $\times$ ca. 80	Maintenance-free up to 1 year	About 10 years for max. 2000 full cycles (80% discharge)
	5–20	Several, about 80		
W	1–5	1 $\times$ ca. 80	1 to 3 years	About 10–20 years at about 20 full cycles;
	5–20	Several, about 80	Several times per year	About 5 years at about 200 full cycles
kW	25–50	Often up to 80	Several times a month	About 5 years at about 1500 full cycles

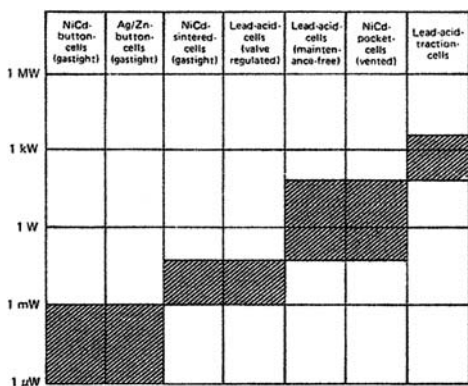


Figure 11.12 Correlation of the types of accumulators to the system-specific power ratings.

11.4.3 Application Technology

The final decision on the battery to be employed follows aspects of application technology. Aspects include the demanded electric power ratings, general operations data (on maintenance, lifespan, reliability), peripheral conditions (such as fitting conditions, mechanical stress, temperatures), and last but not least justifiable costs for investments (see [Tables 11.3a–d](#)).

11.5 DESIGNS OF OPERATING SYSTEMS

11.5.1 Systems with Current Limitation

These systems (see [Figure 11.11](#), top) are preferably applied in connection with gas-tight NiCd accumulators. Systems that operate in the microwatts range are sufficiently protected by a simple ohmic resistor, whereas for higher power ratings a series connection of transistors is advised.

11.5.2 Systems with Voltage Limitation

These are employed especially for all types of lead-acid accumulators and open NiCd accumulators. Principal design is shown by [Figure 11.11](#). The voltage is limited through keeping the resistor branch consisting of T_{SH} and R_{SH} variable and automatically controlled. As long as the battery has not reached its charging limit voltage, the transistor T_{SH} is nonconducting. Above this voltage the regulating device R_G adjusts the transistor in such a way that the battery never reaches its end of charging marginal voltage.

11.5.3 Systems with Two-Step Regulators

Here the constant charging current is switched off at a certain upper limit voltage (e.g. 2.35 V/cell) and switched on again at a slightly lower value. The resulting mean

Table 11.3a Typical power values of Varta batteries for system power ratings in the microwatt range.

		Battery-specific data	
Power data	Desired values	NiCd gas-tight (DK, DKZ)	AgO/Zn gas-tight (VC 568)
<i>Electrical data</i>			
Capacity	Up to 1 Ah	0.01–1 Ah	0.17 Ah
Charging currents	0.1–1 I ₁₀	0.3–3 I ₁₀	0.01–0.3 I ₁₀
Ah efficiency	Over 95%	Over 87%	About 90%
Charging method	I, W, IU, WU	I, W respective of voltage and temperature limits	IU 0.3 I ₁₀ up to 1.95 V/ cell
Self-discharge	Below 10% per month	About 20% per month	About 2% per month
<i>Operating data</i>			
Full cycles	Over 100	300 to 400	About 100
Discharge	To 100%	Up to 100%	Up to 70%
Maintenance	None	None	None
Reliability	100%	99.9%	99.9%
<i>Peripheral data</i>			
Operating position	Any	Any	Any
Tightness	100% tight	Less than 100% tight	Less than 100% tight
Temperature	– 55 to + 65 °C	0 to + 45 °C	0 to + 45 °C
Vibration	} MIL STD 810 C	MIL STD	MIL STD
Shock resistance		810 C	810 C

value of the pulsate charging current is very close to the ideal value if the upper and lower limit values are almost identical (e.g. 50 mV/2.35 V).

11.6 INFLUENCE OF GEOGRAPHIC POSITION

Figure 11.13 shows the Ah balance for different geographic positions in the northern hemisphere (7). These curves allow calculation of a compensating index composed of the ratio of capacity of the critical system to the Ah annual balance. This ratio is therefore a comparative value for the necessary storage capacity.

11.7 SUMMARY

Not only lower costs for solar generators, but also special “solar accumulators” with low costs per kWh are necessary for a wider distribution for photovoltaic systems. These solar accumulators will be distinguishable from present-day lead-acid accumulators because of a substantially lower power density.

Table 11.3b Typical power values of Varta batteries for system power ratings from 1 to 500 mW.

		Battery specific data	
Power data	Desired values	NiCd gas-tight (RS, SD)	Pb valve regulated (accumulator Pb)
<i>Electrical data</i>			
Capacity	Up to 50 Ah	Up to 15 Ah	Up to 10 Ah
Charging currents	0.1–2 I ₁₀	0.5–10 I ₁₀	Up to 4 I ₂₀
Ah efficiency	Over 95%	Over 87%	Over 90%
Charging method	I, W, IU, WU	I, W respective of voltage and temperature limits	IU,U 4 I ₂₀ up to 2.3 V/ cell total charging time 14 h unlimited for 2.25 V/cell
Self-discharge at 20 °C	Below 5% per month	About 35% per month	About 3% per month
<i>Operating data</i>			
Full cycles	Over 2000	Over 1000	About 200
Discharge	Up to 100%	Up to 100%	Up to 100%
Maintenance	None	None	None
Reliability	100%	99.9%	99.9%
<i>Peripheral data</i>			
Operating position	Upright	Upright	Upright
Tightness	Sealed 100%	Vented 100%	Vented
Temperature	– 55 to + 75 °C	– 20 to + 45 °C	– 30 to + 50 °C
Vibrations	} MIL STD 810 C	MIL STD	Limits unknown
Shock resistance		810 C	Limits unknown

Table 11.3c Typical power values of Varta batteries for system power ratings from 0.5 to 500 W.

		Battery-specific data	
Power data	Desired values	Pb, valve-regulated (OPzS, Varta bloc)	NiCd sealed (TX, TP-series)
<i>Electrical data</i>			
Capacity	Up to 10000 Ah	12–12000 Ah	10–1250 Ah
Charging currents	0.01–2 I ₁₀	0.01–2 I ₁₀	0.5–3 I ₁₀
Ah efficiency	About 100%	90–95%	About 80%
Charging method	I, W, IU, WU	IU	IU
		2 I ₁₀ up to 2.4 V/ cell, total charging time: 20 h, at 2.33 V/cell unlimited	2 I ₁₀ up to 1.65 V/ cell, total charging time 12 h, at 1.40 V/cell unlimited
Self-discharge	Below 1% per month	2–3% per month 25% per year	24% per month 48% per year
<i>Operating data</i>			
Full cycles	Some 1000	>1000	>1500
Discharge	Up to 100%	Up to 80%	Up to 100%
Maintenance	None	Maintenance-free for 3 years	Maintenance-free for about 1.5–2 years
Reliability	100%	99.9%	99.9%
<i>Peripheral data</i>			
Operating position	Upright	Upright	Upright
Tightness	Sealed	Vented	Vented
Temperature	– 55 to + 75 °C	– 20 to + 55 °C	– 20 to + 45 °C
Vibrations	} Inapplicable	Inapplicable	Inapplicable
Shock resistance			

Table 11.3d Typical power values of Varta batteries for system power ratings from 0.5 to 5 kW.

		Battery-specific data	
Power data	Desired values	NiCd, vented (series F)	Lead (traction) (PzS)
<i>Electrical data</i>			
Capacity	Up to 1000 Ah	30–300 Ah	50–1200 Ah
Charging currents	0.1–2 I ₁₀	0.5–3 I ₁₀	0.1–2 I ₁₀
Ah efficiency	Over 95%	About 85%	About 80%
Charging method	I, U, IU, WU	IU	IU
		3 I ₁₀ up to 1,45 V/ cell, total charging time: 15 h	2 I ₁₀ up to 2.4 V/ cell, total charging time: 10 h
Self-discharge	Below 1% per day	Max. 3% per day	Max. 1% per day
<i>Operating data</i>			
Full cycles	About 4000	About 3000	Over 1500
Discharge	Up to 100%	Up to 100%	Up to 80%
Maintenance	None	Once a year	Once a week
Reliability	100%	99.9%	99.9%
<i>Peripheral data</i>			
Operating position	Upright	Upright	Upright
Tightness	Sealed	Vented	Vented
Temperature	–55 to +75 °C	–20 to +45 °C	0 to +55 °C
Vibrations	} Inapplicable	Inapplicable	Inapplicable
Shock resistance			

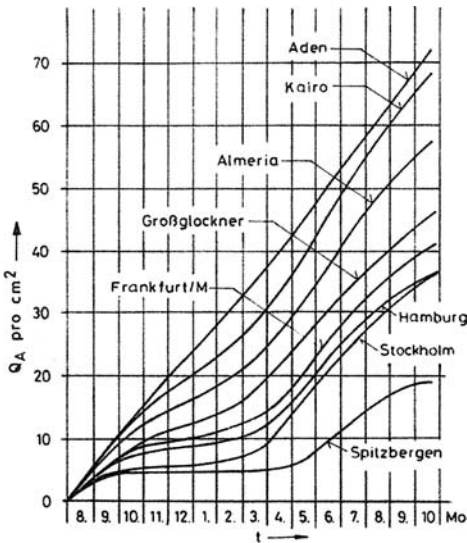


Figure 11.13 Ah balance curve for a horizontally installed 1 cm² silicon solar cell in different regions.

Every component of a solar electric system has to be treated by the described method for dimensioning these systems. Selection according to power ratings of these solar electric systems allows special demands oriented at the power demand to be put to the battery.

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