Short-Course

Solar PV System Installation and Maintenance

NTQF Level IV

Learning Guide -06

Unit of Competence	**Calculating System Components**
Module Title	**Calculating System Components**
LG Code	**EIS PIM4 M01 0120 LO2-LG06**
TTLM Code	**EIS PIM4 TTLM 0120v1**

LO 2: Determine battery capacity-06

Instruction Sheet	Learning Guide:- 06

This learning guide is developed to provide you the necessary information, knowledge, skills and attitude regarding the following content coverage and topics:

- Determining Maximum Depth of Discharge;
- Calculating Battery capacity.

This guide will also assist you to attain the learning outcome stated in the cover page. Specifically, upon completion of this Learning Guide, you will be able to:-

- Determine Maximum Depth of Discharge;
- Calculate Battery capacity

Learning Instructions:

1. Read the specific objectives of this Learning Guide.
2. Follow the instructions described below:
3. Read the information written in the information Sheet 1 (page:22), Sheet 2 (page: 31)
4. Accomplish the Self-Check 1 (page: 30), Self-Check 2 (page: 36)

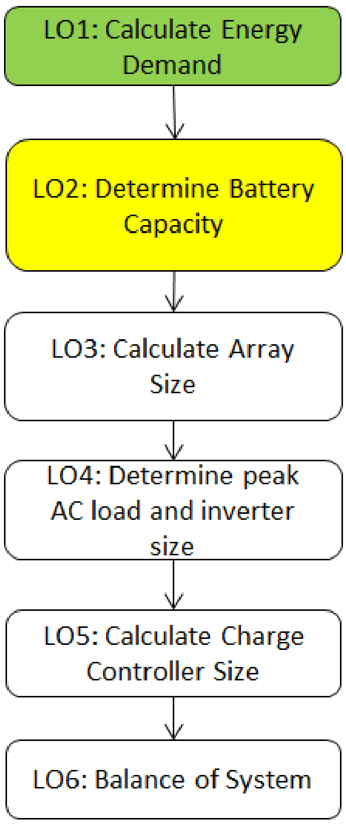
LO2 Calculating System Components

Information Sheet 1	Determining Maximum Depth of Discharge

1 Determining Maximum Depth of Discharge

1.1 Introduction

The next step in the design process is to determine the battery capacity:



1) Site survey
A Consumption
B Climate data

2) PV generator
C Design PV Generator
D Selection of System Voltage

3) Battery sizing (BAT)
E Battery Dimensioning based on consumption

4) Charge Controller (CC)
F Configuration of the Modules (matching modules/CC)
G Charge Controller Dimensioning

5) Inverter (INV)
H Select an Inverter based on the Loads
I Cross-Check Battery/Inverter matching

6) Balance of System (BoS)
J Calculate Cabling diameters and length
K Calculate the Fuses
L Mounting System

3) Sizing the Battery

$$C_{10} = \frac{E \times A}{DOD \times V_{System}}$$

E-Daily energy consumption $[Wh/d]$

A-Days of Autonomy $[d]$)

DOD-Depth of Discharge [%], V-System Voltage[V])

Conversion of the different capacities	
C10	'= C1 / 0,61
C10	'= C5 / 0,88
C10	'= C10
C10	'= C20 / 1,09
C10	'= C100 / 1,25
C10	'= C120 / 1,28

Select the Battery

Based on 12V, 24V e 48V system, determine best battery configuration i.e. either series, parallel or both. For choice of battery capacity, all must be converted to C_{10} capacity, as per table:

Figure 23: Design step 2

In order to calculate the size battery required, it is important to understand the term ''Depth of Discharge'' or DoD and how to determine it.

1.2 Battery overview

The following paragraphs are adapted from (Hankins, 2010) chapter 4.

1.2.1 Energy Storage

Stated simply, a battery is like a tank for electric energy. The solar array produces an electric charge as long as the sun is shining. The charge travels through wires into the battery where it is converted to stored chemical energy. Over the course of several days, a battery may 'fill' with stored energy. It can be compared to a water tank that fills with water collected from the rooftop during rain. And just like a water tank, the battery has a limited capacity. When it is fully charged, it cannot take up any more energy without overflowing -or in case of the battery- without damage.

The same limit applies for discharging: it is impossible to remove more energy from the battery than is put in by charging. And if an appliance, e.g. a light, is left on by accident all night, all electricity will drain from the battery. This can be compared to an open tap of a water tank. The water will flow out and if you forget to close the tap overnight, all water will be gone the next morning.

Figure 24 Water tank as battery equivalent (www.menschenfuermenschen.de)

Figure 25 Example of a Battery (Alibaba.com)

1.2.2 Principle of Operation

Batteries are groups of ‘electrochemical cells’, devices that convert chemical energy into electrical energy. These groups of cells are connected in series. Battery cells should not be confused with solar cells, which operate according to completely different principles.

Battery cells are composed of two ‘electrodes’ (also called plates) immersed in an ‘electrolyte’ solution. When a circuit is formed between the electrodes, a current flows. This current is caused by reversible chemical reactions between the electrodes and the electrolyte within the cell.

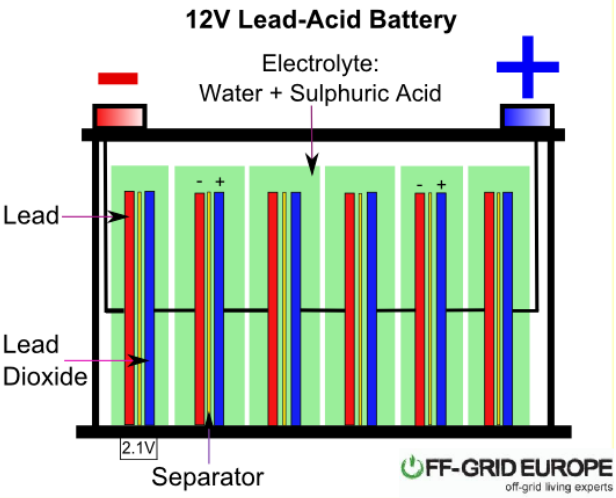


Figure 26: Connection of 6 cells to a 12V battery (off-grid europe, 2017)

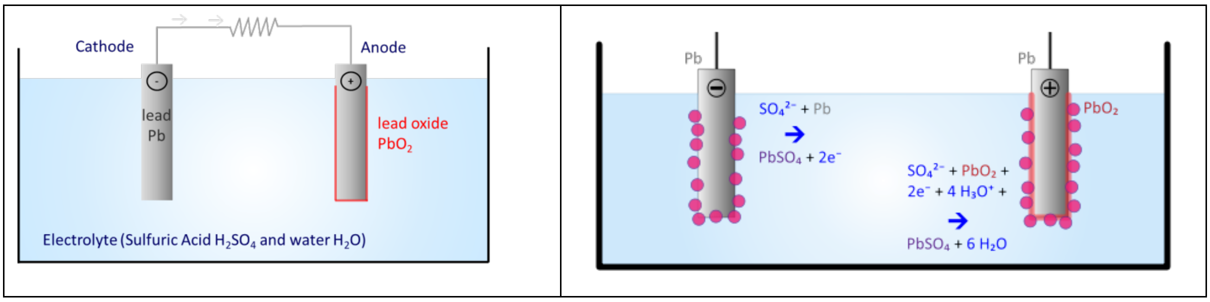


Figure 27: Chemical reaction and electron flow in a battery

Some cells can only be used once – these are called ‘primary batteries’ (i.e. dry cells). Other batteries can be recharged over and over again; these are called ‘secondary batteries’ (or accumulators). Because ordinary dry cells cannot be recharged, this chapter is concerned with rechargeable secondary batteries only.

As a battery is charged, electric energy is stored as chemical energy within the cells. When the battery is being discharged (i.e. when it is connected in circuit with a load), stored chemical energy is being removed from the battery and converted to electrical energy. The most common types of rechargeable battery systems on the world market today are lead-acid, lithium ion, nickel metal hydride and nickel cadmium.

Deep discharge or deep cycle batteries are preferred for solar electric systems because most of their stored energy can be delivered without causing damage to the cells or shortening their life. Shallow discharge batteries, made for automotive purposes, are designed to supply a large amount of power for a short duration. Taking too much energy out of these batteries before recharging them is likely to damage the plates inside.

It is advisable to only use deep cycle batteries in solar systems. If only shallow discharge batteries are available, they should be managed very carefully and never discharged deeply to avoid damage and system failure. In general, car batteries will have a much shorter lifetime when used in solar systems.

1.2.3 Rated Storage Capacity

The amount of energy that a battery can store is called its capacity. A water tank, for example, with a capacity of 8000 litres can hold at most 8000 litres. Similarly, a battery can only store a fixed amount of electrical energy. Battery capacity, typically marked on the casing by the manufacturer, is measured in amp-hours (Ah). This indicates the amount of energy that can be drawn from the battery before it is completely discharged.

Logically, that would mean that a battery of 100Ah capacity gives a current of 1 amp for 100 hours, or 2 A for 50 hours, and 4 A for 25 hours:

$$1\ A \times 100h = 100\ Ah$$

$$2\ A \times 50\ h = 100\ Ah$$

$$4\ A \times 25h = 100\ Ah$$

However, batteries do not follow this logic. The rate at which a battery is discharged affects the capacity of the battery. For example, a battery discharged at a rate of 1 amp might provide that current for 100 hours, giving it a capacity of 100Ah at that rate of discharge; but the same battery discharged at the rate of 4 amps might only deliver that current for 20 hours thus giving it a real capacity of 80Ah.

On battery datasheets this is indicated by C-rates: C100 indicates the capacity of a battery being discharged over 100 hours (at the rate of 1 amp in the above example), C20 indicates the capacity of a battery being discharged over 20 hours (at the rate of 4 amps in the above example).

Thus, the battery in the example has the following capacities: 100Ah at C100 and 80Ah at C20. So when choosing a battery you should be aware of the C-rate to which the rated storage capacity relates.

1.2.4 Charge and Discharge

'Charge current' is the electric current supplied to and stored in a battery. As a water tank will take more or less time to fill depending on the rate at which water enters it, the amount of time required to completely charge a battery depends upon the rate of the current at which it is being charged.

'Discharge' is the state when battery energy is being consumed by a connected load (i.e. appliances). The discharge current is the rate at which current is drawn from the battery. The amount of energy removed from a battery over a period of time can be calculated by multiplying the discharge current by the amount of time the load is used. For example, a lamp drawing 1.2 amps for 4 hours uses 4.8 amp-hours of energy from the battery (1.2A × 4 hours = 4.8Ah).

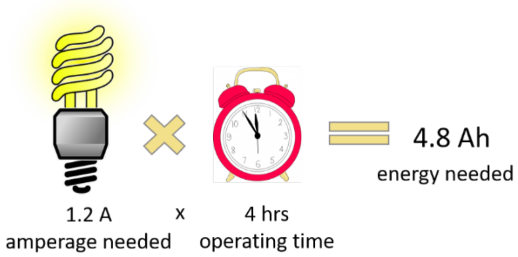


Figure 28 Calculating energy demand

But unlike a water tank, a battery can never be fully discharged. Some of the energy always has to remain in the battery, for lead solar batteries usually min. 20%, otherwise the battery will be damaged permanently and can never be charged again. This state is called "deep discharge". Because batteries also discharge themselves over time, they have to be checked and charged frequently when not in use in order to prevent permanent damage.

1.2.5 State of Charge

Just as one needs to monitor the amount of fuel left in a car's petrol tank, one needs to keep track of how much energy remains in the battery. The 'state of charge' (SoC) is a measure of the energy remaining in the battery. It tells you whether a battery is fully charged, half-charged or completely discharged. The cells of a fully charged battery have a 100 per cent state of charge, while those of a battery with one-quarter of its capacity removed are at a 75 per cent state of charge.

1.2.6 Cycles and Cycle Life

Typically, batteries in PV systems are charged each day by the PV array and then discharged by the load each night (though this is not always the case in larger systems where some loads are also powered during the day). Each charge period together with the following discharge period is called a 'cycle'. For example, in one cycle a 100Ah battery might be charged up to 95 per cent state of charge (12.68V) during the day, and then discharged by lights and television to 75 per cent state of charge that evening. The 'rated cycle life' of a battery (this should be specified by the manufacturer) is the number of cycles a battery is expected to last before its capacity drops to 80 per cent of its original rated capacity. Note that, in off-grid systems, this is typically the number of days the battery will last because each 'day' is more or less the same as one 'cycle'.

1.2.7 Depth of Discharge

Note also that the cycle life is determined by the average depth of discharge per cycle – a battery cycled at 30 per cent will last longer than a battery cycled at 70 per cent – as well as by average battery temperature. The actual cycle life of a battery is greatly shortened by such mistreatment as deep discharge, high temperature and high discharge rates.

'Depth of discharge' (DoD) is another term that manufacturers use to express how much batteries are discharged in a cycle before they are charged again, , in other words, how much was taken out of a battery already. When 20 Ah were already taken from a 100 Ah battery, the DoD is 20%. A battery at 20 per cent DoD is the same as an 80 per cent state of charge battery. A battery at 75 per cent DoD is at a 25 per cent state of charge. Shallow cycle batteries should not be discharged below 20 per cent DoD (80 per cent state of charge) on a regular basis. Even deep cycle batteries should not regularly be discharged below 60 per cent DoD (40 per cent state of charge). Remember, batteries last much longer when they are maintained in a high state of charge.

1.2.8 Solar Batteries

The following paragraph is taken/adapted from (Dobelmann & Klauss-Vorreiter, 2009) chapter 5.

Although the solar battery may look like the battery used in automobiles, inside it is very different. Batteries used for vehicles are designed to provide large amounts of power for a short time while solar batteries are designed to provide a small amount of power continuously for many hours. To provide this kind of power, the solar batteries have thicker lead plates in the inside than car batteries. Car batteries should not be used in solar systems to avoid early system failure.

The type of battery best suited for most solar systems is called a deep discharge battery. It is called that because it is especially designed to deliver a high percentage of its power without any damage. You can regularly use 80% of the power stored in a deep discharge battery without damage (compared to the allowable rate of 10% for a car battery). Therefore the use of a deep cycle battery would necessitate a correspondingly much smaller battery capacity.

1.3 Determining Depth of Discharge

Determining the Depth of Discharge is often a compromise exercise between lifetime and upfront capital layout. If a battery is discharged deeply, the battery size can be much smaller but the lifetime (cycles) will be much less. If a battery is not discharged deeply, a much bigger and more expensive battery is required, but it will last longer (more cycles). Battery cycles vs. Depth of Discharge information can be found on the battery datasheet, normally in a graph format.

In Figure 29 it can be seen that if a particular battery (Moll OPzS Solar range) is discharged to only 20%, it should last around 7500 cycles (green lines), while if it is discharged to 80%, is should last around only 1500 cycles (red line).

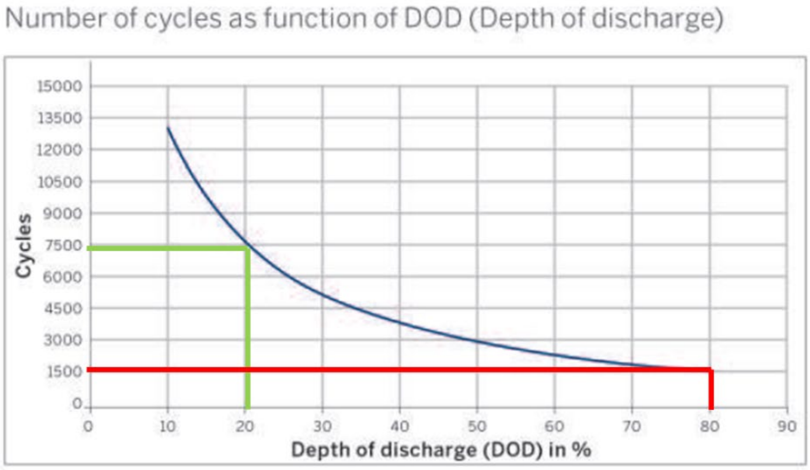


Figure 29 : Cycles vs. DoD

If a battery is only discharged 20%, one would need battery with about 4xtimes higher capacity (and higher price) to get the same energy out as when it is discharged to 80%. The bigger battery will however last much longer.

In order to determine the optimal depth of discharge, it is advisable to not only look at the upfront cost but rather the lifetime cost of the batteries.

As an example, let's assume we require 150Ah of energy for an application and we have 50Ah batteries available. We can set up a table (Table 3) to determine the lifetime cost of batteries for more than one DoD scenario, assuming the battery discharge curve in Figure 29:

Table 3: Comparing Price per Cycle

DoD	Battery available	Energy per Cycle	Energy Required	Batteries required	Price per Battery	Total Price	Cycles	Price per Cycle
20%	50Ah	10Ah	150Ah	15	$100	$1500	7500	20c
80%	50Ah	40Ah	150Ah	4	$100	$400	1500	27c

As can be seen, the initial capital required will be much less if the battery is discharged to 80% ($400 vs. $1500), but the price per cycle is about 35% more expensive (27c vs. 20c) compared to a 20% discharge. Furthermore, the batteries at 80% discharge will have to be replaces much more often (with added labour cost).

It can therefore be seen that it important to look at the lifetime cost of batteries to determine the optimal solution. For instance, if we use the same example, it can be seen (Table 4) that a good compromise may be a DoD of 50%. It will give a good price per cycle at a reasonable cost while also maintaining a reasonable number of cycles.

Table 4: Cycle price vs. Cost

DoD	Battery available	Energy per Cycle	Energy Required	Batteries required	Price per Battery	Total Price	Cycles	Price per Cycle
20%	50Ah	10Ah	150Ah	15	$100	$1500	7500	20c
50%	50Ah	25Ah	150Ah	6	$100	$600	3000	20c
80%	50Ah	40Ah	150Ah	4	$100	$400	1500	27c

Self-Check - 1	Written Test

Instruction: Follow the below selected instruction

N°	Questions and answers	
1	**Deep cycle batteries are preferred for solar systems**	
	True or false:	
2	**The capacity of a battery is the same, regardless of the rate of discharge**	
	True or false:	
3	**The 'rated cycle life' of a battery is the number of cycles a battery is expected to last before its capacity drops to 80 per cent of its original rated capacity.**	
	True or false:	
4	**The best battery is:**	
	A – The cheapest battery	B – The battery with the most cycles
	C – The one that can be discharged deepest	D – A compromise between cost, discharge depth and cycles

Note: the satisfactory rating is as followed

Satisfactory	3 points
Unsatisfactory	Below 3 points

Answer Sheet

Score = ___________

Rating: ____________

Name

Date

Information Sheet 2	Calculating Battery capacity

2 Calculating Battery capacity

2.1 Introduction

The capacity of a battery that is required for an application is a function of the energy consumption that the battery needs to supply, the efficiency of the battery, the system voltage, for how long the battery needs to supply energy (autonomy) and the Depth of Discharge.

2.2 Calculate battery size

2.2.1 Energy Consumption

In Learning Outcome 1, we dealt with the calculation of energy consumption using load tables (page 17).

2.2.2 System efficiency

Storing energy into a battery (converting from electrical energy to chemical energy) and retrieving energy from a battery (converting from chemical energy to electrical energy) imply certain losses. Depending on what type of battery is used, the efficiency of batteries can be more than 90% for lithium-ion down to 70% or less with lead-acid batteries. When calculating battery size for off-grid systems, one will normally increase the size of the battery to make up for losses.

2.2.3 System Voltage

The following paragraph is/are adapted from (Hankins, 2010) Chapter 4.

System Voltage 'System voltage' is the nominal voltage at which the batteries, charge regulator and solar array operate. Also, system appliances often operate at the system voltage. Most small off-grid PV systems (especially solar home systems below 100Wp) use 12V DC as their system voltage. If there is a need for AC power, an inverter is used to convert 12V DC electricity from the battery to the desired AC voltage. Sometimes 24 and 48V DC system voltage is used. In such cases, batteries and solar modules are wired in series or series-parallel so that they are 24 or 48V, and 24 or 48V charge regulators and inverters must be selected. Such systems have less voltage drop in wire runs, so they are often selected to save on cable costs (48V DC systems are common in off-grid telecom systems). However, note that 24 or 48V DC appliances are not readily available, so 12V DC system voltage is usually preferred for DC loads.

From the formulas P=IV and V=IR, it can be derived that $P=I^2R$. It is therefore clear that there is a squared (I^2) relationship between power losses and current i.e. the higher the current, the higher the losses will be.

The selection of the system voltage should aim to reduce the current (in order to reduce losses). There are various ways to determine the system voltage:

The 1-ohm rule: This rule states that the moment the load resistance go below 1 ohm, the next voltage should be selected:

System voltage	**12 V**	**24 V**	**48 V**
Load resistance	1ohm	1ohm	1ohm
Limiting PV power to (1Ω-rule):	144 W	576 W	2304 W

The current limit rule i.e. keeping the current below e.g. 100A:

System voltage	**12 V**	**24 V**	**48 V**
Current	83A	83A	83A
Limiting PV power to:	1000 W	2000 W	4000 W

In practice though, it will largely depend on the available charge controller voltage and power, as well as the available inverter voltage. It is important to size connectors and wires properly to limit losses.

2.2.4 Autonomy

Autonomy is the reserve storage factor, or the number of days of storage needed. This varies with site and is higher for sites with cloudy weather. In sunny areas, depending on the application, this number may be as low as one to two days only. The higher the days of autonomy, the higher the cost of the battery bank and it will increase the risk that, during cloudy weather or winter periods, batteries will not be fully charged and will be damaged by cycling in a low state of charge. For larger systems, a diesel generator may be more cost effective than large battery banks to cater for days of prolonged rain.

2.2.5 Depth of Discharge

This is the deepest depth of discharge that is ordinarily allowed with the battery. Shallow cycle batteries, for example, should not be cycled below 20 per cent depth of discharge, while deep discharge batteries can regularly handle 50 per cent discharges. Lithium-ion batteries can generally handle much deeper discharges of up to 90%.

2.2.6 Calculation formula

For the calculation of the battery, we will use the Adama design as example. The following formula can be used to calculate the battery size:

$$C_{10} = \frac{E * A}{DoD * Vsyst}$$

Where:

- DoD = Depth of Discharge e.g. 50%
- E = Energy consumption (daily) e.g. 5 kWh/day
- A = Autonomy days e.g. = 2 days
- V_{syst} = System Voltage DC e.g. 48 V

For the Adama design, we determined that the daily energy consumption is 12964Wh/d (see Table 2).

The Phocos Anygrid inverter is a 48V inverter, therefore the battery voltage needs to be 48V.

We decided on only 1 day of autonomy to reduce battery costs. There is grid power available to use in case of days without sunshine.

We also decided on a 50% DoD since we will be using lead acid batteries (Hoppecke Sun Power).

The required battery is therefore:

$C_{10} = \frac{12964Wh/day * 1days}{50\% * 48V} = 540.17Ah$

Note that Lithium-ion batteries are normally specified in Wh, therefore we omit the system voltage from the equation to get to the Wh rating.

From Figure 30, we see that the 7 OpzS solar power 730 battery gives us 546 Ah at C10. This is higher than the 540Ah we require.

This battery is a 2V battery and we need 48V. To determine the number of batteries is series:

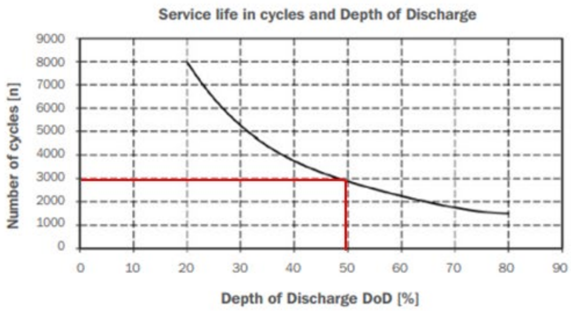
$$n_{series} = \frac{V_{System}}{V_{selected\ battery}} = \frac{48V}{2V} = 24$$

To determine the number of batteries in parallel:

$$n_{parallel} = \frac{C_{10,required}}{C_{10,selected\ battery}} = \frac{540.17Ah}{546Ah} = 0.99 = 1$$

We therefore need one series string of 24 x 2V cells to get a 546Ah, 48V battery.

Type	C_{100}/1.85 V Ah	C_{50}/1.85 V Ah	C_{24}/1.83 V Ah	C_{10}/1.80 V Ah	C_5/1.77 V Ah	max. Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Width W mm	max.* Height H mm	Fig.
4 OPzS solar.power 280	280	265	245	213	182	17.1	4.5	105	208	420	A
5 OPzS solar.power 350	350	330	307	266	227	20.7	5.6	126	208	420	A
6 OPzS solar.power 420	420	395	370	320	273	24.6	6.7	147	208	420	A
5 OPzS solar.power 520	520	490	454	390	345	29.1	8.5	126	208	535	A
6 OPzS solar.power 620	620	585	542	468	414	34.1	10.1	147	208	535	A
7 OPzS solar.power 730	730	685	634	546	483	39.2	11.7	168	208	535	A
8 OPzS solar.power 910	910	860	797	686	590	46.1	13.3	147	208	710	A
7 OPzS solar.power 1070	1070	1002	930	801	691	59.1	16.7	215	193	710	B
8 OPzS solar.power 1220	1220	1145	1063	915	790	63.1	17.3	215	193	710	B
9 OPzS solar.power 1370	1370	1283	1192	1026	887	72.4	20.5	215	235	710	B
10 OPzS solar.power 1520	1520	1425	1325	1140	985	76.4	21.1	215	235	710	B
11 OPzS solar.power 1670	1670	1572	1459	1256	1086	86.6	25.2	215	277	710	B
12 OPzS solar.power 1820	1820	1715	1591	1370	1185	90.6	25.8	215	277	710	B
12 OPzS solar.power 2170	2170	2010	1843	1610	1400	110.4	32.7	215	277	855	B
14 OPzS solar.power 2540	2540	2349	2163	1881	1632	142.3	46.2	215	400	815	C
16 OPzS solar.power 2900	2900	2685	2472	2150	1865	150.9	45.9	215	400	815	C
18 OPzS solar.power 3250	3250	3015	2765	2412	2097	179.1	56.4	215	490	815	D
20 OPzS solar.power 3610	3610	3350	3072	2680	2330	187.3	55.7	215	490	815	D
22 OPzS solar.power 3980	3980	3685	3388	2952	2562	212.5	67.0	215	580	815	D
24 OPzS solar.power 4340	4340	4020	3696	3220	2795	221.2	66.4	215	580	815	D
26 OPzS solar.power 4700	4700	4355	4004	3488	3028	229.6	65.4	215	580	815	D



C_{100}, C_{50}, C_{24}, C_{10} and C_5 =
Capacity at 100 h, 50 h, 24 h, 10 h and 5 h discharge

* according to DIN 40736-1 data to be understood as maximum values

Figure 30: Battery selection

At a dept of discharge of 50%, we can expect around 3000 cycles.

Figure 31: Hoppecke batteries

Self-Check - 2	Written Test

Instruction: Follow the below selected instruction

N°	Questions and answers
1	**Batteries should be fully discharged**
	True or false:
2	**Autonomy refers to how long a battery can supply the load without getting charged**
	True or false:
3	**Lithium-ion batteries can be discharged deeper than lead-acid batteries without problems**
	True or false:

N°	Questions and answers
4	**Calculate the C10 capacity of a battery when the consumption is 850Wh/day, the autonomy is 3 days, the DoD is 50% and the system voltage is 24V**

Note: the satisfactory rating is as followed

Satisfactory	3 points
Unsatisfactory	Below 3 points

Answer Sheet

Score = ___________

Rating: ____________

Name

Date