Energy Unlimited

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Electricity plays an increasing role on board yachts. Modern navigation and communication equipment depends on it, as well as the growing list of household appliances that are taken on board.

This is the concept text for a booklet about electricity on board small and large yachts. The intention of the book is twofold:

Firstly I try to cover in depth a few matters that over and again are subject to discussion and misunderstanding, such as batteries and management of batteries, or electric power consumption of refrigerators, freezers and air conditioning.

My second intention is to help designers, electricians and boat owners to decide on how to manage and generate electricity on board. Several new products and concepts have substantially broadened the range of alternatives here.

Together with some unavoidable theory, I use examples of small and large yachts to clarify the consequences of choosing one alternative or another. The consequences are sometimes so unexpected and far reaching that, writing it all down, I have also helped my own understanding!

Reinout Vader

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Energy Unlimited

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1. Introduction

Victron Energy has been supplying components and systems for autonomous energy supply for some 25 years. These might be systems for sail- or motorboats, inland navigation vessels, off-grid houses, for many types of vehicles, and a nearly endless range of other, often unexpected, applications.

We know from experience that generating and storing electrical energy on a small-scale is a complex business. The components of an autonomous system are costly and vulnerable. For example, the battery, that indispensable storage medium in a small-scale system, often goes flat quickly and unexpectedly, so that the “power fails” and eventually the harm caused by excessive discharge means premature investment in a new battery.

Developments in the field of autonomous energy-supply on board sail- and motorboats are exemplary. The amount of electric (domestic) equipment on board boats is increasing rapidly, while at the same time the space and weight available for energy generation and storage are being kept to an absolute minimum. It goes without saying that living space and sailing characteristics take a higher priority.

Growing demands imposed on autonomous energy systems have spurred the development of new products and concepts. This overview presents new products and concepts, with specific attention being paid to optimum system component integration and day-to-day operation of the complete system.

Where system components are discussed, brands are only mentioned if the products are unique, that is to say available exclusively under that brand, or if other brands are very hard to obtain. The unique Victron Energy products mentioned are:

- **Battery chargers** with adaptive software to automatically optimize charging.

- **Parallel connection** of inverters and combined inverter-battery chargers

The parallel connection option (if needed even in 3-phase configuration) means that there are no limits anymore to the amount of AC power that can be supplied from a battery. As will be shown, this opens the possibility to run all kinds of domestic equipment, including the washing machine and the electric cooker, from the battery. Although the peak power consumption of such equipment is high, the amount of amp-hours needed is quite manageable and much lower than one would expect.

- ***PowerContro*l** is an often overlooked but very convenient feature of the Victron Phoenix Combi and its even more versatile successor, the **Phoenix Multi**: by constantly monitoring the total power drawn from the on-board generator or shore supply, the Phoenix Multi will automatically reduce battery charging when otherwise an overload situation would occur (for example when high power household equipment is switched on).

- The next step*:* ***PowerAssist***. The revolutionary **Phoenix MultiPlus**, also an inverter-battery charger, actually runs in parallel with shore power or an AC generator, and uses the battery as a buffer to “help” the shore power or generator during periods of peak power demand.

The implications *of* ***PowerAssist*** are truly far reaching:
Traditionally the on-board generator had to be dimensioned to the peak power required. The use of power hungry equipment such as air conditioning, a washing machine or an electric stove would require a big and heavy generator and the required shore power capacity would often not even be available. **With *PowerAssist*, shore power and the on-board generator can be reduced to less than half the rating that normally would be required!**

While this overview is directed mainly towards boats, many products and solutions are also applicable in other autonomous energy systems such as can be found in off-grid houses, motor homes, or special purpose commercial vehicles.

2. The battery: preventing premature aging

2.1. Introduction

I like engines. When they go wrong you can listen, and look, and smell, and then take them apart. Parts can be replaced, repaired or overhauled. Then put it all together again, and there they go!

With a battery you can't do that. The battery is a secretive product. From the outside there is nothing to tell us about its quality, possible aging or state of charge. Nor is it possible to take it apart. It could be sawn open, but that ruins it for good and only highly qualified specialists could analyse the content and may be, in certain cases, they could trace the cause of failure.

A battery, when it fails, has to be replaced. That's it.

A battery is expensive, bulky and very very heavy. Just think: with 10 litres of diesel (= 8.4 kg) and a diesel generator you can charge a battery of 24 V 700 Ah (energy content 24 x 700 = 16.8 kWh). Such a battery has a volume of 300 dm^3 (= 300 litres) and weighs 670 kg!

Also, batteries are very vulnerable. Overcharging, undercharging, discharging too deeply, charging too fast, excessive temperature…. All these issues can occur and the consequences can be disastrous.

The purpose of this chapter is to explain why batteries fail, and what to do to make them last longer. And if you want to have a look inside a faulty battery, don't open it yourself. It is extremely dirty work and for the price of a new pair of trousers (the sulphuric acid of the battery will ruin them) buy the standard work of Nigel Calder, "Boatowner's Mechanical and Electrical Manual", and enjoy the many close-up's of failed batteries in chapter 1.

2.2. Battery chemistry

2.2.1. What happens in a cell as it discharges

As a cell discharges lead sulphate forms on both the positive and negative plates through absorption of acid from the electrolyte. The quantity of electrolyte in the cells remains unchanged. However, the acid content in the electrolyte reduces, something noticeable in the change of the specific gravity.

2.2.2. What happens during charging

During charging the process is reversed. On both plates acid is released, while the positive plate converts into lead oxide and the negative plate into porous, sponge-like lead. Once charged the battery can no longer take up energy, and any further energy added is used to decompose water into hydrogen gas and oxygen gas. This is an extremely explosive mixture and explains why the presence of an open flame or sparks in the vicinity of a battery during charging can be very hazardous. It is therefore necessary to ensure that a battery compartment has effective ventilation.

2.2.3. The diffusion process

When a battery is being discharged, ions have to move through the electrolyte and through the active material of the plates to come into contact with the lead and lead oxide that has not yet been chemically converted into lead sulphate. This moving of ions through the electrolyte is called diffusion. When the battery is being charged the reverse process takes place. The diffusion process is relatively slow, and as you can imagine, the chemical reaction will first take place at the surface of the plates, and later (and also slower) deep inside the active material of the plates.

2.2.4. Service life

Depending on construction and use, the service life of a battery ranges from a few years to up to 10 years or more. The main reasons for batteries to age are:

- **Shedding** of the active material. Intensive cycling (= discharging and recharging a battery) is the main reason for this to happen. The effect of repetitive chemical transformation of the active material in the plate grid tends to reduce cohesion, and the active material falls of the plates and sinks to the bottom of the battery.

- **Corrosion** of the positive plate grid. This happens when a battery is being charged, especially at the end of the charge cycle when the voltage is high. It also is a slow but continuous process when a battery is float charged. Oxidation will increase internal resistance and, finally, result in disintegration of the positive plates.

- **Sulphation**. While the previous two reasons for a battery to age cannot be prevented, sulphation should not happen if a battery is well taken care of. When a battery discharges the active mass in both the positive and negative plates is transformed into very small sulphate crystals. When left discharged, these crystals tend to grow and harden and form an impenetrable layer that cannot be reconverted back into active material. The result is decreasing capacity, until the battery becomes useless.

2.3. The most common types of lead-acid battery

2.3.1. Lead-antimony and lead-calcium

Lead is alloyed with antimony (with the addition of some other elements such as selenium or tin in small quantities) or with calcium to make the material harder, more durable and easier to process. For the user it is important to know that compared to lead-calcium batteries, batteries alloyed with antimony have a higher rate of internal self-discharge and require a higher charge voltage, but also will sustain a larger number of charge-discharge cycles.

2.3.2. Wet or flooded versus starved (gel or AGM) electrolyte

The electrolyte in a battery is either liquid (wet or flooded batteries), or starved: formed into a gel (the gel battery) or absorbed in microporous material (the AGM battery).

When nearly fully charged, wet or flooded batteries will start “gassing”, which is the result of water being decomposed into oxygen- and hydrogen gas.

In batteries with starved electrolyte oxygen gas formed at the positive plates migrates to the negative plates where, after a complicated chemical reaction, it is “recombined” with hydrogen into water. No gas will escape from the battery. Hydrogen gas is formed only if the charge voltage is too high. In case of excessive charge voltage oxygen and hydrogen gas will escape through a safety valve. That is why these batteries are also called VRLA (Valve Regulated Lead Acid) batteries.

Then batteries may be distinguished on the basis of their mechanical construction and purpose:

2.3.3. The flat-plate automotive battery (flooded)

This is the battery used in cars. Not suitable for frequent deep discharging as it has thin plates with a large surface area – designed purely for short-term high discharge currents (engine starting). Nevertheless flat-plate heavy-duty truck starter batteries are often employed as house batteries in smaller boats.

2.3.4. The flat-plate semi-traction battery (flooded)

This battery has thicker plates and better separators between the plates to help prevent buckling of the plates and shedding of the active material under cyclic use. It can be used for light duty cycling and is often referred to as a ‘leisure’ duty battery.

2.3.5. The traction or deep-cycle battery (wet)

This is either a thick-plate or a tubular-plate battery. Used for example in forklift trucks, it is discharged down to 60-80% every day and then recharged overnight – day after day. This is what is referred to as cyclic duty.

The deep-cycle battery must be charged, at least from time to time, at a relatively high voltage. How high depends on chemical and constructive details and on the charging time available.

Note: The high charging voltage is needed to reconvert all sulphate into active material, and to help prevent **stratification** of the electrolyte. The sulphuric acid (H_2SO_4) produced as the battery is being charged has a higher density than water and does tend to settle downwards so that the acid concentration at the bottom of the battery becomes higher than at the top. Once the gassing voltage is reached, charging is continued with plenty of current (and therefore a high voltage). The resulting gas generation ‘stirs’ the electrolyte and ensures that it becomes well mixed again.

For the electrolyte in a usually very tall tubular-plate battery to mix well, more gas generation is needed than in a much lower flat-plate battery.

The tubular-plate battery is extremely robust and accepts a very high number of charge-discharge cycles. It is an excellent low cost substitute for sealed gel- or AGM batteries.

2.3.6. The sealed (VRLA) gel battery

Here the electrolyte is immobilised as gel. Familiar as the Sonnenschein Dryfit A200, Sportline or Exide Prevailer battery.

2.3.7. The sealed (VRLA) AGM battery

AGM stands for Absorbed Glass Mat. In these batteries the electrolyte is absorbed (“sucked up”) into a glass-fibre mat between the plates by capillary action. In an AGM battery the charge carriers, hydrogen ions (H_2) and sulphate ions (SO_4), move more easily between the plates than in a gel battery. This makes an AGM battery more suitable for short-time delivery of very high currents than a gel battery. Examples of AGM batteries are the Concorde Lifeline and the Northstar battery.

2.3.8. The sealed (VRLA) spiral cell battery

Known as the Optima battery (Exide now has a similar product), this is a variant of the VRLA AGM battery. Each cell consists of 1 negative and 1 positive plate that are spiralled, thereby achieving higher mechanical rigidity and extremely low internal resistance. The spiral cell battery can deliver very high discharge currents, accepts very high recharge currents without overheating and is also, for a VRLA battery, very tolerant regarding charge voltage.

2.4. Function and use of the battery

In an autonomous energy system the battery acts as buffer between the current sources (DC generator, charger, solar panel, wind generator, alternator) and the consumers. In practice this means cyclic use, but in fact a quite special “irregular” variation of cyclic use. This contrasts with the forklift truck example where the duty cycle is very predictable.
As boats are often also left unused for long periods of time, so are their batteries.

For instance on a sailing yacht the following situations can arise:

- The yacht is under sail or at anchor in a pleasant bay. Those aboard would not want any noise, so all electricity comes from the battery. The main engine or a diesel generator is used once or twice a day for a few hours to charge the house battery sufficiently to ride through the next generator-free period. This is cyclic use, where, significantly, the charging time is too brief to fully charge the battery.

- The yacht is travelling under power for several hours. The alternators on the main engine then have the time to charge the battery properly.

- The yacht is moored at the quayside. The battery chargers are connected to shore power supply and the battery is under float charge 24 hours a day. If the DC concept is used (section 8.2) several shallow discharges may occur every day.

- The yacht is out of service during wintertime. The batteries are either left disconnected for several months, left under float charge from a battery charger, or are kept charged by a solar panel or wind generator.

The number of cycles per year, the ambient temperature and many other factors influencing a battery’s service life will vary user by user. The following briefly discusses all of these factors.

2.5. The lead-acid battery in practice

2.5.1. How much does a battery cost?

Here we only intend to give a rough estimate of price. Besides all the considerations of quality and use, cost is, of course, important.

Battery type	**Application**	**Commonly used system voltage, capacity and energy content**			**Price indication ex. VAT**	**Price indication per kWh**
		V	**Ah**	**kWh**	**USD or EURO**	**USD or EURO per kWh**
Start	Cranking	12	100	1.2	100	80
Spiral-cell	Cranking, bow-thruster	12	60	0.72	250	350
Semi-traction	House battery up to approx. 600 Ah	12	200	2.4	300	125
VRLA AGM battery	House battery up to approx. 600 Ah. Also cranking and bow thruster	12	230	2.8	600	210
Traction (tubular-plate)	House battery up to approx. 2000 Ah	24	1000	24	4.500	190
VRLA-gel Sonnenschein Dryfit A200	House battery up to approx. 600 Ah	12	200	2.4	500	210
VRLA-gel Sonnenschein Dryfit A600	House battery up to approx. 1500 Ah	24	1500	36	11.000	305

The table shows that cost varies greatly dependant on the choice of battery, and particularly that wet batteries are less expensive than VRLA batteries.

VRLA batteries do offer great ease of use, they:

- are maintenance free.
- do not gas (provided that the battery is not charged with excessive voltage).
- can be installed in places with difficult access.

On the other hand sealed batteries are very sensitive to overcharging (the exception is the spiral-cell battery). Overcharging results in gassing (through the safety valve) which means water loss that can never be replenished, resulting in capacity loss and premature aging.

2.5.2. Dimensions and weight

Battery type	V	Ah	kWh	Volume dm^3	Weight kg	Specific volume Wh / dm^3	Specific weight Wh / kg
Start	12	100	1.2	16	28	75	43
Spiral-cell	12	60	0.72	8.5	17.2	81	42
Semi-traction	12	200	2.4	33	60	73	40
VRLA AGM battery	12	230	2.8	33	62	85	45
Traction (tubular-plate)	24	1000	24	280	770	85	32
VRLA-gel Sonnenschein Dryfit A200	12	200	2.4	33	70	72	34
VRLA-gel Sonnenschein Dryfit A600	24	1500	36	600	1440	60	25

This table very clearly shows how heavy and cumbersome batteries are.

Coming back to the comparison in section 2.1:
Compared to the energy released by combustion of diesel fuel, for example, batteries are simply no rivals. Burning 10 litres (weight 8.4 kg) of fuel generates approx. 100 kWh of thermal energy. So when consuming 10 litres of diesel fuel a diesel generator with an average efficiency of 20% will be able to generate 20 kWh of electric energy. This is the energy needed to charge a 24 V 700 Ah battery. Such a battery has a volume of 300 dm^3 (= 300 litres) and weighs 670 kg!

Another telling comparison is heating water. Bringing 1 litre (= 1 kg) of water to the boil in an electric kettle requires 0.1 kWh. To supply the required 0.1 kWh, approx. 4 kg of battery is needed!

2.5.3. Effect on capacity of rapid discharging

The capacity of a battery is dependent on the rate of discharge. The faster the rate of discharge, the less Ah capacity will be available. This is related to the diffusion process (sect. 2.2.3). In general the rated capacity is quoted for a discharge time of 20 hours (discharge current I = C / 20).

For a 200 Ah battery this means that the rated capacity can be delivered at a discharge current of 200 Ah / 20 hours = 10 Ampères.

With a discharge current of 200 A the same battery becomes “flat” far sooner. For instance a 200 Ah gel battery then has an effective capacity of only 100 Ah and therefore becomes flat after 30 minutes. (see also chapter 3: The battery monitor).

The following tables give an impression of the capacity as a function of the discharge current.

The 2nd column of the first table gives the rated capacity as quoted by the manufacturer with the associated discharge time. Often this is 20 hours, but it can also be 10 hours or 5 hours.

The tables show how capacity falls off steeply with increasing discharge current, and that AGM batteries (especially the spiral-cell battery) perform better than gel batteries under high discharge currents.

Type	**Discharge current**	**Rated capacity and related discharge time**	**Discharge time**	**Discharge current**	**Effective capacity 1.83 V / cell (11 V)**		**Discharge time**
	A (rated)		**hours**	**A (C / 5)**	**Ah**	**%**	**hours**
Start	5	100 Ah / 20 h	20				
Spiral-cell	2.8	56 Ah / 20 h	20	11.2	52	93	4.6
Semi-traction	10	200 Ah / 20 h	20	40	150	75	3.75
VRLA AGM battery	11.5	230 Ah / 20 h	20	46	198	86	4.3
Traction (tubular-plate)	200	1000 Ah / 5 h	5	200	1000	100	5
VRLA-gel Sonnenschein Dryfit A200	10	200 Ah / 20 h	20	40	158	79	4
VRLA-gel Sonnenschein Dryfit A600	150	1500 Ah / 10 h	10	300	900	60	3

Type	**Discharge current**	**Effective capacity 1.83 V / cell (11 V)**		**Discharge time**	**Discharge current**	**Effective capacity 1.75 V / cell (10.5 V)**		**Discharge time**
	A (C / 2)	**Ah**	**%**	**Minutes**	**A (C / 1)**	**Ah**	**%**	**Minutes**
Start								
Spiral-cell	28	43	77	92	56	42	75	45
Semi-traction	100	110	55	66	200	90	45	27
VRLA AGM battery	115	157	68	82	230	142	62	37
Traction (tubular-plate)	500	700	70	80	1000	400	40	24
VRLA-gel Sonnenschein Dryfit A200	100	120	60	72	200	100	50	30
VRLA-gel Sonnenschein Dryfit A600	750	375	25	15	1500	0*	0	0*

* With a discharge current of 1500 A (C / 1) the voltage of an A600 battery drops almost immediately to 1.65 V / cell (i.e. 9.9 V and 19.8 V for a 12 V respectively 24 V system).

Discharge current is often expressed as a proportion of the rated capacity. For example for a 200 Ah battery C / 5 means a discharge current of 40 A (= 200 Ah / 5).

2.5.4. Capacity and temperature

The effective capacity of a battery varies in reverse proportion to temperature:

- 10°C	10°C	15°C	20°C	25°C	30°C
80 %	92 %	95 %	100 %	103 %	105 %

2.5.5. Premature aging 1. The battery is discharged too deeply.

The deeper a battery is discharged, the faster it will age due to shedding (sect. 2.2.4.), and once a certain limit is exceeded (approx. 80% depth of discharge) the aging process advances disproportionately fast.

Additionally, if the battery is left discharged the plates will begin to sulphate (sect. 2.2.4.).

As was also explained in section 2.2.4, a battery ages even when kept charged and doing nothing, mainly due to oxidation of the positive plate grid.

The following table gives a rough idea of the number of charge/discharge cycles that batteries can withstand until the end of their service life, and how they could be destroyed by sulphation or due to plate corrosion.

Batteries are considered to have reached the end of their service life when the capacity they can hold has reduced to 80% of the rated capacity.

Type	**Number of cycles until end of service life**		**Resistance to 100 % discharging**	**Expected service life in float or shallow cycle use at 20°C ambient temperature**
	DoD 80 %	**DoD 60 %**		**Years**
Start	Not suitable for cyclic use			5
Spiral-cell	400	650	Irreparably sulphated within a few days	10
Semi-traction	200	350	Irreparably sulphated within a few days	5
VRLA AGM battery	250	800	Survives up to 1 month in short-circuited state	4 - 10
Traction (tubular-plate)	1500	2500	Survives up to 1 month in discharged state	10 – 15
VRLA-gel Sonnenschein Dryfit A200	250	450	Survives up to 1 month in discharged state	4 – 5
VRLA-gel Sonnenschein Dryfit A600	600	900	Survives 1 month in discharged state	15 – 18

Although most batteries will recover from a full discharge, it is nevertheless very detrimental to their service life. Batteries should **never** be fully discharged, and certainly not left in discharged state.

It should also be noted here that the voltage of a battery that is in use is not a good measure for its level of discharge. Battery voltage is affected too much by other factors such as discharge current and temperature. Only once the battery is almost fully discharged (DoD 80% to 90%) will voltage drop rapidly. Recharging should have been started **before** this happens. Therefore a battery monitor (chapter 3) is highly recommended to manage large, expensive battery banks effectively.

2.5.6. Premature aging 2. Charging too rapidly and not fully charging.

Batteries can be quickly charged and will absorb a high charge current until the gassing voltage is reached. While charging with such high current might work well a few times, this will actually shorten the service life of most batteries substantially (the exception: spiral-cell and some other AGM batteries). This is due to accelerated loss of cohesion of the active material, which results in shedding. Generally it is recommended to keep the charging current down to at most C / 5, in other words a fifth or 20 % of the rated capacity.
When a battery is charged with currents exceeding C / 5, its temperature can rise steeply. Temperature compensation of the charging voltage then becomes an absolute necessity (see sect. 2.5.9).

My own experience is that charging a 50 % discharged 12 V 100 Ah flooded battery at 33 A (C / 3) results in a temperature increase of 10 to 15°C. The maximum temperature is reached at the end of the bulk phase. Bigger batteries will become even hotter (because the amount of heat generated increases with volume and the dissipation of heat increases with the available surface) as well as batteries with a high internal resistance, or batteries which have been discharged more deeply.

An example:
Suppose a 50 foot sailing yacht has a 24 V service battery with a capacity of 800 Ah. The maximum charging current would then be C / 5 = 160 A. Then 320 Ah could be charged in 2 hours. If simultaneously there is 15 A consumption, the charging equipment will have to deliver 175 A. During the remaining 22 hours of a 24-hour period an average of 320 Ah / 22 h = 14.5 A can be used, which means a discharge of only 320 / 800 = 40 %. This does not seem much, but unfortunately it is the maximum attainable when the generator period is limited to 2 hours. If used in this manner the cycling process will stabilise between a DoD of 20 % (beyond this point the charging voltage increases and the current accepted by the battery decreases) and a DoD of 20 % + 40 % = 60 %. Discharging more deeply and charging more rapidly would result in considerable loss of service life.

In the example described above the battery is being used in **partially charged state** (between 20 % and 60 % DoD).

Next to sulphation, there are two more reasons why the number of cycles in the partial state-of-charge mode should be limited:

1) Stratification of the electrolyte.
This problem is specific to batteries with liquid electrolyte: see sect. 2.3.6.
As a rule of thumb, one should not extend partial state-of-charge operation beyond approx. 30 cycles, and much less in case of very deep discharges.

2) Cell unbalance.
Cells of a battery never are identical. Some cells do have a slightly lower capacity than others. Some cells will also have lower charge efficiency (see sect. 3.4.) than others. When a battery is cycled but not fully charged, these weaker cells will tend to lag further and further behind the better cells. To fully charge all cells, the battery has to be equalized (which means that the better cells will have to be overcharged, see sect. 4.3.).
Unbalance will increase faster in case of very deep discharges or a very high charge rate. In order to prevent excessive cell unbalance, a battery should be fully recharged at least every 30 to 60 cycles.

2.5.7. Premature aging 3. Undercharging.

As discussed in section 2.2.4, sulphation will occur when a battery is left in fully discharged condition. Sulphating will also take place, although at a slower rate, when a battery is left partially discharged. It is therefore recommended to never leave a battery more than 50 % discharged and to recharge to the full 100 % regularly, for example every 30 days.
Batteries, especially modern low antimony flooded batteries, often are undercharged because the charge voltage is insufficient (see chapter 4).

Along with discharging too deeply, not fully charging is the major cause of premature aging of a battery.

2.5.8. Premature aging 4. Overcharging.

Charging too much is, in sequence, the 3rd main cause of service life reduction of a battery. Overcharging results in excessive gassing and therefore loss of water. In wet batteries water loss through excessive gassing can simply be replenished (yet the accelerated corrosion of the positive plates which takes place simultaneously is irreparable). However, sealed batteries which gas excessively cannot be replenished, and are therefore much more susceptible to overcharging. A frequent cause of excessive charging is the lack of temperature compensation or batteries being simultaneously charged using diode isolators (see chapter 5).

2.5.9. Premature aging 5. Temperature.

The temperature of a battery can vary greatly for various reasons:

- Rapid discharging and, to a much greater extent, rapid charging heats up a battery (see sect. 2.5.6 and 2.5.8).

- A battery’s location. In the engine room of a boat temperatures of 50°C or more can occur. In a vehicle the temperature can vary from - 20°C to + 50°C.

A high average working temperature results in accelerated aging because the rate of the chemical decomposition process in the battery increases with temperature. A battery manufacturer generally specifies service life at 20°C ambient temperature. The service life of a battery **halves** for every 10°C of rise in temperature.

The following table gives an impression of service life at different temperatures.

Battery type	**Service life in shallow cycling or float use (years)**		
	20°C	**25°C**	**30°C**
Start	5	3.6	2.5
Spiral-cell	10	7	5
Semi-traction	5	3.6	2.5
VRLA AGM battery	8	6	4
Traction (tubular-plate)	10	7	5
VRLA-gel Sonnenschein Dryfit A200	5	3.6	2.5
VRLA-gel Sonnenschein Dryfit A600	16	11	8

Finally, temperature plays a big part in charging batteries. The gassing voltage and consequently the optimum absorption and float voltages are inversely proportional to temperature.

This means that at a fixed charge voltage a cold battery will be insufficiently charged and a hot battery will be overcharged.
See section 4.4. for more information on temperature and battery charging.

2.5.10. Self-discharge

A battery at rest loses capacity as a consequence of self-discharge. The rate of self-discharge depends on the type of battery and temperature.

Type	**Alloy**	**Self-discharge per month at 20°C**	**Self-discharge per month at 10°C**
Start	Antimony (1,6 %)	6 %	3 %
Spiral-cell	Pure lead	4 %	2 %
Semi-traction	Antimony (1,6 %)	6 %	3 %
VRLA AGM battery	Calcium	3 %	1.5 %
Traction (tubular-plate)	Antimony (5 %)	12 %	6 %
VRLA-gel Sonnenschein Dryfit A200	Calcium	2 %	1 %
VRLA-gel Sonnenschein Dryfit A600	Calcium	2 %	1 %

When not in use, open lead-antimony batteries must be recharged after no more than 4 months, unless the average ambient temperature is low.
Sealed batteries can be left without recharge for a period of 6 to 8 months.

When not in use for a long period of time, it is important to disconnect the battery from the electric system, so that no accelerated discharging can take place as a result of current leaks elsewhere in the system.

3. Monitoring a battery’s state of charge. ‘The battery monitor’

3.1. The different ways of measuring a battery’s state of charge

3.1.1. Specific gravity (SG) of the electrolyte

As explained in sect. 2.2.1, the electrolyte of a lead-acid battery consists of a mixture of water and sulphuric acid. When fully charged, the active material in the negative plates is pure sponge lead; in the positive plates it is lead oxide. The concentration of sulphuric acid in the electrolyte (and consequently the SG) is then high.

During discharging the sulphuric acid from the electrolyte reacts with the active material in the positive and negative plates forming lead sulphate and water. This reduces the sulphuric acid concentration and consequently the SG of the electrolyte.

During discharging, the depth of discharge (DoD) of the battery can be tracked quite well by using a hydrometer to monitor the SG of the electrolyte. The SG will decrease as shown in the following table:

Depth of discharge (%)	Specific gravity	Battery voltage
0	Between 1,265 and 1,285	12.65 +
25	1,225	12.45
50	1,190	12.24
75	1,155	12.06
100	1,120	11.89

During charging the reverse process takes place and sulphuric acid forms once again. Because sulphuric acid is heavier than water, in batteries with liquid electrolyte (this does not apply for gel and AGM batteries) it settles downwards, so that the acid concentration increases at the bottom of the battery. However, above the plates the acid concentration in the liquid does not increase until the gassing level is reached!

Some useful information about electrolyte:

- **Stratification**

Only once the **gassing voltage** (2.39 V per cell, or 14.34 V for a12 V battery at 20°C) is reached will the electrolyte slowly become well mixed again by the gas bubbles.
The time needed depends on the construction of the battery and on the amount of gassing. The amount of gassing in turn depends on the charge voltage, on the amount of antimony doping and age of the battery.
Batteries with relatively high antimony doping (2.5 % or more) in general do gas sufficiently during the absorption charge for the electrolyte to become homogeneous again.
Modern low antimony batteries (1.6 % or less antimony content) however gas so little that a normal charge cycle is not sufficient. It then takes weeks of float charging (with very little gassing) before the electrolyte is well mixed again. **As a result flooded batteries, after having been fully charged, may nevertheless show a low hydrometer reading**!
Note: Vibration and motion in a boat or vehicle will in general adequately mix electrolyte.

- **Temperature correction for hydrometer readings:**

SG varies inversely with temperature. For every 14°C of temperature increase above 20°C, the hydrometer reading will decrease with 0.01. So a reading of 1.27 at 34°C is equivalent to a reading of 1.28 at 20°C.

- **Specific gravity variations per region:**

The SG values as mentioned in the table above are typical for a moderate climate.
In hot climates SG is reduced as shown in the table below in order to diminish the effect of temperature on service life of a battery

Fully charged SG, moderate climate:	1.265	-	1.285
Fully charged SG, sub tropical climate:	1.250	-	1.265
Fully charged SG, tropical climate:	1.235	-	1.250

3.1.2. Battery voltage

Battery voltage too can be used as a rough indication of the battery's state of charge (see preceding table, section 3.1.1).
Important: the battery should be left undisturbed for several hours (no charging or discharging) before a valid voltage measurement is possible.

3.1.3. Amp-hour meter

This is the most practical and accurate way to monitor a battery's state of charge. The product designed for this is the battery monitor. The following sections look in more detail at the use of the battery monitor.

3.2. The battery monitor is an amp-hour meter

The battery monitor's main function is to follow and indicate the DoD of a battery, in particular to prevent unexpected total discharge.
A battery monitor keeps track of the current flowing in and out of the battery. Integration of this current over time (which if the current would be a fixed amount of amps, boils down to multiplying current and time) gives the amount of amp-hours flowing in or out of the battery.
For example: a discharge current of 10 A for 2 hours means that the battery has been discharged by 10 x 2 = 20 Ah.

3.3. Energy efficiency of a battery

When a battery is charged or discharged losses occur. The total quantity of electric energy that the battery takes up during charging is approx. 25 % greater than the energy given out during discharging, which means an efficiency of 75 %. High charge and discharge rates will further reduce efficiency. The greatest loss occurs because the voltage is higher during charging than during discharging, and this occurs in particular during absorption. Batteries that do not gas much (low antimony batteries) and that have a low internal resistance are the most efficient.
When a battery is used in the partial state-of-charge mode (see the example in section 2.5.6.), its energy efficiency will be quite high: approx. 89 %.

To calculate Ah charge or discharge of a battery, a battery monitor only makes use of current and time, so compensation for the overall efficiency is not needed.

3.4. Charge efficiency of a battery

When a battery is charged, more Ah has to be “pumped” in the battery than can be retrieved during the next discharge. This is called charge efficiency, or Ah or Coulomb efficiency (1 Ah = 3600 C).

The charge efficiency of a battery is almost 100 %, as long as no gas generation takes place. Gassing means that part of the charging current is not transformed into chemical energy that is stored in the plates, but used to decompose water into oxygen and hydrogen gas (this is also true for the “oxygen only” end of charge phase of a sealed battery, see section 2.3.2.). The “amp-hours” stored in the plates can be retrieved during the next discharge whereas the “amp-hours” used to decompose water are lost.

The extent of the losses, and therefore the charge efficiency depends on:

A. The type of battery: low gassing = high charge efficiency.

B. The way in which the battery is charged. If a battery is mainly used in partial state of charge (see the example in section 2.5.6.) and only charged up to 100 % now and again, the average charge efficiency will be higher than if a battery is recharged to 100 % after each discharge.

C. Charge current and voltage. When charging with a high current and therefore also a high voltage and a high temperature, gassing will start earlier and will be more intensive. This will reduce charge efficiency (and also the overall energy efficiency).

In practice charge efficiency will range in between 80 % and 95 %. A battery monitor must take the charge efficiency into account, otherwise its reading will tend to be too optimistic. If the charge efficiency has to be pre-set manually it is advisable to initially choose a low value, for example 85 %, and adjust later to suit practice and experience.

3.5. Effect on capacity of rapid discharging

As discussed in sect. 2.5.3. The capacity of a battery is dependent on the rate of discharge. The faster the rate of discharge, the less Ah capacity will be available.

Back in 1897, a scientist named Peukert discovered that the relationship between the discharge current I and the discharge time T (from fully charged to fully discharged) may be described approximately as follows:

$C_p = I^n \times T$

where C_p is a constant (the Peukert capacity) and n is the Peukert exponent. The Peukert exponent is always greater than 1. The greater n is, the poorer the battery performs under high rates of discharge.

Peukert's exponent may be calculated as follows from measurements on a battery or using discharge tables or graphs.
If we read (from a discharge table) or measure discharge time T_1 and T_2 for two different discharge currents (I_1 and I_2), then:

$C_p = I_1^n \times T_1 = I_2^n \times T_2$

and therefore:

$n = \log(T_2 / T_1) / \log (I_1 / I_2)$

As shown in the tables of section 2.5.3, increasing the discharge current from C / 20 to C / 1 (= increasing the discharge current of a 200 Ah battery from 200 / 20 = 10 A to 200 / 1 = 200 A) can reduce effective capacity by as much as 50 % for a mono block gel battery.

A battery monitor should therefore compensate capacity for the rate of discharge.
In practice this is quite complicated because the discharge rate of a house battery will vary over time.

3.6. Is capacity "lost" at high rates of discharge?

Section 2.5.3 cites the example of a battery where the rated capacity under a 20-hour discharge was 200 Ah, thus C_{20} = 200 Ah. The corresponding discharge current is:

$I_{20} = C_{20} / 20 = 10$ A

Under a discharge current of 200 A the battery was flat in 30 minutes. So although we started with a 200 Ah battery, it was flat after discharging only 100 Ah.

This does not mean that, with a discharge current of 200 A, the 100 Ah capacity difference ($C_{20} - C_1 = 200 – 100 = 100$ Ah) has "disappeared". What happens is that the chemical process (diffusion, see sect. 2.2.3.) is progressing too slowly, so that the voltage becomes unacceptably low. A battery discharged with 200 A and "flat" in 30 minutes will therefore also be (nearly) fully charged again after recharging 100 Ah, while the same battery which is discharged with I_{20} = 10 A and is flat in 20 hours will be nearly fully charged after recharging 200 Ah.

In fact a battery which has been discharged at a very high rate will recover over time and the remaining capacity can be retrieved after the battery has been left at rest for several hours or a day.

3.7. Other Useful features of a battery monitor

In my opinion, apart from a voltmeter and an alarm function, very useful features are event counting and data logging

3.7.1. Event counting

Event counting means that specific events; especially events that are potentially damaging or that on the contrary are needed for battery maintenance are stored in a memory of the battery monitor.
Such events could be:

- over voltage
- under voltage
- number of charge-discharge cycles
- 100 % discharge
- 100 % recharge

3.7.2. Data logging

Data logging would mean that, in addition to specific events, at regular intervals the status of the battery is stored in order to be able to reproduce a history of use at a later date.

4. Battery charging: the theory

4.1. Introduction

Writing about battery charging would be easy if there was one recipe, independent of the conditions of use and valid for all types of lead acid batteries. But this is not the case.

Additional complicating factors are that there is often more than one charging device connected to the battery, and that the net charging current is not known because of consumers that are also connected to the battery.

Voltage limited charging is the best way to eliminate the influence of consumers as far as possible. And working with 2 voltage limits, the absorption and float voltage limits discussed later in this chapter, is a good and generally accepted method to charge batteries which have been deeply discharged, as fast as possible.

A further refinement of the standard 3 stage (bulk – absorption – float) method is **adaptive charging**: see sect 5.3.2.

4.2. Three step (I U_o U) charging

4.2.1. The bulk charge

When starting to charge a battery, voltage immediately jumps to approx. 2.1 V / cell (12.6 V for a 12 V battery and 25.2 V for a 24 V battery) and then slowly rises until the first voltage limit is reached.
This is the current limited or bulk phase of the charge cycle, during which the battery will accept the full available charge current.

For big battery banks it is advisable to limit the current to C / 5 or, even better, C / 10, meaning that 10 to 20 % of the total capacity is charged per hour. For example 100 A to 200 A for a 1000 Ah battery.
A less expensive smaller battery bank is often charged, although this may reduce service life, at a higher rate, for example C / 3.

A deeply discharged battery will accept a current of this order of magnitude until it is about 80 % charged. It will then reach the first voltage limit. From there onwards, instead of “absorbing” all of the current being “offered”, charge acceptance reduces rapidly. Therefore this first voltage limit is called the absorption voltage and the subsequent phase of the charge cycle the absorption phase.

A high bulk-charging rate will heat the battery, increase gassing and increase the absorption time needed to fully charge the battery. In other words: a high charging current will only shorten charge time to a limited extent.

In any case the charge current must be limited to C / 5 or less once the gassing voltage has been reached (at 20°C the gassing voltage is approximately 2.4 V / cell, or respectively 14.4 V and 28.8 V). Otherwise the active mass will be pushed out of the plates due to excessive gassing.

4.2.2. The absorption charge

When the pre-set absorption voltage limit has been reached, charging is limited to the amount of current that the battery will absorb at this voltage.
During the absorption phase the current will steadily decrease as the battery reaches its fully charged state.

As explained in sect. 2.2.3, charging (and discharging) a battery means that a diffusion process must take place

The diffusion process in fact explains a lot about charging and discharging batteries:

- When a battery has been subjected to a fast but shallow discharge, little diffusion deep inside the active material has taken place and the chemical reaction is limited to the surface of the plates. To recharge, a short or even no absorption time at all will be needed (the battery in a car is charged at a fixed 14 V). To recover from a long and deep discharge, a long absorption period will be needed in order to reconvert the active material deep inside the plates.

- Thin plate starter batteries need less absorption charging than thick plate or tubular plate heavy-duty batteries.

- Absorption is a trade off between voltage (increasing the voltage results in stronger electric fields which will increase diffusion speed) and time. Applying a high voltage will however heat up the battery, increase gassing to a level where the active material is pushed out of the plates and, in case of VRLA batteries, cause venting which will dry out and destroy the battery.

So what does this mean in terms of absorption voltage and absorption time?
We can distinguish between 3 groups of batteries:

1) **Flooded lead-antimony batteries**
Here we have a rather wide trade-off band of absorption voltage against time, ranging from 2.33 V / cell (14 V) and a long absorption time to 2.6 V / cell (15.6 V) and a much shorter absorption time.
To avoid excessive gassing, charge current should be limited to at most C / 5 (20 % of the rated capacity) or, even better, C / 10 of the capacity of the battery (for example 40 A for a 400 Ah battery) once the gassing voltage has been reached. This can be achieved by either current limiting or by limiting the rate of voltage increase to about 0.1 V per cell per hour (0.6 V per hour for a 12 V battery or 1.2 V per hour for a 24 V battery). See section 5.3.2.
It is also important to know that batteries do not need to be fully recharged after every discharge. It is very acceptable to recharge to 80 % or 90 % (partial state of charge operation, preferably including some gassing to limit stratification) on average and to fully recharge once every month.

2) The **Spiral cell AGM battery** stands apart because it is sealed and nevertheless accepts a wide absorption voltage range.

3) Other **VLRA batteries** have a limited absorption voltage range that should **never be exceeded**. Higher voltages will result in venting. The battery will dry out and be destroyed.

4.2.3. The float charge

After the battery has been fully charged it is kept at a lower constant voltage to compensate for self-discharge, i. e. to keep it fully charged.

As mentioned earlier, if maintained for long periods of time (several months) the float voltage may not deviate more than 1 % from the voltage recommended by the manufacturer, after compensating for temperature.
Excessive voltage results in accelerated aging due to corrosion of the positive plates. The rate of positive plate grid corrosion will roughly double with every 50 mV of increase in cell voltage (0.3 V respectively 0.6 V for 12 V and 24 V batteries).
Insufficient voltage will not keep the battery fully charged, which will eventually cause sulphation.

Regarding float voltage we must distinguish between flooded and VLRA batteries:

1) The recommendations for float charging **flooded batteries** vary from 2.15 V to 2.33 V per cell (12.9 V to 14 V for a 12 V battery). The flooded battery types that have been discussed have **not been designed for float charging over long periods of time** (i. e. several months or years).
When float charged at the higher end of the 2.15 V to 2.33 V range, service live will be shortened due to corrosion of the positive plate grids, and batteries with a high antimony content will need frequent topping up with demineralised water.
When float charged at 2.15 V per cell, aging and gassing will be under control, but a regular refreshing charge at a higher (absorption) voltage will be needed to maintain the fully charged state.
In other words: the high end of the 2.15 V to 2.33 V range is fine for a few days or weeks, but not for a 6 months winter period.

The following table shows how much water is lost due to gassing in case of a relatively new low antimony battery (gassing increases with age):

Battery (fully charged)	V / cell	Batt. V	Gas generation per 100 Ah battery capacity	Water consumption per 100 Ah battery capacity	Topping up interval	Water lost per charge cycle	Ah ”lost” per 100 Ah batt. capacity
Open-circuit	2.13	12.8	20 cc / h	0.1 l / year	5 y		44 / y
Float	2.17	13	25 cc / h	0.1 l / year	5 y		54 / y
Float	2.2	13.2	60 cc / h	0.3 l / year	1.5 y		130 / y
Float	2.25	13.5	90 cc / h	0.4 l / year	1 y		200 / y
Float	2.3	13.8	150 cc / h	0.6 l / year	10 m		300 / y
Absorption	2.33	14	180 cc / h	0.8 l / year	7 m	2 cc	2 / cycle
Absorption	2.4	14.4	500 cc / h	2.2 l / year	3 m	3 cc	3 / cycle
Absorption	2.45	14.7	1 l / h	4.2 l / year		4 cc	4 / cycle
Absorption	2.5	15	1.5 l / h	6.5 l / year			

Gas generation and water consumption is based on a 6 cell (= 12 V) battery.
The topping up interval is based upon 0.5 l of water lost per 100 Ah. The water surplus in the battery is approximately 1 l / 100 Ah.

The formulas:
a) 1g of water can be decomposed into 1.85 l of oxygen + hydrogen gas
b) 1 Ah “lost” due to gassing generates 3.7 l of gas in a 6 cell (= 12 V) battery

The table shows that a float voltage of 13.5 V (13.5 V is an often recommended float level for the flooded batteries under consideration here, as lower float voltages do not completely compensate self-discharge) or higher will result in topping up needed more than once a year. Please also note that batteries with more antimony doping will consume 2 to 5 times more water!

To my opinion, instead of trying to find a delicate balance between insufficient voltage to compensate for self-discharge and to much gassing at a higher voltage, it would be better to leave the battery open circuited and recharge, depending on temperature, at least once every 4 months, or to reduce float voltage to a very low level, for example 2.17 V per cell (13 V respectively 26 V), and also recharge regularly at a higher voltage. This regular refreshing charge should be a feature of the battery charger. See section 5.3.2.

2) All **VLRA batteries** mentioned can be float charged for long periods of time, although some studies have shown that a treatment similar to the one proposed here for flooded batteries will increase service life (see for example “Batterie Technik” by Heinz Wenzl, Expert Verlag, 1999).

4.3. Equalizing

When not charged sufficiently, batteries will deteriorate due to the following reasons:
- sulphation
- stratification (flooded batteries only)
- cell unbalance, (see sect. 2.5.6).

Batteries will in general reach their fully charged state, including equalization, during the absorption charge or when float charged for a sufficiently long period of time.
If they have been used in partial state of discharge mode for some time, they will recover by:
- repetitive cycling and charging with the appropriate absorption voltage and time
- an absorption or float charge during a longer period of time
- a real equalization charge, see below.

An equalizing charge is done by first charging the battery as usual, and then continue charging with a low current (3 % to 5 % of its Ah capacity, i. e. 3 to 5 A for a 100 Ah battery) and let the voltage increase to 15-16 V (30-32 V for a 24 V battery) until the specific gravity (SG) stops increasing. This will take 3 to 6 hours and by then all cells should give the same reading. Be sure to isolate the battery from all loads sensitive to over-voltage during this period.
Especially heavy-duty traction batteries may need a periodic equalization charge.

How often should a battery be equalized?
It all depends on type and usage. For batteries with high antimony doping, the best way to find out is to check SG after a normal charge:

- If all cells are equal and at 1.28, there is no need to equalize
- If all cells are between 1.24 and 1.28, it would be good to equalize when convenient, but there is no urgency
- If the SG of some cells is less than 1.24, an equalization is recommended.
- If all cells are below 1.24, the battery is undercharged and the absorption time or voltage should be increased.

On VLRA batteries and low antimony flooded batteries the SG cannot be measured, respectively the reading will be unreliable. The easiest way to check if they are really charged to the full 100 % is to monitor the charge current during the absorption charge. The charge current should steadily decrease and then stabilise: a sign that the chemical transformation of the active mass has been completed and that the main remaining chemical activity is gassing (decomposition of water into oxygen and hydrogen).

4.4. Temperature compensation

As has already been mentioned in sect. 2.5.9, temperature is of importance when charging batteries. The gassing voltage and consequently the optimum absorption and float voltages are inversely proportional to temperature.

This means that in case of a fixed charging voltage a cold battery will be insufficiently charged and a hot battery will be overcharged.

Both effects are very harmful. Deviations of more than 1 % of the correct (temperature dependent) float voltage can result in a considerable reduction of service life (according to some studies up to 30 % when the battery is float charged for long periods of time), particularly if the voltage is too low and the battery does not reach or stay at 100 % charge, so that the plates start to sulphate.
On the other hand over-voltage can lead to overheating, and an overheated battery can suffer “**thermal runaway**”. Because the gassing voltage decreases with increasing temperature, the absorption and float charge current will increase when the battery heats up, and the battery becomes even hotter, etc. Thermal runaway quickly results in destruction of the battery (the excessive gassing pushes the active mass out of the plates), and there can be a risk of explosion due to internal short-circuits and high quantities of oxygen and hydrogen gas coming out of the battery.

The charging voltage, as quoted by European battery manufacturers, applies at 20°C battery temperature and may be kept constant as long as the temperature of the battery remains reasonably constant (15°C to 25°C).

Although manufacturers’ recommendations differ to some extent, a temperature compensation of - 4 mV / °C per cell is a generally accepted average. This means – 24 mV / °C for a 12 V battery and – 48 mV / °C for a 24 V battery.

Where the manufacturer specifies an absorption voltage of for example 28.2 V at 20°C, then at 30°C the absorption voltage must be reduced to 27.7 V. This is a difference of 0.5 V that certainly cannot be neglected. When in addition to an ambient temperature of 30°C, the internal temperature of the battery rises another 10°C, which is quite normal during charging, the absorption voltage must be reduced to 27.2 V. Without temperature compensation the charge voltage would have been 28.2 V which would quickly destroy a gel or AGM bank worth some ten thousand dollars!

What the above means is that **temperature compensation is important**, and must be implemented, especially on large, expensive house batteries, and when a high rate of charge current is used.

All charging voltages mentioned in this and in other chapters are subject to temperature compensation.

4.5. Overview

The following table gives an overview of how batteries can be recharged after a 50 % discharge. In practice recommendations can vary from one manufacturer to another and also depend on how the battery is used. **Always ask your supplier for instructions!**

Type	**Alloy**	**Approximate absorption time at 20°C after 50 % DoD**	**Float voltage at 20°C**
Automotive	Antimony (1.6 %)	4 h at 2.50 V / cell (15.0 V) 6 h at 2.45 V / cell (14.7 V) 8 h at 2.40 V / cell (14.4 V) 10 h at 2,33 V / cell (14 V)	2.33 V / cell (14 V) after a few days decrease to: 2.17 V / cell (13 V)
Spiral-cell	Pure lead	4 h at 2.50 V / cell (15.0 V) 8 h at 2.45 V / cell (14,7 V) 16 h at 2.40 V / cell (14.4 V) 1 week at 2.30 V / cell (13.8 V)	2.3 V / cell (13.8 V)
Semi-traction	Antimony (1.6 %)	5 h at 2.50 V / cell (15.0 V) 7 h at 2.45 V / cell (14.7 V) 10 h at 2.40 V / cell (14.4 V) 12 h at 2.33 V / cell (14 V)	2.33 V / cell (14 V) after a few days decrease to: 2.17 V / cell (13 V)
Traction (tubular-plate)	Antimony (5 %)	6 h at 2.50 V / cell (15.0 V) 8 h at 2.45 V / cell (14.7 V) 10 h at 2.40 V / cell (14.4 V)	2.3 V / cell (13.8 V) after a few days decrease to: 2.17V / cell (13 V)
VRLA-gel Sonnenschein Dryfit A200	Calcium	4 h at 2.40 V / cell (14.4 V) voltage not to be exceeded!	2.3 V / cell (13.8 V)
VRLA-gel Sonnenschein Dryfit A600	Calcium	4 h at 2.34 V / cell (14.04 V) voltage not to be exceeded!	2.25 V / cell (13.5 V)

Notes:

1) In practice, when shore power is not available, batteries on a boat tend to be charged as fast as possible, with shortened absorption time or no absorption period at all (partial state of discharge operation). This is quite acceptable, as long as a charge to the full 100 % is applied regularly (see sect. 4.3).

2) When charging at a voltage exceeding the gassing voltage, either the current should be limited to at most 5 % of the Ah capacity of the battery, or the charge process should be carefully monitored and the voltage reduced if the current tends to increase to more than 5 % of the Ah capacity.

3) When float charging batteries at 2,17 V per cell a regular refreshing charge will be needed.

4) About service life and overcharging:
Starter- or bow thruster batteries are often charged in parallel with the house battery (see sect. 5.2). The consequence is that these batteries will frequently be charged at a high voltage (15 V or even more) although they are already fully charged. If this is the case, VRLA batteries should not be used for this purpose because they will start venting and dry out. The exception is the spiral-cell VLRA battery, that can be charged at up to 15 V without venting.
Flooded and spiral cell batteries will survive, but age faster. The main aging factor will be corrosion of the positive plate grid, and the corrosion rate doubles for every 50 mV of voltage increase per cell. This means that an Optima battery for example, which would last 10 years at its recommended float voltage of 13.8 V, would age 4 times faster at 15 V (((15 – 13.8) / 6) / 0.05 = 4), reducing service live to 2.5 years if it would constantly be charged at 15 V. Similar results are obtained for flooded batteries. While this calculation is theory and has not been tested in practice, it nevertheless shows that regular overcharging during short periods (in practice only during the absorption charge period of the house battery) of starter or bow thruster batteries does not decrease service live to an unacceptably low period.

4.6. Conclusion: how should a battery be charged?

As mentioned earlier, there is no simple recipe that can be applied to all batteries and operating conditions. Also, there is no greater variety of operating conditions and types of batteries than can be found on a yacht.

To get a better idea of how batteries are used and what this means for charging, let us again take the example from section 2.4. Let us assume that the yacht has 3 batteries on board: a house battery, a starter battery and a bow thruster battery.

How are these different batteries used, and how should they be charged?

4.6.1. The house battery

In sect. 2.4 and 2.5.6 three conditions of use were described:

1) Cyclic use, in the partial state of charge mode, when sailing or at anchor. Important here is charging as fast as the battery permits. Temperature compensation is a must to prevent early failure due to overheating and excessive gassing.

2) A mixture between float use and short, shallow discharges when motoring or moored. The risk here is that a 3-step alternator regulator (when motoring) or a charger, (when connected to shore power) is frequently triggered by these shallow discharges to go into bulk and then absorption mode. The result could be that the battery is continually subjected to absorption charging and will be overcharged. Therefore, ideally, the length of the absorption phase should be in accordance with the preceding DoD. See section 5.3.2. for the **adaptive charging** method, a Victron Energy innovation.
Flooded batteries, if being float charged without any discharge occurring, should be switched to the lower 2.17 V per cell level and be regularly topped up with an absorption charge at 2.4 V / cell or more. Again, see section 5.3.2.

3) For long periods of time the battery is left open circuited or float charged, in wintertime for example. As discussed in sect. 4.2.3, most **flooded batteries** will deteriorate quickly if float charged at 2.3 V per cell for a long time. Ideally charge voltage should be lowered to between 2.15 V and 2.2 V per cell, or left open circuited and recharged regularly. When the average temperature is 20°C or less, at least every 4 months. At higher temperatures they should be recharged more often.
From my personal experience and from numerous discussions with boat owners, I do also prefer to leave **sealed Exide/Sonnenschein Dryfit A200 batteries or equivalent** open circuited or on a lower than recommended float level instead of float charging them at 13.8 V, because, although in theory they can be float charged during long periods of time, only too often the result was damage due to overcharging.

4.6.2. The starter battery

The starter battery is subject to 2 conditions of use:

- Shallow discharge due to starting the engine once or twice a day.

- No discharge at all. The best would be no recharge either, apart from an absorption charge once in a while.

In practice however the starter battery will very often be charged in parallel with the house battery, which is acceptable as long as the right type of battery is used and some decrease of service live is accepted (see note, sect. 4.5).

4.6.3. The bow thruster battery

When used, discharge can be deep, and fast recharge will be required. In general the most practical solution is to charge the bow thruster battery in parallel with the house battery. Often spiral-cell batteries are used, because of their very high peak current capability. These same batteries will accept a wide recharge voltage range and are very tolerant to overcharging.

5. Charging batteries with an alternator or a battery charger

5.1. The alternator

The main engine of a boat is normally fitted with a standard automotive alternator. Standard automotive alternators have a built-in regulator with temperature compensation. The temperature is measured in the regulator itself. This is a suitable arrangement for cars, where the battery temperature will be roughly the same as the temperature of the regulator.

Moreover, in cars the battery will virtually always be fully charged. The battery will only be discharged to a small extent during engine starting. After that the alternator delivers sufficient power, even with the engine idling, to supply all consumers and to recharge the battery. Because the battery is actually never deeply discharged, and in general plenty of charging time is available, the absorption phase discussed in chapter 4 is superfluous. The alternator charges with a current dependent on engine rpm until the pre-set float voltage is reached. Then the alternator transfers to constant voltage. Generally the voltage is pre-set at 2.33 V / cell at 20°C, i.e. 14 V for 12 V systems and 28 V for 24 V systems.

This charging system works perfectly given the following conditions:
- the battery is a flat-plate automotive battery
- the battery is nearly always fully charged
- the temperature difference between the regulator on the alternator and the battery is limited
- the voltage drop along the cable between battery and alternator is negligible (i.e. less than 0.1 V, including switches, isolators, etc.).

Problems occur as soon as one of the above conditions is no longer fulfilled.

The following sections shortly discuss the practice of charging batteries with an alternator.

For an exhaustive discussion of alternators, alternator regulators, isolators and other related equipment, I recommend reading Nigel Calder’s standard work “Boatowners Mechanical and Electrical Manual” as well as a visit to the websites of Ample Power (amplepower.com), Balmar (balmar.net) and Heart Interface (xantrex.com).

5.2. When the alternator has to charge more than one battery

5.2.1. Introduction

The bare minimum on a boat is two batteries: one to start the main engine and a house (or accessory or service) battery. To make sure that the engine can always be started, all accessories (navigation equipment, lighting, autopilot, refrigerator, etc.) are supplied by the house battery.

The starter battery (sometimes 2, for 2 engines) should have no other load than the starter motor of the main engine and must never be allowed to discharge, otherwise the engine cannot be started.

Often there is a third battery on board, the bow thruster battery, and there may be even a fourth, the electronics (navigation) battery.

The batteries are separated from one another by relays, diode isolators, or other devices that will be briefly discussed in the next sections. In larger systems the starter battery often has its own dedicated alternator. Battery voltages may also be different, some 12 V (starting and electronics) others 24 V (house and bow thruster)

5.2.2. The problem

When using a standard automotive alternator-regulator to charge several batteries simultaneously, the following problems arise:

- In a boat, cable runs are often much longer than in cars so that there is more voltage drop between alternator and battery (example: the voltage drop along a 5 metre long, 10 mm^2 cross-section cable is 0.5 V at a current of 50 A).

- Diode battery isolators cause additional voltage drop: 0.4 to 0.8 V for silicon diodes and 0.1 to 0.4 V for FET transistors used as diodes.

- The alternator in the engine compartment registers an ambient temperature of 40°C or even higher while the house battery, lower down in the boat, is much colder e.g. 20°C. This results in an additional under-voltage of approx. 0.6 V or even 1.2 V for 12 V or 24 V systems respectively.

- The house battery will usually be deeply discharged and should really be charged with a high (absorption) voltage. This is particularly the case when the alternator on the main engine is the only source of power and runs briefly every day to charge the batteries.

- In contrast, the starter battery and often also the bow thruster battery are practically always fully charged and do not need any absorption charging.

- Often different battery types are used for starting, for the bow thruster and for house service. These different batteries all have their own charging recipe.

5.2.3. A wide range of solutions

It would be exaggerating to say that there are as many solutions as boats, but there are certainly many ways to, more or less, overcome the above-mentioned problems. Several, but certainly not all, will be discussed hereafter:

5.2.3.1 Keeping it simple and low cost: the microprocessor controlled battery combiner

Let the alternator charge the starter battery, and connect the service battery to the starter battery with a battery combiner (for ex. a Cyrix battery combiner from Victron Energy). When one of the 2 batteries is being charged (the starter battery by the alternator or the service battery by a battery charger), the Cyrix will sense the increasing voltage and connect both batteries in parallel. As soon as the voltage decreases the Cyrix will disconnect the batteries from each other.
The advantage is simplicity and cost: the alternator does not have to be modified or replaced. The drawback is a somewhat longer recharge time of the house battery because bulk charge will stop at approximately 30 % DoD (or worse in case of important voltage drop in cabling or a low alternator voltage due to high temperature) and then be followed by float charge. This means that the battery will be cycled between 30 % and 70 % DoD. The solution is to oversize the house battery by 20 % to 50 % and do a 100 % recharge when shore power is available.

5.2.3.2 Increase alternator voltage

Most alternators with built-in regulators can be modified so as to deliver a higher voltage. Adding a diode in series with the voltage sense input of the regulator increases output voltage by approx. 0.6 V.
This is a job for the specialist. We will not dwell on it here, but it is a low cost improvement that, together with 5.2.3.1, will charge batteries quite fast. Severe overcharging is a risk only in case of very intensive motoring every day, and even that problem can be solved by temporarily switching off the alternator (but **never** disconnect the main output of the alternator from the battery with the engine running, because the resulting voltage spike might damage the rectifier diodes in the alternator).

5.2.3.3 A multi-step regulator with temperature and voltage compensation

When choosing a multi-step regulator (bulk-absorption-float, see chapter 4), I would suggest to go for the best and choose a model with:

- Voltage sensing. This requires additional voltage sensing wires to measure and regulate voltage directly on the terminal posts of the house battery or on the DC bus. Voltage-drop in cabling and isolators is then automatically compensated.

- Temperature compensation. This requires a temperature sensor to be mounted on the house battery.

This solution is often used when an additional high output alternator is fitted.

5.2.3.4 The starter battery.

The solutions as suggested in 5.2.3.2 or 5.2.3.3 will improve charging of the house battery, but what about the starter battery?

Let us assume that when the main engine is running, the batteries are charged in parallel by using battery combining relays, or a diode or FET isolator. Nearly all of the charging current will then flow to the house battery because this battery has the greatest capacity, the lowest internal resistance, and is partially or fully discharged. This means that the voltage drop across the isolator and wiring from alternator to house battery will be higher than from alternator to starter battery. It might very well be that to achieve an absorption voltage of, say, 14.4 V on the house battery, the output voltage of the alternator has to increase to 15.4 V (i. e. a voltage drop of 1 V from the alternator to the house battery).

With 15.4 V on the alternator output the voltage on the starter battery could very well be 15 V (!) because only a small percentage of the current flows to the starter battery. The result is that the starter battery, already fully charged, is “forced” to 15 V although it should be floated at, say, 13.8 V.

What to do?

a) Improve the situation by reducing voltage loss as much as possible and leave it at that. The starter battery might need early replacement, depending on how frequently the conditions referred to above occur and which type of starter battery is used.

Gel batteries or flat plate AGM batteries are not recommended here, because they are relatively sensitive to overcharging (they will start venting and dry out). A wet battery (low cost) will survive if topped up with water when needed, and an Optima AGM spiral cell battery is also a good option because of its wide charge voltage range and its tolerance to overcharging. See sect. 4.5 for an estimate of battery service live when overcharged.

b) Add 1 or 2 diodes in the wiring to the starter battery to reduce voltage. Now the risk becomes undercharging, if the service battery is only occasionally charged sufficiently to reach the absorption voltage level (think of a sailing yacht on a long trip).

c) Insert a series regulator in the wiring to the starter battery, like the “eliminator” from Ample Power.

d) Charge the starter battery with a separate dedicated alternator.

5.2.3.5 The bow thruster battery

Optima is the ideal battery for this application. It can deliver extremely high currents and also withstands high recharge currents as well as a wide recharge voltage range. So alternative a) of 5.2.3.4 would be advisable.

5.3. Battery chargers. From AC current to DC current

5.3.1. Introduction

In chapter 3 and 4 we have discussed how batteries should be charged, and how batteries will fail if not properly charged.
In section 5.2 it became apparent that charging batteries with the alternator on the main engine is a question of compromising.

With battery chargers it’s somewhat less complicated, because most high output chargers have temperature and voltage sensing facilities. Some also have 2 or 3 outputs. And nearly all have 3-step charging.
There is a great variety of chargers to choose from and it is also much easier to install dedicated chargers for the different batteries on board than adding additional alternators on the main engine.

5.3.2. Optimised charging

I hope it became clear from the previous chapters that charging batteries requires careful consideration, especially when conditions of use do change over time.

Victron Energy has incorporated in its latest battery chargers the knowledge that resulted from practical experience, discussions with battery manufacturers, and numerous lab tests on a wide range of batteries.

The innovation of the charger is in its microprocessor controlled **‘adaptive’** battery management system:

- The user can make his choice between 5 different charging recipes depending on which battery type has to be charged. All recipes can be modified to fit a particular battery type and brand.

- When recharging a battery, the Phoenix charger will automatically adjust absorption time to the preceding DoD. When only shallow discharges occur (a yacht connected to shore power for example) the absorption time is kept short to prevent overcharging. After a deep discharge the absorption time is automatically increased to make sure that the battery is fully recharged.

- If the absorption voltage setting exceeds 14.4 V, the ***BatterySafe*** mode is activated: the rate of increase of voltage once 14.4 V has been reached is limited in order to prevent excessive gassing. The ***BatterySafe*** feature allows for very high charge rates without risking damage due to excessive gassing.

- The charging recipes for flooded batteries include two float charge levels. If only very shallow discharges occur, a float level of 2.3 V / cell (13.8 V respectively 27.6 V) is maintained, with regular short absorption charges. In case of no discharge at all, after a time which depends on the intensity of previous use, the charger switches to the ***Storage*** mode: the float level is decreased to 2.17 V / cell (13 V respectively 26 V), with a regular short absorption charge. The ***Storage*** mode will carry flooded batteries through their winter rest without any additional care needed (except for topping up, if needed, with demineralised water before the winter rest starts!).

5.3.3. Charging more than one bank

The problem has been discussed under section 5.2. There are 2 solutions to the problem. The second best solution is the multiple output battery charger

5.3.3.1 The multiple output battery charger

In its simplest and most common configuration a multiple output battery charger has 2 or 3 outputs, which each can supply the full rated output current and are isolated from each other by diodes. The charge voltage is regulated on the primary side of the diodes and is slightly increased to compensate for the average voltage drop over the diodes. Including the cable to the battery terminals the voltage drop at full output current can exceed 1.5 Volt. At close to no load the voltage drop will reduce to less than 0.5 Volt. This means that a charge voltage of for ex. 14.4 V will drop to 13.4 V at the full output current. This is OK as long as during charging DC loads on the system are small or nonexistent: at the end of the charge cycle the current will drop off and the 14.4 V absorption voltage will eventually be reached.

Temperature compensation
Temperature compensation will not be accurate because the different banks will also have different temperatures. Temperature compensation is especially important in case of sealed VRLA batteries, see section 4.4.

Voltage sensing
Compensation of the voltage drop by measuring the charge voltage directly on the terminals of one of the batteries will result in a perfect charge of one bank, and possibly overcharging others, see for ex. note 4 of section 4.5.

5.3.3.2 A dedicated charger for each battery

This is the best solution, at a price. A compromise can be to take good care of the expensive house bank, if needed including temperature compensation and voltage sensing, and to use a smaller multi output charger for the other batteries.

5.3.3.3 The microprocessor controlled battery combiner

Charge the expensive house bank with a good charger, including temperature compensation and voltage sensing. And connect other batteries to the house battery with microprocessor controlled battery combiners, for ex. the Cyrix battery combiners from Victron Energy.
The Cyrix will also make sure that all batteries are parallel connected to the alternator when the main engine is running, see 5.2.3.1.

6. Electric equipment and energy consumption

6.1. Introduction

Now that we know, more or less, how to charge batteries, it is time to discuss the consumers, which will discharge the batteries.
In order to better understand the impact on energy consumption of the different consumers on board, it is advisable to think in 3 categories:

- **Continuous consumers**, which could for example, be the standby power taken by the VHF or the SSB, the refrigerator and the freezer.

- **Long duration consumers** (navigation lights, autopilot, cabin lighting, water maker, air conditioning) that need power from between one hour to several hours a day.

- **Short duration consumers** (pumps, electric winches, bow thruster, microwave, washing machine, dishwasher, electric stove) that need power for between a few seconds up to, say, one hour per day.

In my experience everybody, myself included, tends to underestimate the daily energy consumption of continuous and long duration consumers and to overestimate energy consumption of short duration consumers.

6.2. Power and energy

Especially when the source of electricity is a battery, it is important to differentiate between power and energy.

Power is instantaneous, it is energy per second, and is measured in Watts (W) or Kilowatts (1 kW = 1000 W).

Energy is power multiplied by time. A battery stores energy, not power.
Low power but consumed over a long period can result in a lot of energy consumed and drain a battery. Power is measured in Watt-hours (Watts x hours, or Wh) or Kilowatt-hours (1 kWh = 1000 Wh).

Energy is also the product of battery capacity (Ampere-hours) and voltage: Wh = Ah x V and
kWh = Ah x V x 1000.

So a power of 2 kW during 1 hour is 2 kW x 1 hour = 2 kWh of electric energy, and will drain
2 kWh / 12 V = 2000 Wh / 12 V = 167 Ah from a 12 V battery.

2 kW during 1 second (i. e. 1 / 3600 of an hour) amounts to (2000 / 3600) / 12 = 0.046 Ah. Next to nothing!

2 kW during 1 minute (i. e. 1 / 60 of an hour) amounts to (2000 / 60) / 12 = 2,7 Ah. A notebook battery would do this (if it could deliver very high currents)!

2 kW during 10 hours will drain 2000 x 10 / 12 = 1667 Ah. A huge battery!

As a preparation for the chapters to come, some examples of power and energy consumption of household appliances and other equipment are discussed in the next sections.

6.3. Refrigeration

6.3.1. Introduction

More often than not, refrigeration on board is a nightmare, or at least a headache.

On small yachts the refrigerator often takes more energy from the battery than all other equipment together.
On medium sized yachts it is the refrigerator plus freezer that will drain the battery.
And on larger yachts it is because of the air conditioning that a generator has to run day and night.

In order to understand why, and see whether anything can be done about it, some theoretical background is needed. This is the subject of the next section.

6.3.2. Theory of the heat pump

Nearly all refrigeration systems are of the compressor heatpump type.

Operation is as follows:
The compressor, driven by a DC or AC electric motor compresses a gas (freon, until this was forbidden because it destroys the ozone layer in the upper atmosphere) which is cooled down in what is called the condenser. The condenser often is a small radiator with a fan in the cupboard under the sink, or it is a much larger naturally ventilated radiator at the back of the refrigerator (normal household type refrigerator), or it can be water-cooled. In the condenser the gas condenses to liquid and in that process a lot of heat is taken from it. The liquid then moves to the evaporator, which is the cold plate in the refrigerator or freezer. There the pressure is reduced and the liquid evaporates. To evaporate a lot of heat has to be absorbed; this heat is removed from the refrigerator or freezer. The gas then goes to the compressor, and so on.

The amount of energy needed for drawing a certain quantity of heat from the surroundings with a heat pump may be calculated with the formula;

$CoP = n_r \times n_c = n_r \times Tlow / (Thigh - Tlow)$

where CoP is the Coefficient of Performance, Tlow is the temperature of the evaporator expressed in degrees Kelvin (=°C + 273), Thigh is the temperature of the condenser, likewise expressed in degrees Kelvin, and n_r is a factor (the efficiency, always less than 1) which gives the CoP in practice compared to the theoretical CoP n_c.
(Note: the CoP formula used here is a simplification of what happens in practice, but it is nevertheless an adequate tool to find out what measures can be taken to reduce electricity consumption)

An example for a refrigerator:

Temperature cold side: -5°C i.e. Tlow = 268°K (this is not the average temperature in the refrigerator but the temperature of the evaporator or cold plate in the refrigerator).
Temperature hot side: 45°C i.e. Thigh = 318°K
Efficiency: 25 %

Then the CoP is:

$CoP = 0.25 \times 268 / (318 - 268) = 1.34$

This means that for every kWh of heat that leaks in through the refrigerator’s insulation, or is drawn away from food or drink put into the refrigerator while still warm, 1 / 1.34 = 0.75 kWh of electric energy is needed to “pump” this heat out again.

6.3.3. The refrigerator and freezer in practice

When running, the average compressor motor of a refrigerator or freezer takes about 50 W, or 4.2 A from a 12 V battery. The compressor motor is controlled by a thermostat that switches it on when the temperature increases to a pre-set value, and switches it of again after the temperature has been brought down to a few degrees below the pre-set value. The on / off ratio is called the duty cycle.
A duty cycle of 100 % results in a daily capacity drain from a battery of 4.2 A x 24 h = 101 Ah. A nightmare!
A duty cycle of 50% results in 50 Ah daily consumption and a duty cycle of 25 % translates to 25 Ah daily consumption.

What we want is low energy consumption. How can this be achieved?

1) **Improve the CoP**, either by decreasing the temperature difference between the evaporator and the condenser, or by increasing the efficiency of the compressor.

If for example the temperature of the condenser were to be reduced by outside water cooling to 20°C (this requires a high quality water cooled condenser), instead of the 45°C which is not uncommon when the evaporator sits in the cupboard under the sink, then we would have:

CoP = 0.25 x 268 / (293 – 268) = 2.68

So, now only 1 / 2.68 = 0.37 kWh is needed per kWh of heat leakage. In other words: 50 % less electricity needed!

Further improvement would be achievable by increasing the surface of the evaporator in the refrigerator so that a temperature of a few degrees above 0 cools the fridge to the same temperature as the -5°C in our example.

And then the efficiency of the compressor and motor could be improved. This is a difficult one, as all small compressors have similar specifications.

2) **Improve insulation**
Let us first look at how much energy is needed to cool down food or drinks in a refrigerator.

It is important to know here that the specific heat of water is 1.16 Wh per °C.
The specific heat of other drinks and food is similar. This means that to cool down 1 litre of water or other drinks, or 1 kg of food, by 1°C, 1.16 Wh of heat has to be removed.

So, if you were to put 5 litres of mineral water, warmed up in the sun to 35°C, into the refrigerator and allow it to cool to 10°C, then 5 x (35 - 10) x 1.16 = 0.145 kWh of heat must be drawn from the refrigerator.
At a CoP of 1.34, the amount of electrical energy needed is 0.145 / 1.34 = 0.108 kWh, i.e.
0.108 / 12 = 9 Ah out of a 12 V battery. Not to bad, 9 Ah, even though we have assumed a very low CoP.

Conclusion:
It is bad insulation and / or a bad CoP, and not cooling down the drinks and food that are the reason for high power consumption of the refrigerator and freezer on board.
Therefore: **insulate!**

The benchmark for energy consumption is standard household equipment, which nowadays has excellent insulation:
The yearly energy consumption of a modern refrigerator is about 100 kWh, which translates to 100 / 365 = 0.27 kWh per day, or 0.27 x 1000 / 24 = 11 W (!) average power consumption. If fitted with a 12V DC compressor, Ah consumption would be 0.27 x 1000 / 12 = 23 Ah per day from a 12 V battery.
The yearly energy consumption of a modern freezer is about twice as high, and would take 46 Ah per day from a 12 V battery.

If permanent AC power from an inverter is available anyway (see chapter 8) it is certainly advisable to install a standard household refrigerator and freezer.

6.3.4. Air conditioning

Air conditioning requires enormous amounts of electric energy. Especially small airco sets, with 1 kW to 5 kW cooling power (3.400 to 17.000 Btu) in general have a low efficiency. If a generator is running anyway, no problem, except perhaps for fuel consumption. But as soon as soon as air conditioning also has to run on battery power, efficiency becomes extremely important.

Just like the refrigerator and freezer, an air conditioner is a heat pump with a compressor-motor, a condenser (on a boat always water-cooled because of the high power involved) and an evaporator.

What does the CoP formula tell us when applied to air conditioning?
Let us assume:
-condenser temperature: 27 °C (cooling water of 25 °C)
-evaporator temperature: 15 °C (room temperature of 25 °C)
-efficiency: 25 %

Then CoP = 0.25 x 288 / (300 – 288) = 6

Well, in practice the CoP of a small airco system ranges between 2 and 3!
This has mainly to do with a much higher condenser temperature and a much lower evaporator temperature than we have assumed.

Assuming a CoP of 2.5, 2 kW of cooling power will require 2 / 2.5 = 0.8 kW of electric power, which would, in 10 hours time, draw 0.8 x 1000 x 10 / 24 = 333 Ah from a 24 V battery.

6.4. Electric winches, windlass and bow thruster

More and more common, even on smaller boats, these products will draw very high currents, but for a short period.

- An electric winch or windlass on a 15 m boat is in general powered by a 1 horsepower motor (1 HP = 0.736 kW) and will draw at nominal load 736 / 12 = 61 A from a 12 V battery (current draw can increase to several hundreds Amps if the winch is under a near stalling load!). If operated for 1 minute, the Ah consumption will be 61 / 60 = 1 Ah (see sect. 6.2). So energy consumption is not the issue, but it is very important to properly dimension the fuse, contactors, cabling, and batteries to withstand the high currents and eliminate the risk of fire due to overheating.

- A bow thruster will often take even more power, for example 300 A from a 24 V battery if fitted with a 10 HP motor. Current draw will be 10 x 736 / 24 = 300 A. One minute of operation will result in 300 / 60 = 5 Ah taken from the battery.

6.5. A battery powered washing machine and dishwasher?

A washing cycle at 60 °C with a standard household washing machine takes 0.9 kWh of electric energy, or 900 / 24 = 38 Ah from a 24 V battery. At 40°C this reduces to 0.6 kWh or 600 / 24 = 25 Ah from a 24 V battery. The energy required for dishwashing is of the same order of magnitude.

Most of the energy goes into heating the water (hence the large difference in energy consumption between a 60 °C cycle and a 40 °C cycle), and using hot fill (supplying the washing machine and dishwasher with water at the right temperature instead of cold water) would further reduce energy consumption to a few hundred Wh!

A standard household dryer, though, takes 3 kWh, which means 3000 / 24 = 125 Ah from a 24 V battery. This is because preheated air is used to evaporate all the remaining moisture. And I do not know of any dryer heating the air with a hot water heat exchanger instead of an electric heater…

A wash-dry cycle of a small washer-dryer as is often used on boats will take approx. 2.7 kWh.

6.6. Ever thought that electric cooking on battery power was feasible?

I didn’t, until I made the calculations and verified in practice.

And since that time I have a two-hob electric induction stove on my trimaran, powered by a 24 V 200 Ah house battery and a 2.5 kW Multi.

When compared to other electric stove, my preference goes to induction. With electric induction it is not the hob that is heated, but the bottom of the pan directly. The heating is therefore extremely fast and the hob does not become hotter than the bottom of the pan, which increases safety.
For that reason electric induction is also 20 % more efficient than other electric stoves (this is not just theory, I have measured it).

But now the theoretical background, which is very simple:
As stated in section 6.3.3, the heat capacity of water is 1.16 Wh per °C. Bringing 1 litre of water of 20 °C to the boil would therefore take 1.16 x (100 – 20) = 93 Wh. In practice it takes more than 100 Wh, depending on the heat capacity of the pan and other losses, which can be reduced by starting with warm water from the boiler instead. So the figure to remember is 100 Wh per litre.

And now the actual cooking:
Today the meal is spaghetti with a home made sauce and a pudding to finish. We are cooking for 4 persons.

For the spaghetti we bring 4 litres of water to the boil, add the spaghetti, bring the pan to the boil again and leave it boiling slowly for 8 minutes. Power consumption: 400 Wh to boil the water, 100 Wh to boil it once more, and 400 W for 8 minutes to keep the spaghetti boiling, total 400 + 100 + 400 x 8 / 60 = 550 Wh.

For the sauce we fry the onions (150 Wh), add the meat and fry again (150 Wh), add fresh tomatoes, herbs, etc and bring the sauce to the boil (1 litre, so 100 Wh) and leave the sauce simmering for 20 minutes (200 W during 20 minutes), total 150 + 150 + 100 + 200 x 20 / 60 = 470 Wh.

For the desert we heat 2 litres of cold milk right from the refrigerator (300 Wh), plus 3 minutes of simmering (30 Wh), total 300 + 30 = 330 Wh.

Total energy needed: 550 + 470 + 330 = 1350 Wh, or 1350 / 24 = 56 Ah from a 24 V battery.

I have also verified the above in practice and the result is that for most meals with 3 hot courses and intended for 4 persons indeed 1200 to 1400 Wh, or 50 to 60 Ah from a 24 V battery is needed.

6.7. The diving compressor

I like diving. What I do not like is that after the dive I have to lift anchor, head for a harbour and lug my bottles to a diving club in order to have them refilled. Why not install a diving compressor on board?

A small diving compressor is powered by an electric motor of around 3 kW, and the start-up current is about 10 times the rated current. It will trip the shore power circuit breaker in the harbour, and a diesel generator will have to be substantially over dimensioned to start it.

The solution is to drive the compressor with a 3-phase motor and ad a variable frequency drive, with a three phase output to drive the motor and a single phase input to connect to an inverter, diesel generator or shore power. The 1 to 3-phase frequency drive (readily available up to 3 kW output power from several frequency drive manufacturers, like ABB, Hitachi or Mitsubishi) will eliminate the start up surge and allow the 3-phase motor to be supplied by a single phase supply.

Can the house battery + an inverter be used to run the compressor?
The answer is yes. I do it myself all the time.
It takes about 30 minutes to fill a 10 l bottle, which translates to (3 kW / 24 V) x 0.5 = 62 Ah drained from a 24 V battery.

6.8. How to deal with the inrush current of AC electric motors

Electric motors rated in the kW range have very high inrush currents and an inverter or diesel generator has to be substantially over dimensioned to run them (examples: pumps, air conditioning, and the diving compressor discussed in the previous section). As discussed in the previous section, a solution is to use 3-phase motors and a 1 to 3-phase variable frequency drive.

6.9. Conclusion

The refrigerator, a continuous consumer of electricity, will if not carefully engineered, drain the battery and consume more energy than high power but short time consumers like a washing machine, dishwasher or even an electric stove.

7. Generators

7.1. AC Generators

7.1.1. A diesel engine will last longer if it has to work

In order to generate a stable 50 Hz or 60 Hz output, the diesel engine powering the generator must rotate at a fixed and stable frequency. For 50 Hz output this is 3000 rpm or 1500 rpm, depending on the number of poles of the generator (3000 rpm / 60 seconds = 50 rotations per second = 50 Hz). When a diesel engine runs at relatively high rpm and with nearly no load the internal temperature will be low and service life will be reduced.
It is therefore not recommended to run a genset 24 hrs per day, with nearly no load. And the noise, fumes and odours are not to look forward to either.

7.1.2. A hybrid or battery assisted AC system

A first improvement is to run the generator during periods of high power demand only, and install a battery and inverters to generate AC when the generator is off.

An even better system is obtained by operating one or more Phoenix Multi's or MultiPlus units in parallel with the genset (see for example par. 10.6).
The advantages are:
- uninterrupted AC supply
- relatively more load on the generator, less space needed, less noise and less weight because a smaller genset can be used: the MultiPlus will absorb peak loads taking energy from the battery, and recharge whenever "surplus" power is available (see for ex. par. 10.6.5. or "Achieving the impossible" and many other examples on our website).

7.1.3. Don't forget the problem of limited shore power

A washing machine, dishwasher, electric cooker, air-conditioning: it is all feasible with a big enough generator. But in Europe power from the shore side is often limited to 16 A or even less
(16 A x 230 V = 3,68 kW). Here also the MultiPlus can help to increase available power to the required level.

7.1.4. 3000 rpm or 1500 rpm (in a 60 Hz environment: 3600 rpm or 1800 rpm)

A, more expensive, 1500 rpm genset is the right choice if intensive use is to be expected.
A 3000 rpm genset is in general designed for a limited number of operating hours, and is not made to operate at full load for long periods of time.
Some generator suppliers are wildly optimistic about the maximum output of their product. A way to find out is to look for gensets from different suppliers but with the same engine and then compare the rated output.

7.2. DC Generators

Next to conventional 50/60 Hz AC generators, some generator suppliers are also offering DC generators. Outputs of up to 10 kW, which means a battery charging current of up to some 300 A at 28 V, are attainable.
DC generators are smaller and lighter, and have a higher efficiency than AC generators. Moreover, engine rpm can be harmonised with power demand, so that efficiency remains high even under partial load.
The idea is to use the DC generator to charge the batteries, and use inverters to supply the AC load. Sizing of the DC generator is a question of acceptable running hours per day.
Please keep in mind however that the battery should be sized for the huge charge current. For a charge current of 300 A for example, battery capacity should be 300 A / 5 = 1500 Ah (see par. 2.5.6.)
It should be noted here that some manufacturers of AGM batteries claim much higher charge currents without appreciable reduction of service life.

8. Micro power generation: thinking different

8.1. Introduction

For the purpose of this book micro power generation is defined as power generation for systems requiring, on average, between a few hundred Watts and up to 10 kW of electric power. Over a period of 24 hours this equates to in between 24 x 0.2 = 4.8 kWh and 24 x 10 = 240 kWh of electric energy per day.
As will be shown, 240 kWh is the upper range of the amount of electric energy needed by a few families to live comfortably, be it in a small community of one or a number of houses, in a mobile home or on board a boat.

It is within this range that several recent technical developments make it worthwhile to “rethink” power generation.

A very important characteristic of the application considered here is that the amount of electric power required will at times be nearly zero and at other moments increase to several times the average. When a petrol or diesel fuel powered AC generator is used to supply the required electricity, it has to be sized for the highest power demand that is to be expected, and therefore will run at practically no load during most of the time. Very inefficient in terms of wear and fuel consumption, not to speak about noise, maintenance and pollution.

A problem more specific to boats (and motor homes) is shore power. The rating of the shore power outlet is often insufficient to supply a washing machine, an electric stove or air conditioning. And when crossing the Atlantic voltage is different and frequency is 60 Hz instead of 50 Hz, or the other way round.

Of increasing importance on boats is also weight and volume.

In the following sections new technologies and concepts to improve the performance of micro power generation are presented and discussed.

8.2. New technology makes the DC concept more attractive

8.2.1. The DC concept

In the DC concept the battery is the hart of the system.
All power generated or taken from a shore power outlet is converted to DC or generated as DC. The sources of electric power are connected to a DC bus, to which the battery is also connected.
Likewise, all consumers are either DC or are supplied from the DC bus by an inverter.

In the DC concept the battery is a buffer of electric energy that compensates for any imbalance between energy suppliers and energy consumers.

In fact all smaller boats do use the DC concept:

Power is generated by one or more alternators on the main engine, and often also by alternate sources like solar or wind power, or a water generator. All sources of electric power are connected to a DC bus, to which the house battery is also connected. All consumers, such as navigation equipment, cabin lighting, etc. are supplied from the DC bus.

As electronic power conversion technology improves, more and more household appliances, which do require an AC supply, are also being connected to the DC bus, with an inverter.

In the next sections 2 new developments that substantially increase the attractiveness of the DC concept are presented.

8.2.2. DC generators

Next to conventional 50/60 Hz AC generators, some generator suppliers are offering DC generators. DC generators are smaller and lighter, and have a higher efficiency than AC generators. Moreover, engine rpm can be harmonised with current demand, so that fuel efficiency remains high even under partial load.

8.2.3. Unlimited inverter power

Sinusoidal inverters have now become generally accepted.

New is the possibility to connect inverters in parallel.
Victron Energy has developed inverters and inverter-chargers (bi-directional converters) that can be parallel connected in either single or three-phase configuration.
The parallelable inverter/ charger modules are the Multi 12/2500/120 and Multi 24/3000/70, which have a continuous output power of 2 kW at 12 V input and 2.5 kW at 24 V input respectively.
Up to 6 modules can be connected in parallel per phase. Taking as an example the 24 V model, the output power which can be reached is as follows:

Single phase	Continuous output	P30	Maximum output
6 x Multi i 24/3000	6 x 2.5 = 15 kW	18kW	30 kW

Three phase	Continuous output	P30	Maximum output
18 x Multi 24/3000	18 x 2.5 = 45 kW	54 kW	90 kW

Where previously installation of an AC generator was a must, parallel inverters are now an alternative.

8.3. The AC concept can be improved with *PowerControl*

8.3.1. The AC concept

In the AC concept one or more petrol or diesel fuel-powered generators are the hart of the system. Whenever AC power is needed a generator is started. The generator has to be rated to meet the highest power demand that is expected.
In general the generator, together with a battery charger, is also used to charge one or more small service batteries for navigation equipment, lighting, DC pumps, etc.

Likewise, shore power has to be rated to meet the highest power demand that is expected. Shore power must also match the frequency and voltage of the on-board AC equipment. If not, a frequency converter (also called shore converter) is needed.

The AC concept is the preferred solution when a lot of power is required.

8.3.2. The AC concept with generator free period

As power demand decreases, the drawbacks of the AC concept become more and more prominent. The generator will operate without any load at all for long periods of time, or will have to be started and stopped frequently, often operating with hardly any load. This of course means noise, pollution, fuel consumption, wear and maintenance while at same time, on average, electric power consumption is low.

A way to improve on this situation is the generator free period, which requires in addition to the generator a big battery, battery chargers and inverters. When the generator is off, all consumers are supplied with energy stored in the battery. Periodically, in general when a lot of AC power is required anyway, the generator is started and then also used to recharge the battery.

Although much better than the “generator only” concept, there still is a lot of room for further improvement. This is the subject of the next sections.

8.3.3. *PowerControl*

The AC concept with generator free period is at its best when the generator runs for as short a time as possible. This means that a substantial amount of power will be needed to quickly recharge the battery. The generator then needs to be rated for the maximum AC load to be expected **plus** the power needed for the battery chargers.

A more effective solution is ***PowerControl***.
With ***PowerControl*** the output current of the generator is continuously monitored and the power taken to recharge the battery is automatically adjusted so that the total load of the generator remains within a pre-set limit.

This is a feature that comes with the remote control panel of the Phoenix Combi and and its successor: the Phoenix Multi.

An example:
A boat is equipped with a generator and a Phoenix Multi 24/3000/70.
The generator is used to run a small washing machine that takes 2 kW when the water heater is on and 150 W when only the motor driving the tumbler is running. Average load: 500 W.
The battery to be recharged is 24 V 400 Ah. The maximum charge current from the Multi is 70 A.
Maximum AC load to be expected: 2 kW for the washing machine plus 2.1 kW to recharge the battery (70 A x 30 V = 2.1 kW).
Generator rating needed: 2 + 2.1 = 4.1 kW minimum, if one wants to run the washing machine and charge the battery simultaneously. In practice, in order to avoid running the generator at full load (and risking overload conditions), a 5 kW model should be chosen.
Alternatively, battery charging could be stopped when running the washing machine. This would increase the running time of the generator and result in an average load of only 500 W during the washing period. Generator needed: minimum 2 kW, in practice 3 kW.

With the ***PowerControl*** feature on the Multi one could still use a 3 kW generator and simultaneously run the washing machine and charge the battery. With help of the Multi remote panel, the current limit of the generator would be set at, for example, 10.5 A which would limit the output power of the generator to a safe 10.5 A x 230 V = 2.4 kW, which is 80 % of the rated 3 kW. After starting the generator, the Multi would automatically switch from inverter mode to charger mode and start charging the battery with 70 A.

When switching on the washing machine, the Multi will continue to charge at 70 A when only the motor of the washing machine is running (80 % of the time). The load of the generator would then be
150 W + 2.1 kW = 2.25 kW, less than the pre-set limit of 2.4 kW.

As soon as the heater switches on (20 % of the time) the washing machine takes 2 kW, so that only
2.4 kW - 2 kW = 400 W is left for charging the battery. With ***PowerControl*** the Multi will then **automatically** reduce charge current to approx. 400 W / 30 V = 13 A.

The example shows that with ***PowerControl*** the generator is used much more effectively. For 80 % of the time that the washing machine was on, the battery has also been charged with the maximum available charge current.
Without ***PowerControl*** the battery charger would have been switched off during the entire washing period.

Similarly, with ***PowerContol*** charging would be reduced, but not stopped, while using the microwave, a hot water kettle, an AC motor powered water maker, etc.

The example above is also applicable to shore power. The current limit should then be set at the rating of the circuit breaker protecting the shore power outlet. Of course this rating should be sufficient to supply the most power hungry piece of equipment on board. In our example this would be the washing machine, so in Europe the minimum shore power rating should be 2 kW / 230 V = 9 A.
Often the rating is lower, for example 6 A or even 4 A, not enough to run the washing machine. This brings us to ***PowerAssist***, the subject of the next section.

8.4. New: the hybrid or battery assisted AC concept, or “achieving the impossible” with *PowerAssist*

8.4.1. *PowerAssist*

The next level in generator and shore power support is to actually help the generator or shore supply when otherwise an overload would occur.
This is what the Phoenix MultiPlus does with ***PowerAssist***.

Continuing our example of section 8.3.3., one may want to run a 2 kW air conditioning compressor and at the same time do the washing, bringing the peak power to 4 kW. Or to heat water in a hot water kettle (2 kW), or simply make coffee (1 kW), or use an electric stove (6 kW) instead of gas.
With the MultiPlus this is all feasible. When the AC power required increases beyond a pre-set limit, the Multi will stop charging the battery and operate as an inverter in parallel with the generator or shore power. In our example the generator would be boosted from 3 kW to 3 + 2.5 = 7.5 kW. As will be shown in the next chapters, the saving in weight and fuel consumption of the electric power supply system can be substantial.

The MultiPlus solves the problem of insufficient shore or generator power by adding additional power taken from the battery.

8.4.2. Other advantages when operating Multi’s together with a generator

In the previous sections we explained the advantages of ***PowerControl*** and ***PowerAssist***: the possibility to use a smaller generator, or to reduce generator running hours, to increase the AC load, or to boost shore power.

Other advantages are:

Uninterrupted AC power
AC power will always be available, either from the Multi’s, or from the generator or shore power.
A digital clock or the settings of a video recorder will not be reset every time that the generator is stopped.

Immediate availability of AC power
When installing sufficient Multi power any AC appliance on board can be switched on without the need to start the generator first.

Redundancy
When several Multi’s are operating in parallel, a faulty unit (although unlikely that this would happen) can be isolated from the healthy ones. There is a second AC redundancy because of the presence of the Multi’s and a generator. And finally there are at least 2 sources of DC power to recharge the battery: one or more Multi’s and the alternator on the main engine.

8.4.3. Shore power

We have seen that one way to cope with insufficient shore power is the MultiPlus: with ***PowerAssist*** shore power can be boosted to up to 4 times its nominal rating.

An alternative is to use the DC concept for shore power. In other words: use a battery charger to convert shore power to DC and convert DC back to AC with the inverters or Multi’s which are on board anyway. The house battery will supply additional energy when a lot of power is required on board, and will be recharged by the battery charger during periods of low power demand.

For more details, see sect. 8.5.3.

8.5. Thinking different

8.5.1. Daily energy needed

Both for the DC concept and the battery assisted AC concept the first question to ask is not "*what is the maximum AC power to be expected?*" and then size inverters and the generator to that power.
Instead the first question should be "*what is the daily electric energy need?*"

It is the daily energy need that determines the rating of the source of electric power.

The daily run-time needed to produce the required energy is calculated with the following formula:
run-time (hours) = daily energy need (kWh) / output of the source(s) of electric power (kW)

Alternatively, if the requirement is to limit generator run-time to a certain amount of hours, the formula is:
output of the source(s) of electric power = daily energy need / run-time
Some examples:

8.5.1.1 Daily energy needed: 4 kWh (see chapter 9)
Source: alternator on the main engine supplying 100 A into a 12 V system, i. e.
100 A x 12 V = 1.2 kW
Daily run-time needed: 4 kWh / 1.2 kW = 3.3 h
(In practice the run-time will be somewhat longer due to losses in the system and possibly a reduced current absorption capacity of the battery at the end of the charge cycle, but for a first approximation the calculation is ok)

8.5.1.2 Daily energy needed: 14 kWh (see chapter 10)
Source: diesel generator, but should not run more than 4 hours per day
Minimum rating of the generator: 14 kWh / 4 h = 3.5 kW

8.5.2. Battery capacity

When power generation is limited to a few hours per day (alternator on the main engine or generator with generator free period), the size of the battery is determined by the amount of energy that the battery has to supply during the periods that the main engine or generator are off: the generator free period.
In practice, due to the short recharge periods, the battery will be recharged to not more than 80 % (20 % DoD). The battery also should not be discharged to more than 70 % (70 % DoD). This would mean a usable battery capacity of at most 70 % - 20 % = 50 %. We should include a safety margin: when a battery has been discharged to 70 % there is no margin left if anything unexpected happens. There is no general rule for the amount of margin, but let's take 10 %. This leaves us with 40 % usable capacity and a DoD of 60 %. Then we have to build-in a factor of 0.8 to account for 20 % capacity loss when the battery gets older: 40 % x 0.8 = 32 %.

And finally, if we discharge a battery faster, or slower, than rated (the rated discharge time is in general 20 hours, see sect. 2.5.3) another correction factor will have to be applied. In most cases the time between recharges of the house battery is 8 to 12 h, and 32 % discharge in 8 hours is equivalent to 32 x 24 / 8 = 96 % discharge in 20 h. Very close to the rated discharge time, so no additional correction needed for batteries rated at 20 h, and a positive correction for tubular plate traction batteries, for Exide / Sonnenschein A600 cells (see sect.2.5.3.).
(I imagine a breath of relief here: the usable capacity would have gone to nearly zero if even more corrections had to be applied)

Conclusion:
Calculating battery capacity is quite complicated. The purpose of this book is to look at the big picture, so we need a rule of thumb.

Practice:
The rule of thumb from practice is that in case of 2 recharges per day, battery capacity should at least be twice the daily Ah consumption.
If for example daily consumption is 128 Ah (see sect. 9.3), battery capacity should be 256 Ah. Assuming a constant discharge rate over 24 hours, our 256 Ah battery would be subjected to a discharge of 128 / 2 = 64 Ah over a period of 12 hours.

Theory:
The rule of thumb derived from theory is that the usable battery capacity is 32 % of the nominal capacity. Assuming a maximum period of 12 h between recharges and a consumption of 128 / 2 = 64 Ah during that period, 32 % usable capacity would in this example mean that we need a battery of 64 Ah / 0.32 = 200 Ah.

The positive difference between practice and theory of 265 - 200 = 65 Ah can be seen as compensation for the fact that the discharge rate is not constant but will depend on which consumers are switched on, and when. Recharge periods may also vary in length.
In other words: theory leads to the same result as the rule of thumb.

We now have two simple methods to estimate the capacity needed for the house battery:

1) **The capacity of the house battery should be at least three times the expected discharge during the generator free period.** (100 % / 32 % = 3.1)

2) **If the house battery is recharged two times per day, its capacity should be at least twice the daily Ah consumption.**

Two examples:

Maximum amount of energy that will be taken from the battery during the generator free period: 4 kWh
Minimum capacity of the battery (12 V system): 4 kWh x 3 / 12 V = 1000 Ah
Minimum capacity of the battery (24 V system): 4 kWh x 3 / 24 V = 500 Ah

Daily amount of energy that will be taken from the battery: 4 kWh, i. e. 4000 / 12 = 333 Ah for a 12 V system
Recharges per day: 2
Minimum size of the battery (12 V system): 333 x 2 = 666 Ah

8.5.3. Shore power

When the generator on board has been sized to supply the maximum expected power need, quite naturally, the shore power connection will also have to be rated to supply the maximum expected power consumption on board.

Let’s assume that the microwave oven, rated at 1500 W, is the most power hungry appliance. At 1500 W, the microwave will take 1500 / 230 = 6.5 A from a 230 V shore outlet. This is already more than the usual 4 A or 6 A shore outlet rating. If at the same time the electric water heater switches on (4 to 5 A) and your coffee machine (4 A) is just starting to spread the lovely smell of freshly made coffee, your power draw increases to 6.5 + 4 + 5 = 15.5 A. In other words: you are not far from tripping even a 16 A shore outlet!
Not to mention a washing machine (9 to13 A), a dishwasher (also 9 to 13 A) or an electric stove (16 to 35 A).

The result is that the generator has to be started even when moored in the marina. Not the way to make friends on the neighbouring boats.

The solution is to think differently and to implement the DC or the hybrid concept for shore power. Once more the question then is not “*what is the maximum AC power to be expected?*” but instead “*what is the daily electric energy need?*”

The microwave for example takes 6.5 A, but only for 5 minutes, at most. If this current could be averaged over 50 minutes, then the 6.5 A would reduce to one tenth (0.65 A) but during a ten times longer period: 50 minutes instead of 5 minutes.

This is exactly what the DC or the hybrid concept do: using the house battery to average peaks in power consumption (“peakshving”).

The example described in chapter 9, where indeed a microwave oven is the most power hungry appliance, will show that the daily energy consumption when moored is 1.6 kWh, which translates to an average power of 1600 / 24 = 66 W, or 5.6 A taken from a 12 V house battery. And 66 W is a current of only 66 / 230 = 0.3 A from the shore power outlet!
In practice, due to losses and some reserve to charge the battery, shore current will be 2 to 4 times higher, but even 1 A still is next to nothing.

The example from chapter 10 shows that with more electric equipment on board, shore power can be reduced from 8 kW (3 phase 16 A shore outlet needed) to a mere 1.3 kW (6 A 230 V shore outlet).

What the examples show is that the DC or hybrid concept reduces the shore power rating needed by a factor of 4 to 10, making it much easier to find a suitable berth in today's overcrowded marina's.

But reduction of shore power rating is not the only advantage of the DC and the hybrid concept, here is the complete list:

Up to ten times less shore power needed
As will be shown in more detail in the next chapters, implementing the DC or hybrid concept really results in a breathtaking reduction of the required shore outlet rating.
The average power demand is in general less than one ¼ or even, depending on the power consumption profile on board, less than $^1/_{10}$ of the peak power demand. Therefore the battery charger needed to connect to shore power will also be quite small and represents a small investment compared to the total cost of the electric infrastructure on board.
And a low power shore socket to connect to will be much easier to find in an overcrowded marina than a 16 A or a 3 phase socket!

Built-in clean, stable and no-break AC power
Whatever goes wrong with shore power, the battery + inverters or Multi's are there to guarantee uninterrupted power.

DC concept only: built-in frequency and voltage conversion
Battery chargers will operate on a 50 Hz and on a 60 Hz supply. With an autotransformer or a wide input range (90 V to 260 V AC) battery charger **one can connect to shore power anywhere in the world, without the need for an expensive and cumbersome shore power converter.**

9. Up to 4 kWh required per day (170 Watt average)

9.1. Introduction

It is now time to go on board and see how things work out in practice.

Of course all boats are different, depending on purpose, budget and ownership. Some boats are equipped to cross the Atlantic or to sail around the world. Others are intended to travel along rivers and canals. And still others go out fishing for a day. Some boats are sailed and maintained by the owner, others are part of a charter fleet. Then similar electric installations can be found in mobile homes for example, or off-grid houses.

I have chosen here to take sea-going yachts as the example, because that is what I know about first hand. It is not very difficult to adapt the reasoning given in this and the following chapters to other applications.

The first boat we will board is fairly simple in terms of electric installation, and electric power consumption has been kept as low as possible. It would typically be a motorboat of up to 9 metres or a sailing boat of up to 12 metres.
The boat has a 12 V electrical system and, to start with, we list all electric equipment and current consumption.

9.2. Equipment and current consumption

9.2.1. **Navigation instruments** (wind set, log, depth sounder, etc): less than 0.2 A

9.2.2. **GPS**: about 0.2 A

9.2.3. VHF

Standby consumption is low (approx. 0.1 A). Transmitting does take a good deal of current (approx. 5 A) yet is brief, so that consumption in Ah remains quite low.

9.2.4. **Tricolour navigation light or anchor light**: 25 W

(25 W / 12 V = 2.1 A)

9.2.5. Autopilot

The autopilot can be one of the biggest consumers if used for long periods of time. The motor’s current consumption is easily 5 A. When running with a duty cycle of 30 % the average consumption would be 5 x 0.30 = 1.5 A.
Please bear in mind that this is a very rough approximation. Power consumption of the autopilot will in practice depend on the boat, trimming, the seas, etc.

9.2.6. Radio

Particularly on longer cruises, the (car) radio is often turned on. Its current consumption is about 1 A.

9.2.7. Cabin lighting

These days lighting consists of halogen lamps (10 W to 20 W) and fluorescent tubes (approx. 8 W). Incandescent bulbs are not recommended because they take up to 5 times more current for the same amount of light produced. Assuming 10 lighting points and thrifty use, consumption would be limited to approx. 10 Ah per 24-hour period.

9.2.8. Refrigerator

Refrigeration has been discussed in sect. 6.2.
In this example we will assume that we have a refrigerator on board with a 50 W compressor running with a 50 % duty cycle. In my experience this is an average refrigerator in terms of energy consumption, when cruising in a temperate climate.

9.3. Consumption over a 24-hour period when sailing

Our starting point is one 24-hour period under sail (when travelling under power the current consumption is not of importance, because the alternator on the main engine can easily keep up with consumption).
We will now determine the battery capacity needed for supplying all consumers during one 24-hour period.
In the table that follows the consumers have been divided into continuous (C), long duration (L), and short duration (S) consumers.

Consumers	**Consumption**		**Time / 24-hours**	**% on**	**Consumption / 24-hour period**	
	Watt	Amp	Hours	%	kWh	Ah (12 V)
C Navigation instruments		0.2	24			5
C GPS		0.2	24			5
C VHF standby S transmitting		0.1 5	24 0.2			2 1
C Refrigerator, air-cooled heat exchanger	50	4.2	24	50		50
L Tricolour navigation light or anchor light	25	2.1	8			17
L Autopilot		5	20	30		30
L Radio		1	3			3
S Cabin lighting	200		0.6			10
S Other						5
Total consumption per 24-hour period					1.5	128
Average consumption per 24-hour period	64	5.3				
Minimum battery capacity required, assuming 2 recharges per day (see sect. 8.4.2)						256

It is noticeable that the refrigerator is by far and away the biggest consumer. The refrigerator’s current consumption could be halved by using a more expensive water-cooled heat exchanger instead of an air-cooled heat exchanger and by improving insulation. The total consumption per 24-hour period would then reduce to 103 Ah. Using a gas refrigerator (only useable on motorboats in calm waters) would even reduce current consumption to 78 Ah.

9.4. At anchor or moored without 230V shore power pick-up

Once again, our starting point is one 24-hour period, but this time the following applies for motorboats and sailing boats.

Consumers	**Consumption**		**Time / 24-hours**	**% on**	**Consumption / 24-hour period**	
	Watt	Amp	Hours	%	kWh	Ah (12 V)
C Refrigerator, air-cooled heat exchanger	50	4.2	24	50		50
L Masthead light	25		8		0.2	17
L Radio		1	3			3
S Cabin lighting, ten 20 W lighting points	200		0.6			10
S Other						5
Total consumption per 24-hour period					1.0	85
Average consumption per 24-hour period	42	3.5				
Minimum battery capacity required, assuming 2 recharges per day (see sect. 8.4.2)						170

9.5. The extra’s

Even the relatively small boats that we are considering here often have (or the crew might wish to have!) some extra safety and comfort on board. A few optional extras are suggested below. For some an inverter is needed. Because today inverter efficiencies are higher than 90%, the losses in the inverter are ignored in the energy consumption calculations.

9.5.1. Electronic navigation system

Quite common today even on smaller yachts.

9.5.2. SSB

Very useful on ocean trips.

9.5.3. Radar

Increases safety when sailing at night or in bad weather.

9.5.4. Microwave oven

A microwave oven uses a great deal of energy (up to 1.5 kW) for a brief time. When the microwave is used for 12 minutes per day the consumption in Ah out of a 12 V battery is 1500 x 0.2 / 12 = 25 Ah.

9.5.5. Space heating

One should always opt for a diesel burner so that current consumption stays confined to diesel pump and fans. The current consumption is then kept down to approx. 5 A.

9.5.6. Air conditioning

Especially when operating on battery power, it is important to carefully look at the expected energy consumption.

9.5.7. Water maker

Some very efficient water makers are now available that work on 12 V DC. Current consumption is only 10 to 20 A for 30 to 60 litres of fresh water per hour. This has made a water maker (and thus also a freshwater deck shower!) a realistic extra for small boats used for blue water cruising.

The following table sums up the additional luxury that could be found on smaller boats. Power consumption has been based on a crew of 2 or 3.

Consumers	**Consumption**		**Time / 24-hours**	**Consumption / 24-hour period**	
	Watt	Amp	Hours	kWh	Ah (12 V)
C Electronic navigation system		2	24		48
C SSB		12	0.1		7
L Radar		3	8		24
S Microwave oven	1500		0.2	0.3	25
L Heater		5	6 x 0.5 = 3		15
L Air-conditioning, cooling capacity 2 kW	700		6 x 0.5 = 3	1	(90)
L Water maker, 150 litres per day		10	5		50
Consumption per 24-hour period				2.0	169
Average consumption per 24-hour period	85	7			

With all the additional equipment on board (except for the airco), the total energy need per day amounts to:
- when sailing: 1.5 + 2.0 = 3.5 kWh, or 128 + 169 = 297 Ah
- at anchor : 1.0 + 2.0 = 3.0 kWh, or 85 + 169 = 254 Ah

Which translates to the following minimum battery capacity and average discharge current:
- when sailing: 297 x 2 = approx. 600 Ah and 12.3 A discharge current
- at anchor : 254 x 2 = approx. 500 Ah and 10.5 A discharge current

We are now going to see how to produce the required energy, for the “basic” yacht (1.0 to.1.5 kWh needed), and for the “full featured” yacht (3.0 to 3.5 kWh needed).

9.6. How to recharge the battery

9.6.1. Generate current with the main engine.

The main engine usually has a 14 V / 60 A alternator fitted. This means that the alternator will deliver 60 A at 6000 rpm. Suppose that the diameter ratio between the engine pulley and the alternator pulley is 2:1, then the main engine would have to run at 3000 rpm to attain 60 A charging current. In practice nobody does this, because it makes too much noise. For generating current the engine generally runs between 1500 and 2000 rpm. The charging current will then be 40 % to 80 % of the rated value, i.e. 30 to 50 A.
This means that to charge the house battery, 2 to 3 engine hours are needed per day for the “basic” yacht and 7 to 8 engine hours per day for the full-featured yacht.
Not an attractive proposition, unless:
-you are intending to travel under power a good distance every day
-the boat is mainly used for day trips

If the intention is to live on board for days or weeks without shore power available, running the engine for several hours per day only for recharging the battery (i. e. at nearly no load) is bad for the engine, and very unpleasant for the crew and eventual neighbours.

How can this be done better?

9.6.2. **Increase battery capacity** so that you can sail or lie at anchor for several days.

This is a simple and inexpensive solution that only makes sense, however, if you always expect to be travelling for longer periods under power within a few days, or will have shore power available.

9.6.3. A second or bigger alternator

Please refer to chapter 4 and 5 for precautions to take.

Increasing the charge current to 80 A would result in an acceptable 1 to 2 daily engine hours for the basic yacht. But bear in mind that there is a limit to the charge current that a battery will accept without damage, see section 2.5.6.
Automotive batteries, Optima, and the Sonnenschein Dryfit A200 or Sportline VLRA battery can be charged at a C / 3 rate up to 80 % capacity, with an absorption voltage limit of 2.4 V / cell (**in particular a VLRA battery must be temperature compensated due to heat generation at this high charge rate!**). Charging at 80 A and C / 3 requires a battery capacity of 80 x 3 = 240 Ah which is less than the 258 Ah required for the basic sailing yacht. As discussed earlier, more capacity will increase service life. Some other batteries should be charged at C / 5 or less so that at least 80 x 5 = 400 Ah is required.

To limit engine run time to 2 hours (2 sessions of 1 hour) on the full featured yacht would require 150 A alternator output and a battery of 297 Ah x 2 = 594 Ah (still only 3 batteries of 230 Ah each), or, if the maximum charge rate is C / 5, a 150 A x 5 = 750 Ah battery.
Please also note that alternators have a low efficiency (about 50 %), that means the power taken from the engine would be 150 x 15 / 0.5 = 4.5 kW

Two remarks about efficiency here:

1) In order to account for losses in the battery (energy efficiency in partial state-of-charge operation: approximately 89 %, see sect. 3.3.), in cabling, in diode isolators or battery chargers and, for some consumers, an inverter, a recharge voltage of 15 V respectively 30 V will be assumed in all calculations regarding battery charging. In other words: an efficiency of $\eta = 12 / 15 = 80\ \%$ is assumed.
-discharging a battery with 150 Ah at 12 V means an energy consumption of 150 Ah x 12 V = 1.8 kWh
-recharging 150 Ah at “15 V” means an energy supply of 150 Ah x 15 v = 2.25 kWh
-the difference, 2.25 – 1.8 = 0.45 kWh, is lost in the process.

2) An energy consumption of 4 kWh, the subject of this chapter, and for nearly the full 100 % via the battery, requires 4 kWh / 0.8 = 5 kWh to be supplied by the alternator. With 50 % alternator + belt efficiency, the main engine will have to supply 5 kW / 0.5 = 10 kWh. And then the engine runs with a load of only 10 to 20 %, meaning a fuel efficiency of something like 10%…
Efficiency of the complete chain: $\eta = 0.8 \times 0.5 \times 0.1 = 0.04$ (= 4 %).

9.6.4. Solar cells

In the summer in the Netherlands, for example, solar cells, mounted horizontally, deliver approx. 300 Wh per day and per m^2 (1 m^2 = 2 off 50 W panels). This boils down to 25 Ah per day and per m^2 in a 12 V battery. In the Mediterranean area this rises to approx. 35 Ah, and in the Caribbean to 50 Ah. Solar cells can therefore make a considerable contribution, especially on multihulls and motorboats that often have a lot of deck or roof space available.