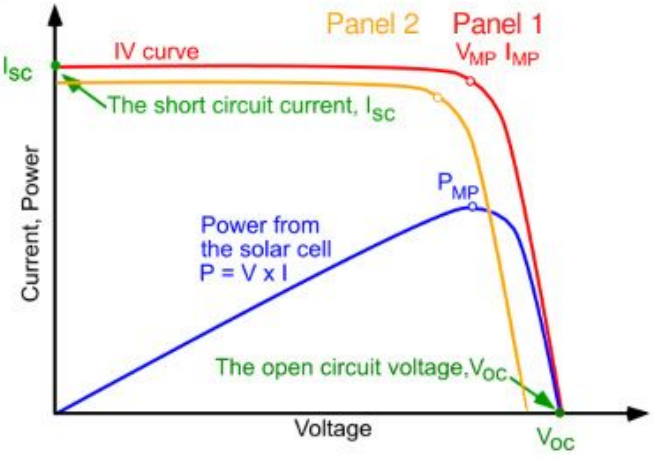
BLUEWATER CRUISING ASSOCIATION

Making and Storing Power at Sea

Saturday, February 18, 2023
9:00 - 12:00

Presenter: Bjarne Hansen, M.E.Sc.



Hoku Pa'a

35' Niagara

Overview

- Safety (Low-voltage DC and AC Mains systems)
- Definitions & Theory (Volts, Amps, Ohms, Watts)
- Power Sources (Solar, Wind, Hydro, Fossil-fuel)
- Installation (Mounting, Common problems)
- Power Budget (Calculating & Measuring loads, Spreadsheet)
- Storage Systems (Battery types, Charge Controllers)
- Avoiding Problems (Preventive Maintenance, RFI)
- Supplies & Resources
- Closing remarks and Questions

Safety

- We want to avoid two main dangers:
  - **Electrocution**
  - **Fire**

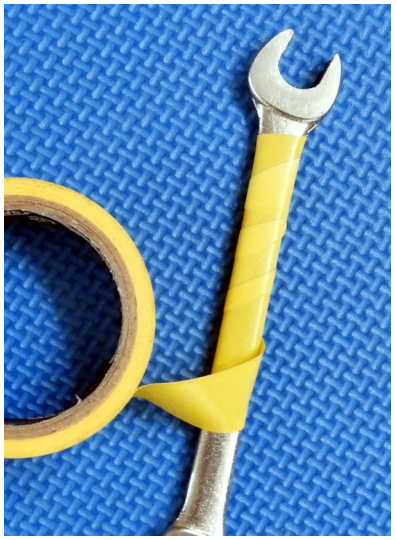
- From the two main types of electrical systems:
  - **High Voltage** (e.g. AC Mains)
  - **Low-voltage DC** (usually 12 VDC on a boat)

Safety – Electrocution

- There are some **higher-voltage systems** aboard, including:
  - AC Inverters and their outlets
  - Shore-power connections and outlets
  - Ignition systems on gasoline engines
  - Radars (older-style) with magnetron, and microwave ovens
  - Antenna connections on HF radios
- These higher-voltage sources can give a **painful, even lethal, shock**. So:
  - ***Disconnect power on these systems*** before working near or on them.

Safety - Fire

Lower-voltage systems can also be dangerous. Not from electrical shock, but due to heating from high current, and sparks can ignite flammables (e.g. propane)



You should:

- ***Disconnect power if practical. If not, then be careful not to create a short circuit (e.g. from metal tools), and***
- ***Don't perform electrical work near flammables***

Safety - Fire

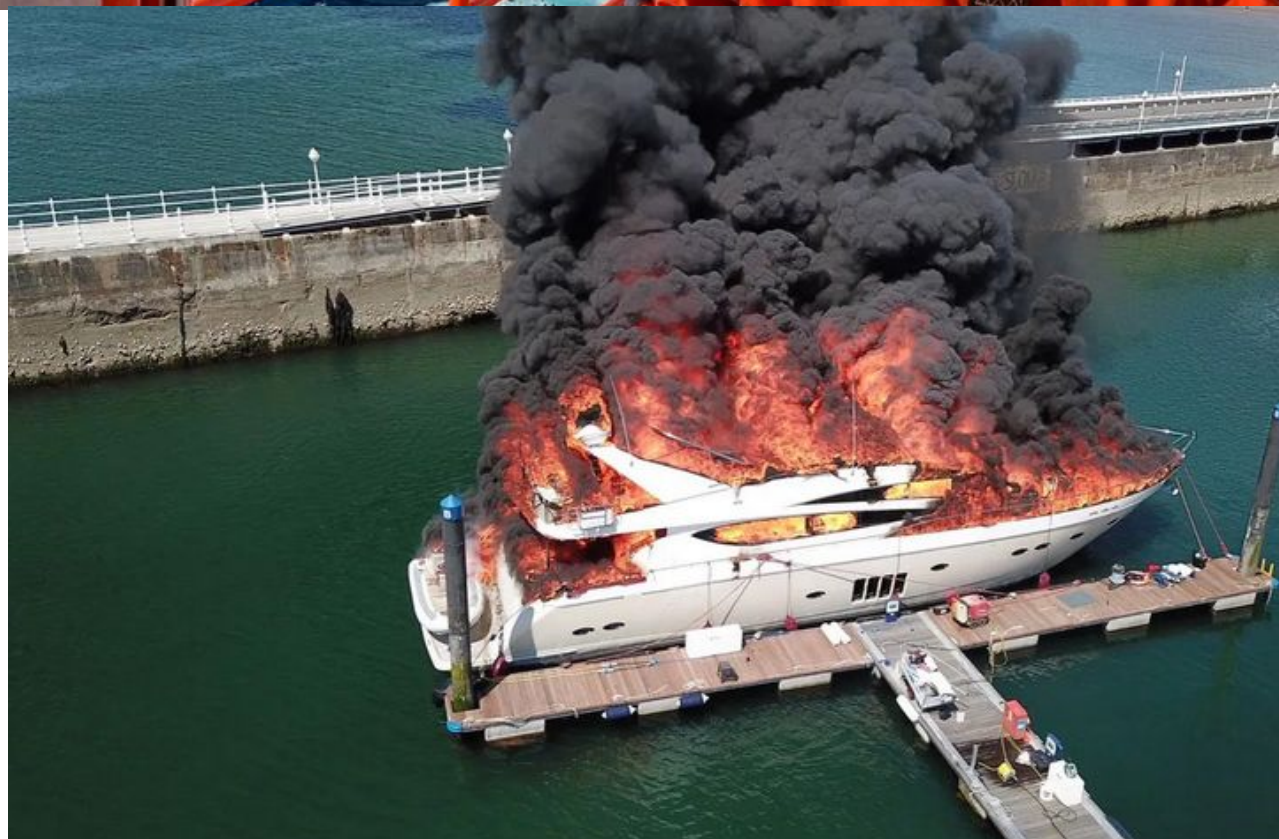
Analysis of boat-loss claims (Boat US, 2015-2019) revealed **top causes of boat fires** (excluding external sources):

1. **Engine electrical (21%)**
2. Engine non-electrical (19%)
3. Fuel (14%)
4. **Batteries (10%)**
5. **AC electrical (9%)**
6. **DC electrical (6%)**
7. Unknown, or Other Causes (21%)

https://www.boatus.com/expert-advice/expert-advice-archive/2021/february/analyzing-onboard-fire-claims

Safety - Fire

More recently, we see a lot of interest and analysis of high-profile **boat fires where lithium batteries are believed to be involved.**



Safety

Preventive checks and maintenance are your best defence.

- **Engine electrical** -> inspect wiring harnesses, tighten connections, service alternator and starter
- **DC electrical** -> keep diagrams / photos, inspect wires and connections, follow *TC / ABYC* recommendations when making changes
- **AC electrical** -> inspect shore cable and fittings, use latest safety-improved plugs
- **Battery overcharge** -> monitor batteries and charging states, replace outdated/malfunctioning chargers

Safety

Lead-acid Batteries have 2 Additional Safety Hazards

- **Hydrogen gas** is released during charging, and can cause an explosion. Ensure battery compartments are vented, don’t overcharge, keep sparks away.
- **Sulphuric Acid** is contained inside these batteries. It’s very corrosive. Wear eye protection, don’t splash battery contents. Neutralize spills with baking soda.

Safety

Lithium Batteries have 1 Additional Safety Hazard

- **Lithium metal and compounds** are very chemically reactive. Lithium batteries can release noxious gases and burn when physically damaged. Don’t open or damage the battery enclosure. Only use lithium batteries that have built-in protection against overheating and overcharging.

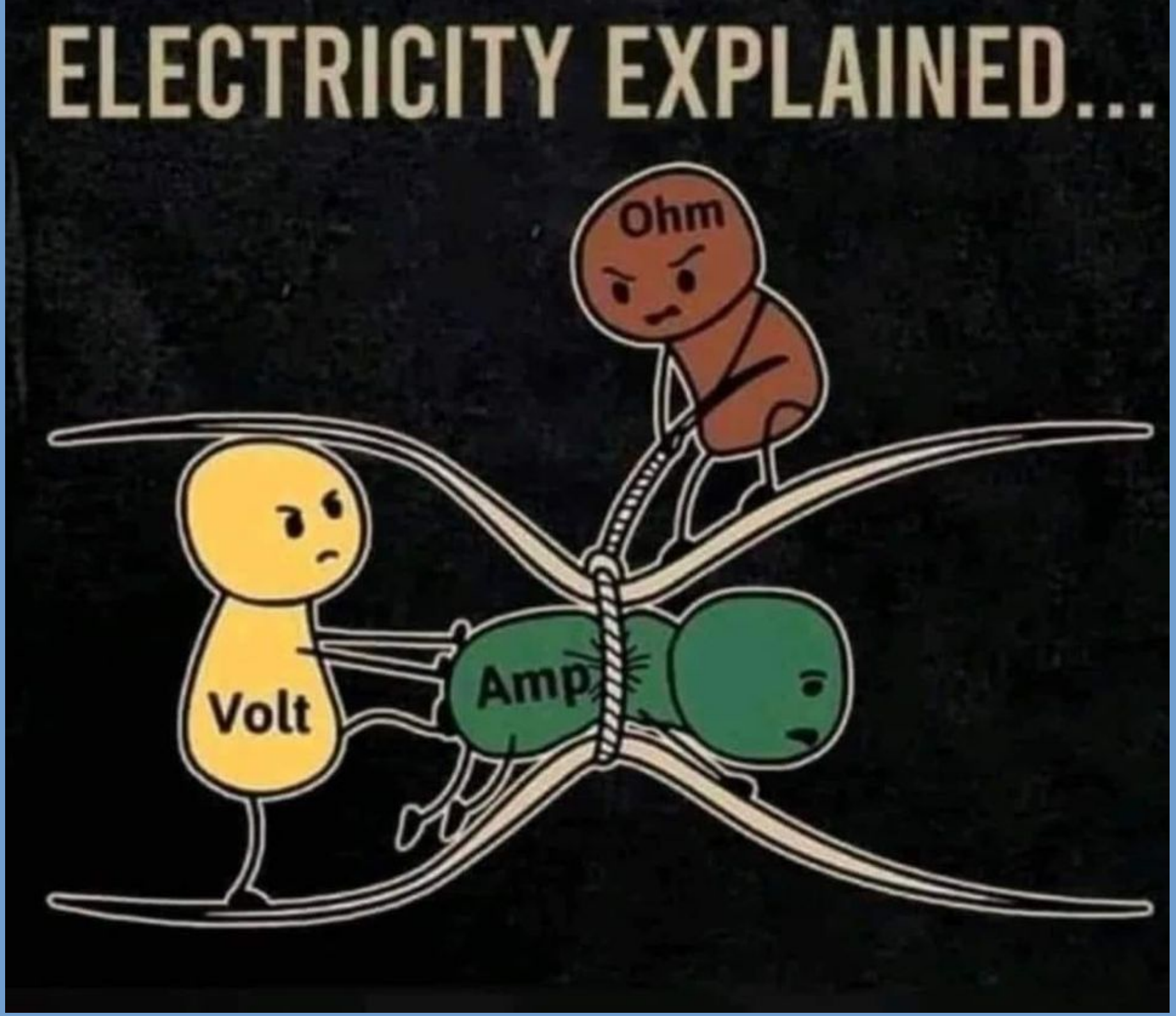
Questions?

Bullseye Electric Ray

What is Electricity ?

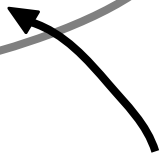
- Electricity is the flow of electrons

  Invisible: can only see/feel its effects


ELECTRICITY EXPLAINED...
Ohm
Volt
Amp

Definitions & Theory

Volts, Amps, Ohms, Watts



Just 2 formulas!

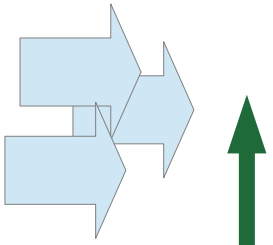
Electricity is a lot like Water

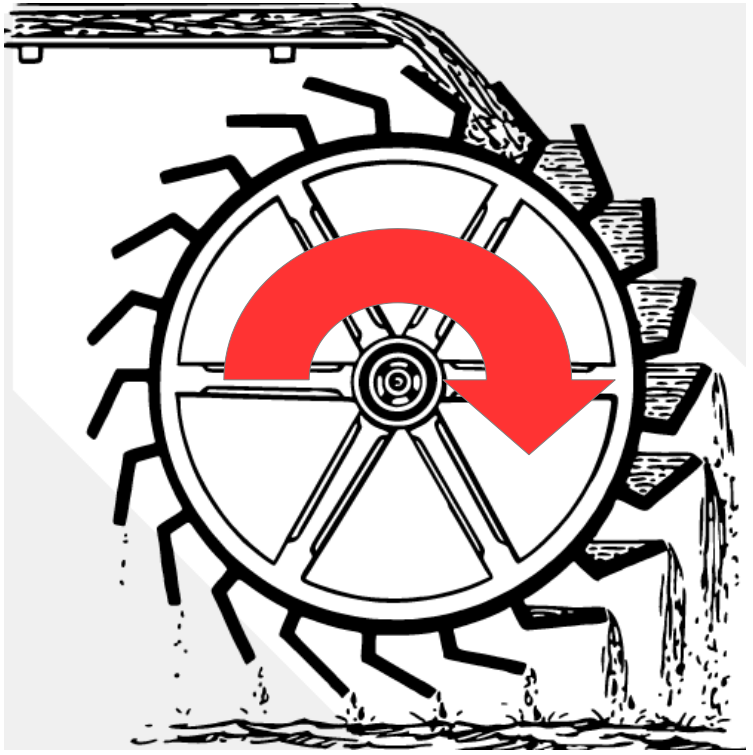
Current & Voltage

	Definition	*Units*	*Similar To:*
Current	# of electrons flowing per second	**Amperes [A]**	How much water is flowing (current)
Voltage	Amount of energy per electron	**Volts [V]**	Height of the water (pressure)

Current = Flow Rate

Voltage = Height, Pressure

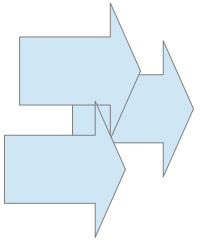




Resistance & Power

	Definition	*Units*	*Similar to:*
Resistance	How easy is current flow	**Ohms [Ω]**	How easily waterwheel turns
Power	Rate at which energy is being transfered	**Watts [W]**	Rate of Work done by water

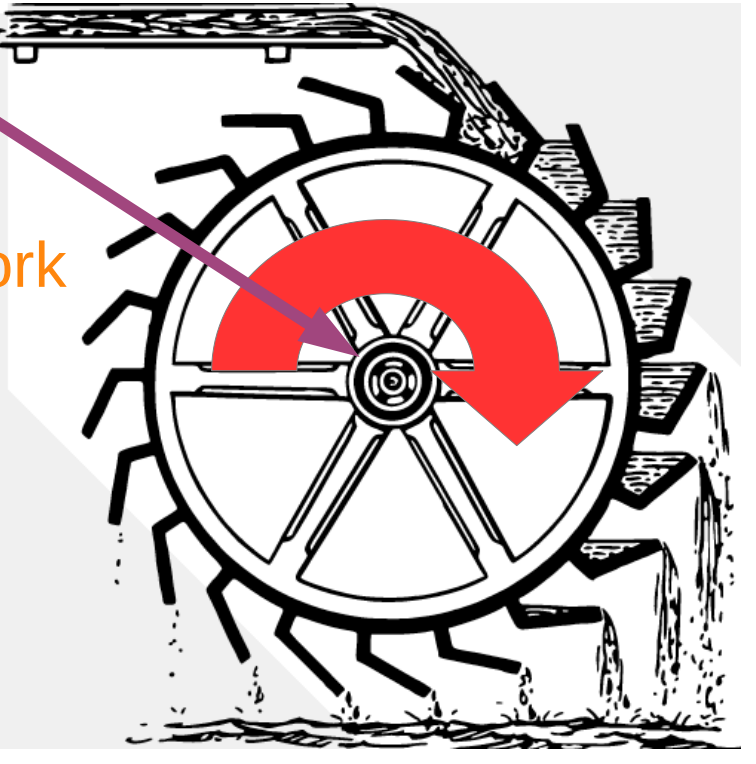
Current = Flow Rate



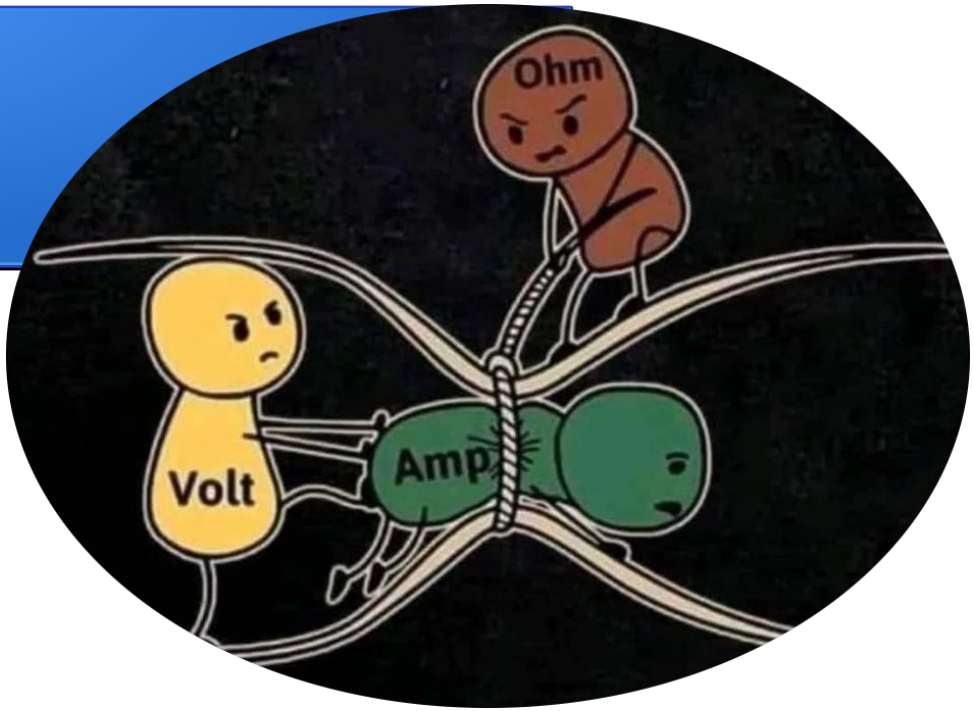
Voltage = Pressure

Resistance = Friction

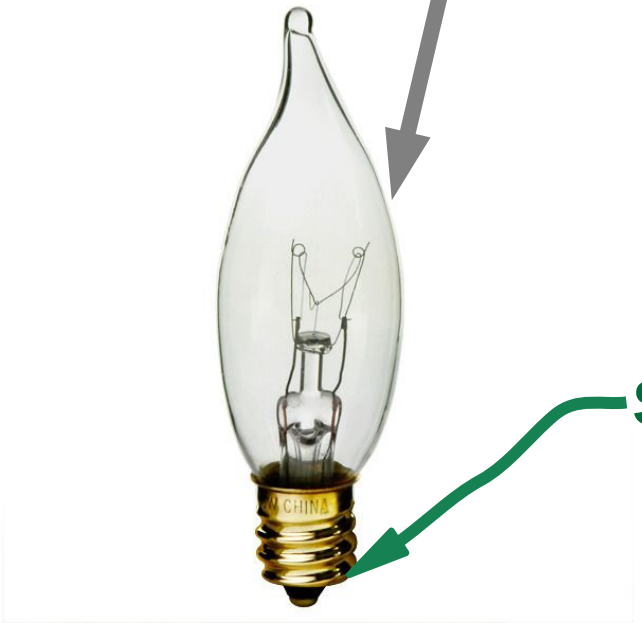
Power = Rate of Work



Voltage, Current, Resistance & Power



High Resistance
Low Power
Low Current



Low Resistance
High Power
High Current

Same Voltage

Only Two Equations

Used when figuring out an **Energy Budget,** or comparing specs on electrical parts

V = Voltage, measured in Volts (V)
R = Resistance, measured in Ohms (Ω)
I = Current, measured in Amperes (A)
P = Power, measured in Watts (W)

① **Resistance = Voltage / Current** ← Ohm's Law

$$R = \frac{V}{I} \qquad V = I \times R \qquad I = \frac{V}{R}$$

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② **Power = Voltage * Current** ← Joule's Law

$$P = V \times I \qquad V = \frac{P}{I} \qquad I = \frac{P}{V}$$

Calculate Current: ...an example

What's the drain on my battery?

We know the Voltage and Power.

We want to calculate the Current.

3 Watts at 12 Volts

$$P = V \times I$$

Joule's Law

$$I = \frac{P}{V}$$

$$I = \frac{3 \text{ Watts}}{12 \text{ Volts}}$$

$$I = 3 \ / \ 12$$

I = 0.25 Amps

Measuring V, I, R

- Use a regular multimeter for low currents < 10A and AC or DC Voltages < 250 V
- Inexpensive meter fine for 99% of boat use
- Additional nice features include:
  - Alligator clips
  - Display with 'hold' reading
  - Auto-off
  - Continuity 'beep'

Measuring High Current

- Use a Clamp-on Ammeter for higher currents (e.g. Starter current, which can be > 100 A)
- Most models come with leads for regular V, Ω measurements

Since there is no electrical connection needed, this is convenient and there is no risk of short circuit

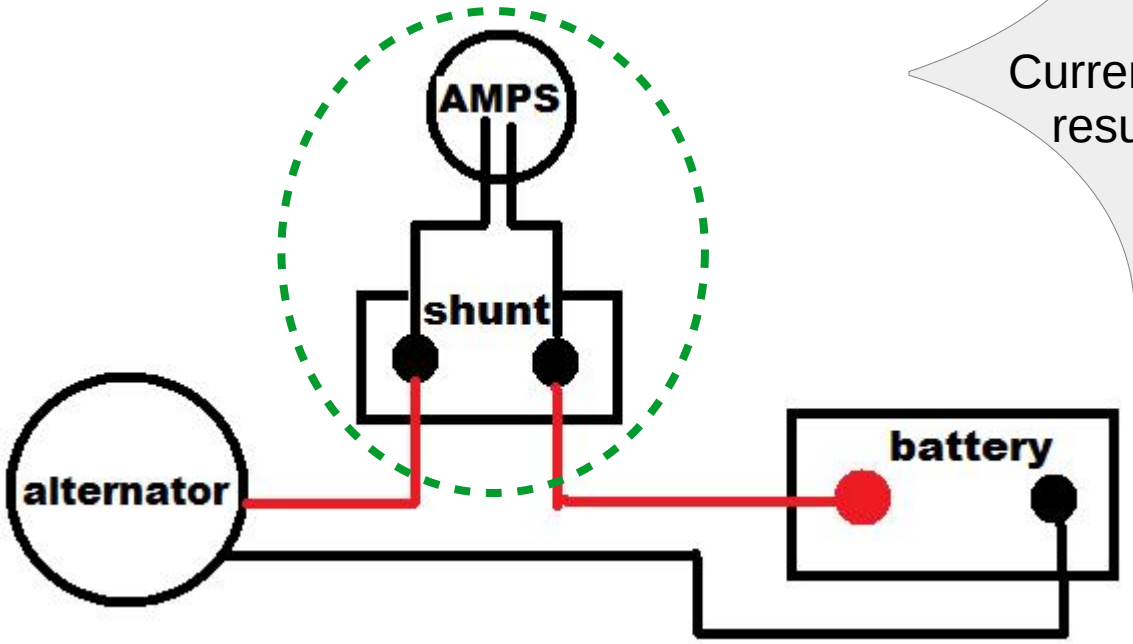
Not as accurate as a direct-connection measurement

Readings can be affected by ambient magnetic fields.

Built-in Current Measurement

- Boats with a battery-monitor likely have a shunt resistor in series with the main battery cable. The battery monitor measures the very low voltage that develops across the shunt when current flows

Recall the formula
V = I * R
Current through a resistor (shunt) results in a voltage difference that the meter reports



Questions?

Power Self-sufficiency

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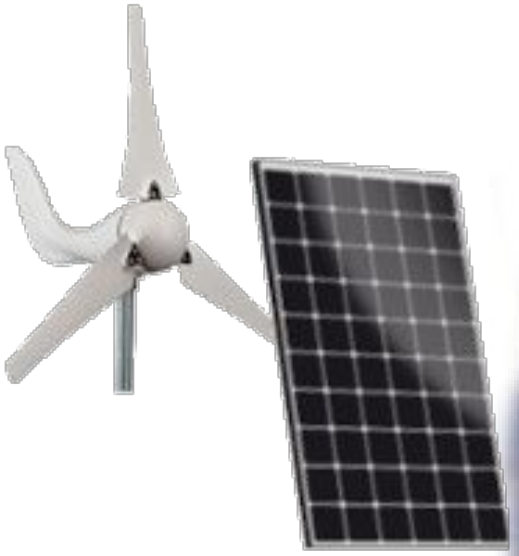
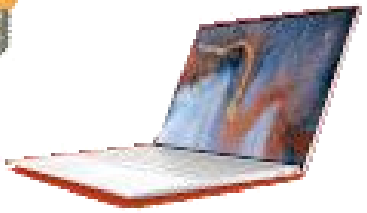
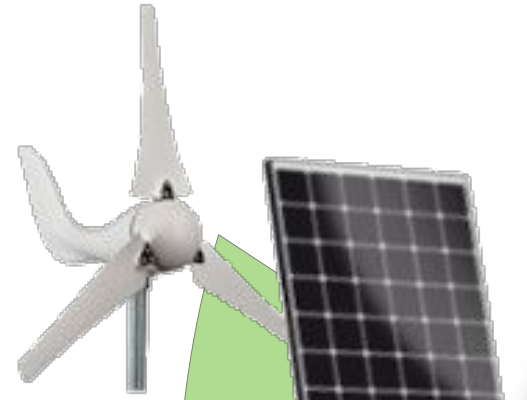
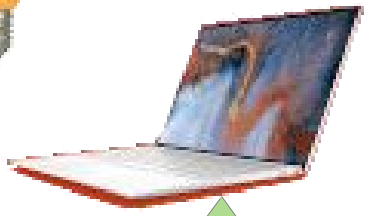
Power Self-sufficiency





Power Self-sufficiency





Power Sources

- **Solar**
- **Wind**
- **Water flow**
- **Fossil-fuel (e.g. gasoline)**

Power Sources

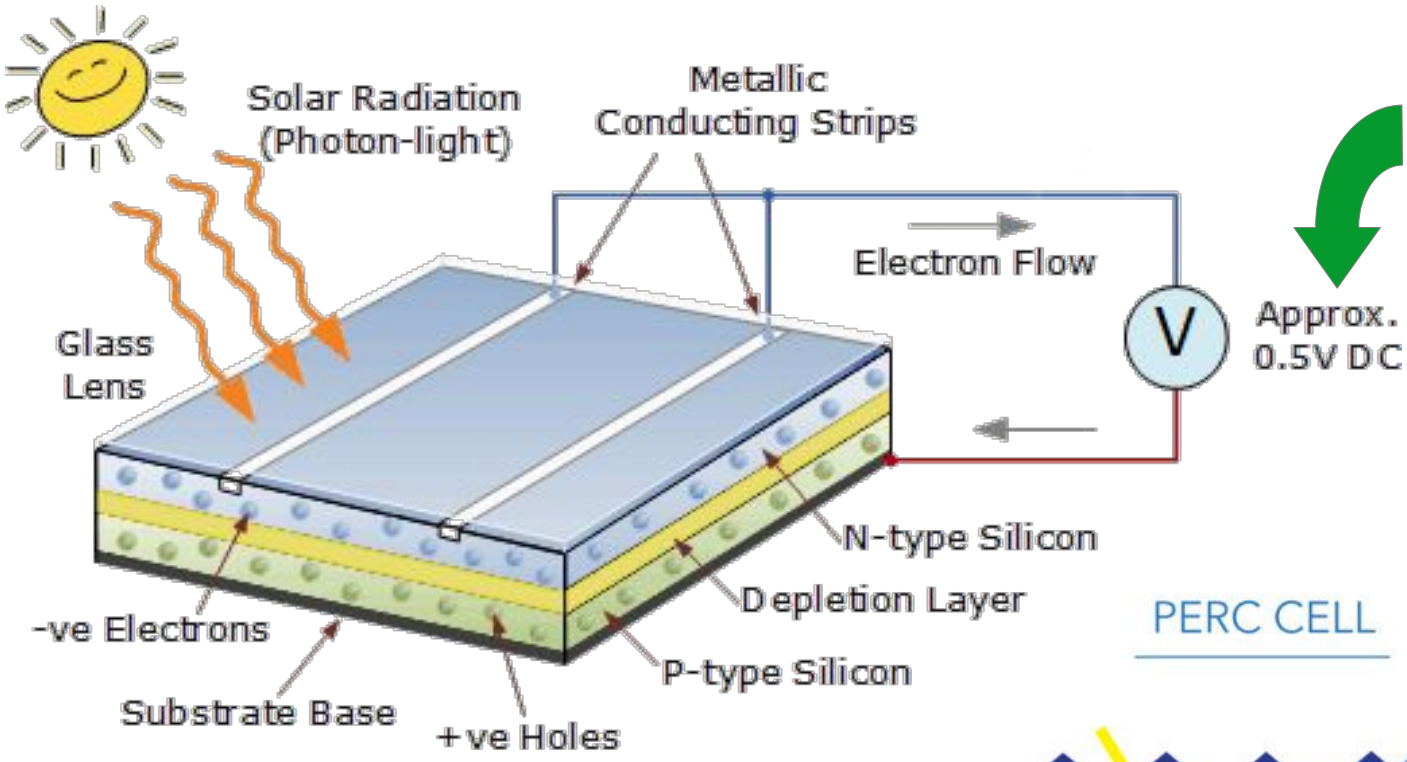
Solar

Three main parts of an installation:

- **Solar Panels**
- **Mounting System**
- **Charge Controllers**

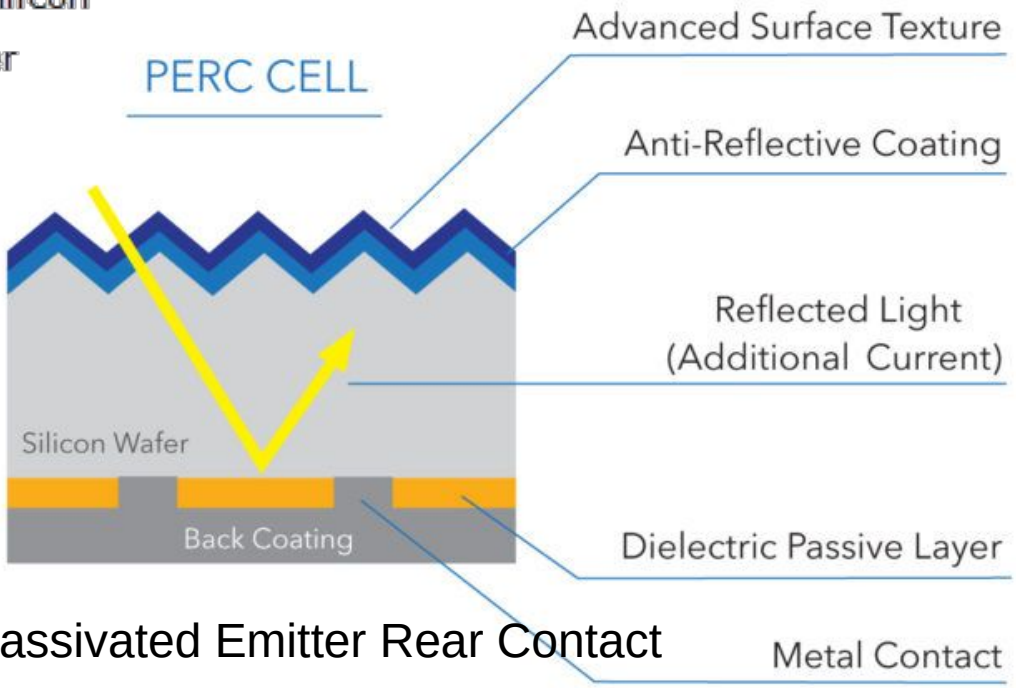
Solar Panels used to be the most expensive component. Now they comprise probably less than half of the total system cost.

Solar Panels



This is why panels need lots of cells

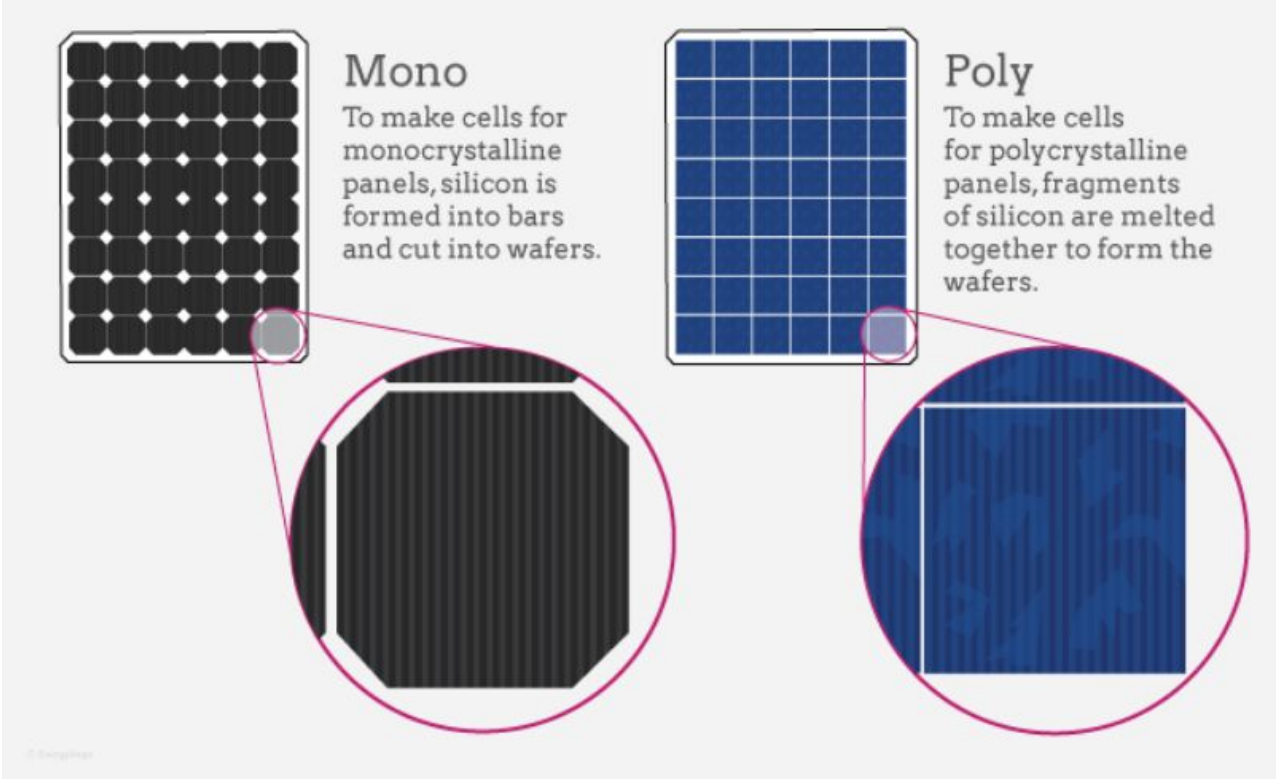
- Standard Single Solar Cell



- **PERC** - Passivated Emitter Rear Contact

Solar Panels

Monocrystalline **Polycrystalline**



Mono

- **more efficient:** may get 5 – 20 W more per panel
- **more expensive:** 5% to 10% more for given power output

Solar Panels

Rigid

Flexible

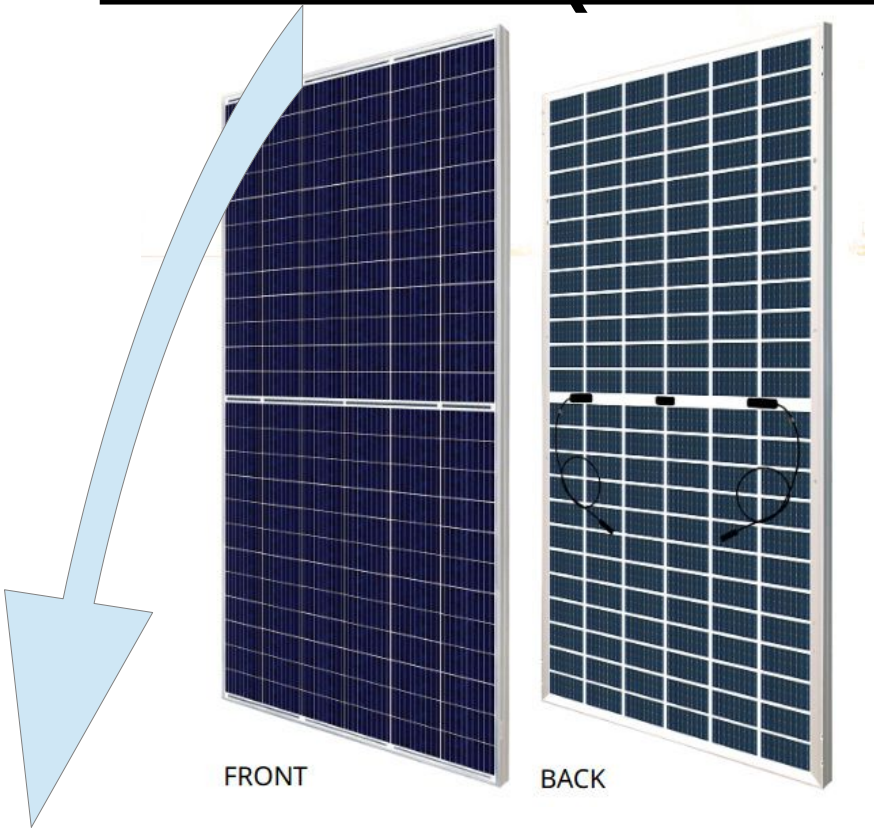
Rigid

- **more durable:** 20-30 year warranty vs. 2-10 year warranty
- **more heavy:** 18 lbs vs. 4 lbs (100 W size)
- **less expensive:** about $1 / Watt vs. $2 / Watt

Solar Panels

Single-sided

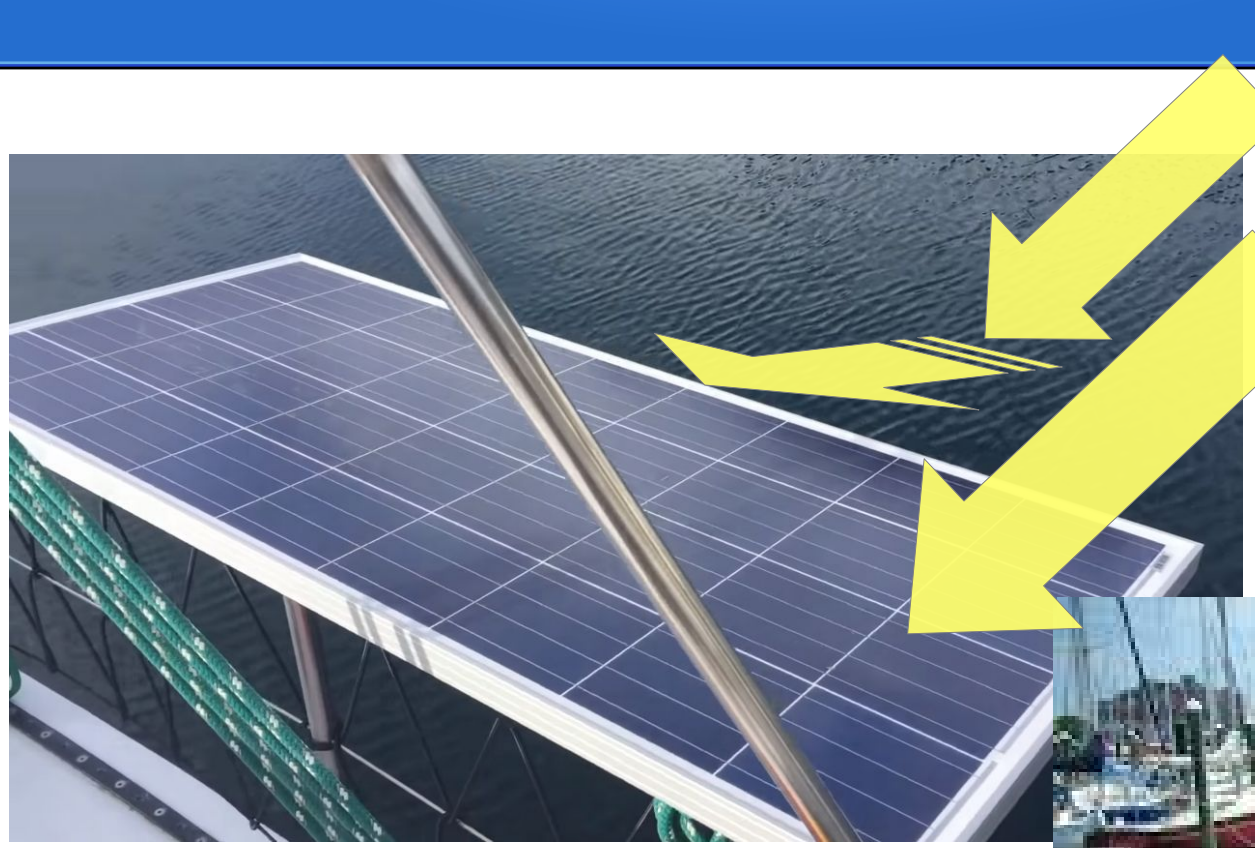
Dual-sided (BiFacial)



BiFacial

- **Efficiency:** up to 20% more power for given size
- **Durability:** double-sided glass decreases micro-cracks
- **Availability:** currently only available in 300+ Watt sizes

Solar Panels



Dual-sided (BiFacial)

captures **direct & reflected light**

Solar Panels

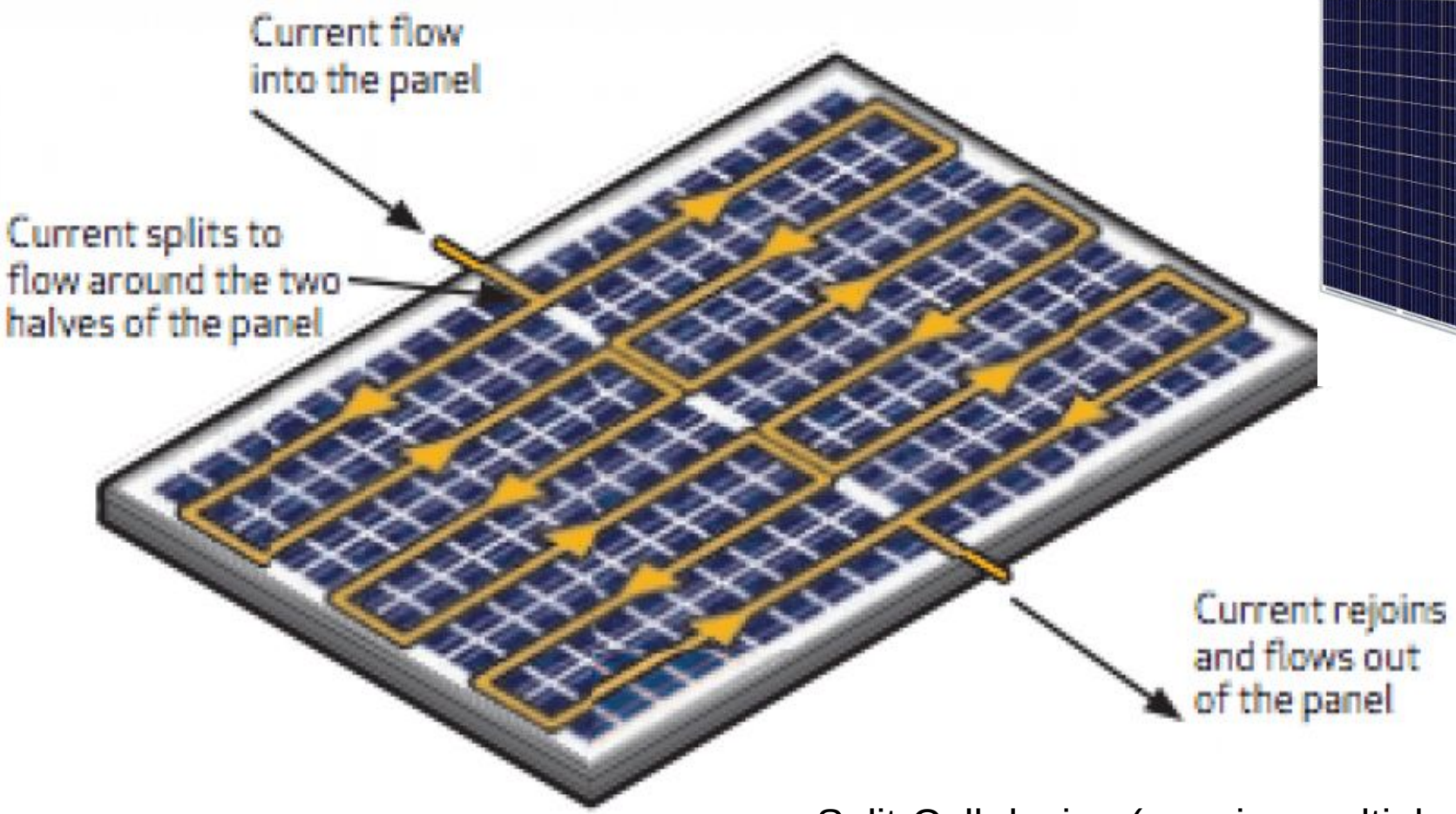
Why Is Shadowing Bad?

Current flows sequentially through each cell in the **string.**

A single shadowed cell blocks most of the current of the **entire string.**

Solar Panels

Split Cell panels help against shadowing



Split-Cell design (or using multiple smaller panels) means less loss due to shadows

Solar Panels

Steps for Selecting Panels

- **Choose Mounting Location**

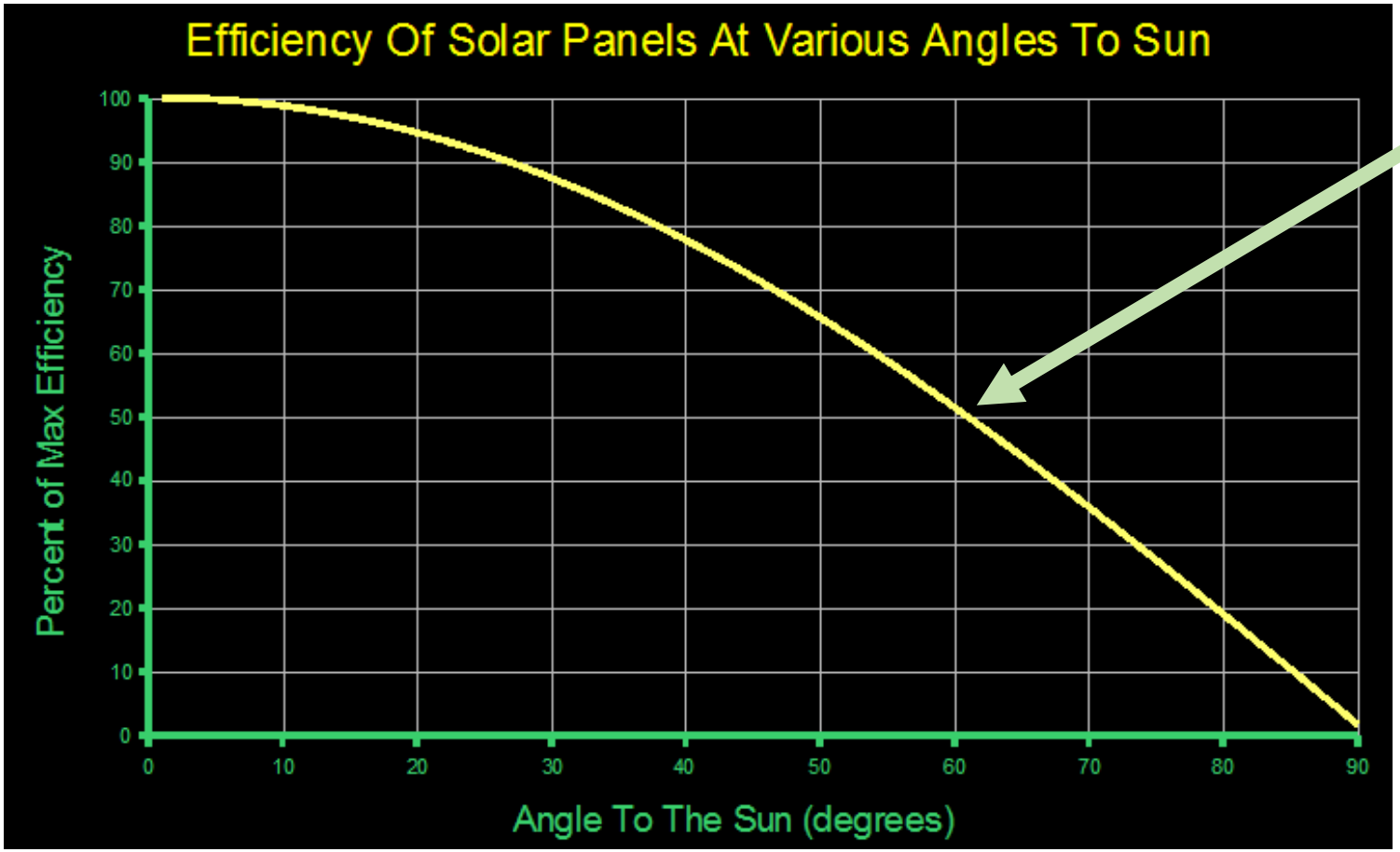
  consider *Shadowing, Protection, Wire Routing*

- **Decide on a mounting method**
- **Measure Max Dimensions that will fit**
- **Select biggest Panel(s) based on *efficiency, warranty, availability, cost***

Mounting: Aim Those Solar Panels !

- **Shaded panels output less than 1/3 usual power**, *even if only one cell is blocked. Some panels have bypass diodes so blocking one cell won't keep the rest of the cells from working. Split-cell panels have multiple independent strings of cells.*

- Panels not **pointing at the sun** won't give max performance.



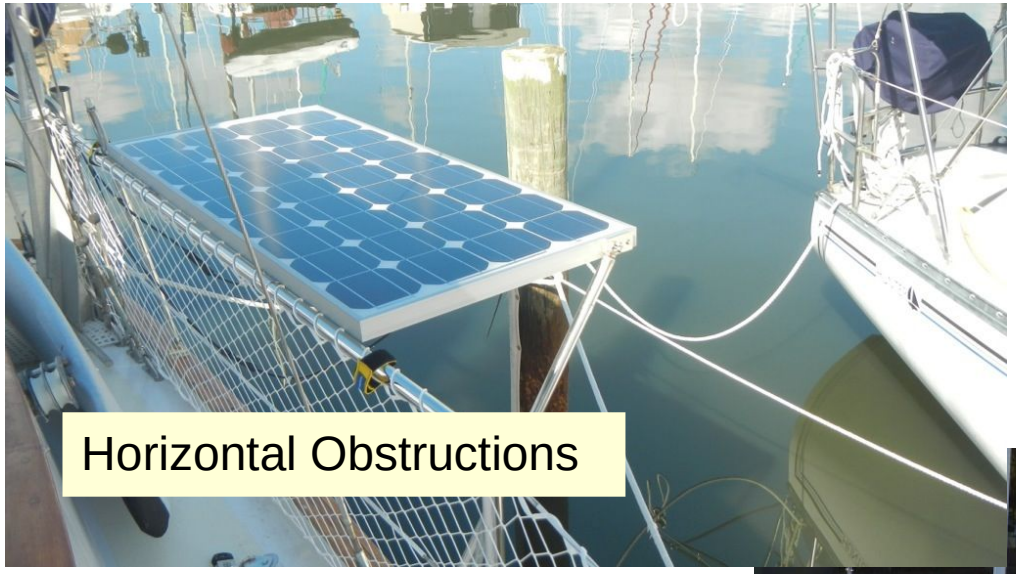
At 60° to the sun, output drops to 1/2 of full output.

Solar Panels

Lots of Mounting locations

Solar Panels

Factors to Consider



Horizontal Obstructions

Easily-undone Hardware (theft)

Shadowing !!!

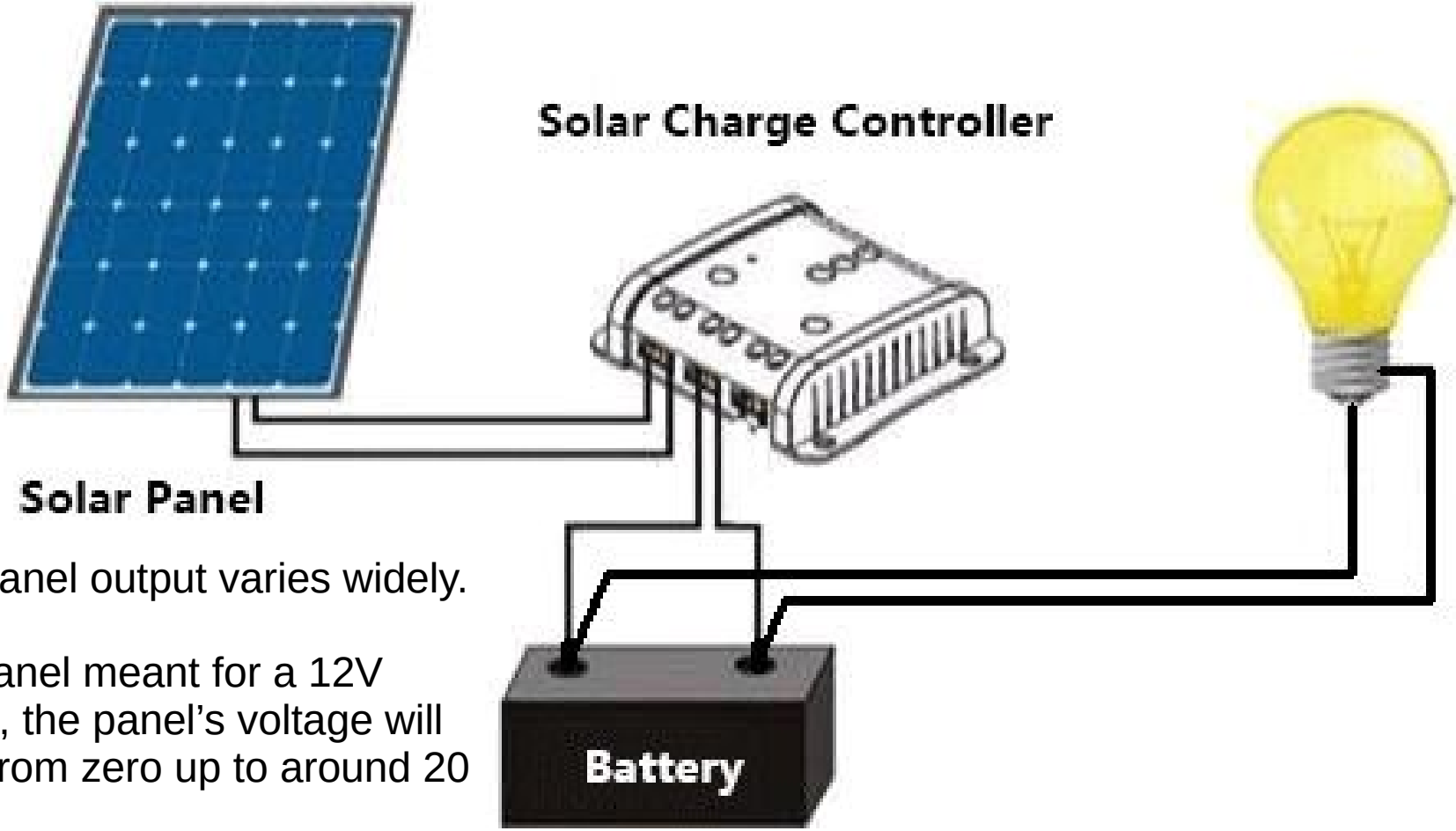
Solar Panels

Factors to Consider

Questions?

Charge Controllers

Regulates the charging of your batteries.



Solar panel output varies widely.

On a panel meant for a 12V system, the panel's voltage will range from zero up to around 20 Volts.

Charge Controllers

Two main types:

PWM – Pulse Width Modulation

Input connects directly to **Output,** so input voltage approximately equals output (battery) voltage

Turns ON – OFF at varying duty cycle to control the charging rate. Stops at fixed setpoint.

Least expensive method.

MPPT – Maximum Power Point Tracking

Input passes through a DC-DC converter, so **input voltage is not forced to equal output voltage**.

Controller picks the voltage at which the solar panel is most efficient, independent of battery voltage.

More expensive, but increases efficiency by ~20%.

Charge Controllers

How does MPPT work?

V_{oc} Open-circuit Voltage

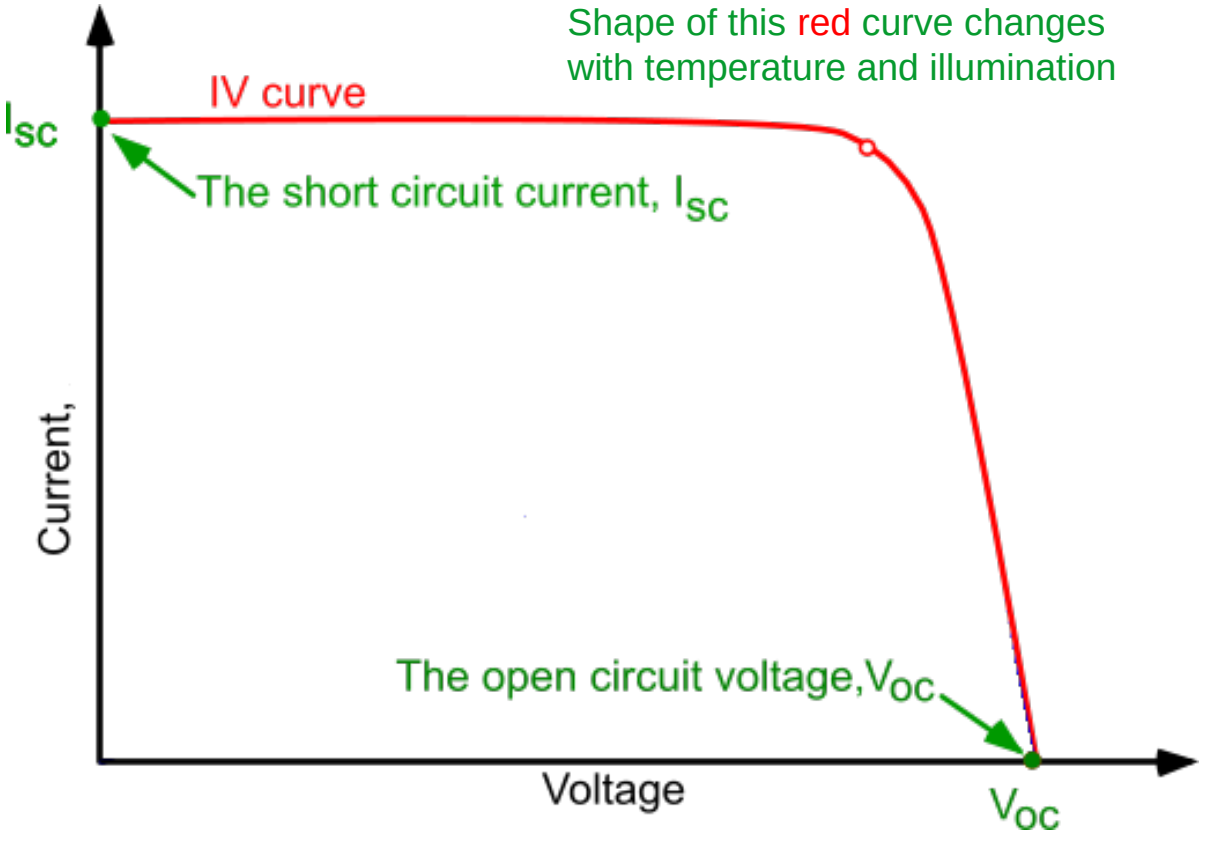
Voltage of the panel when no load is connected.

I_{sc} Short-circuit Current

Current from the panel when it is short-circuited.

V_{oc} & I_{sc} are found in panel's specs

Panel operates at any combination of voltage and current shown in **red.**



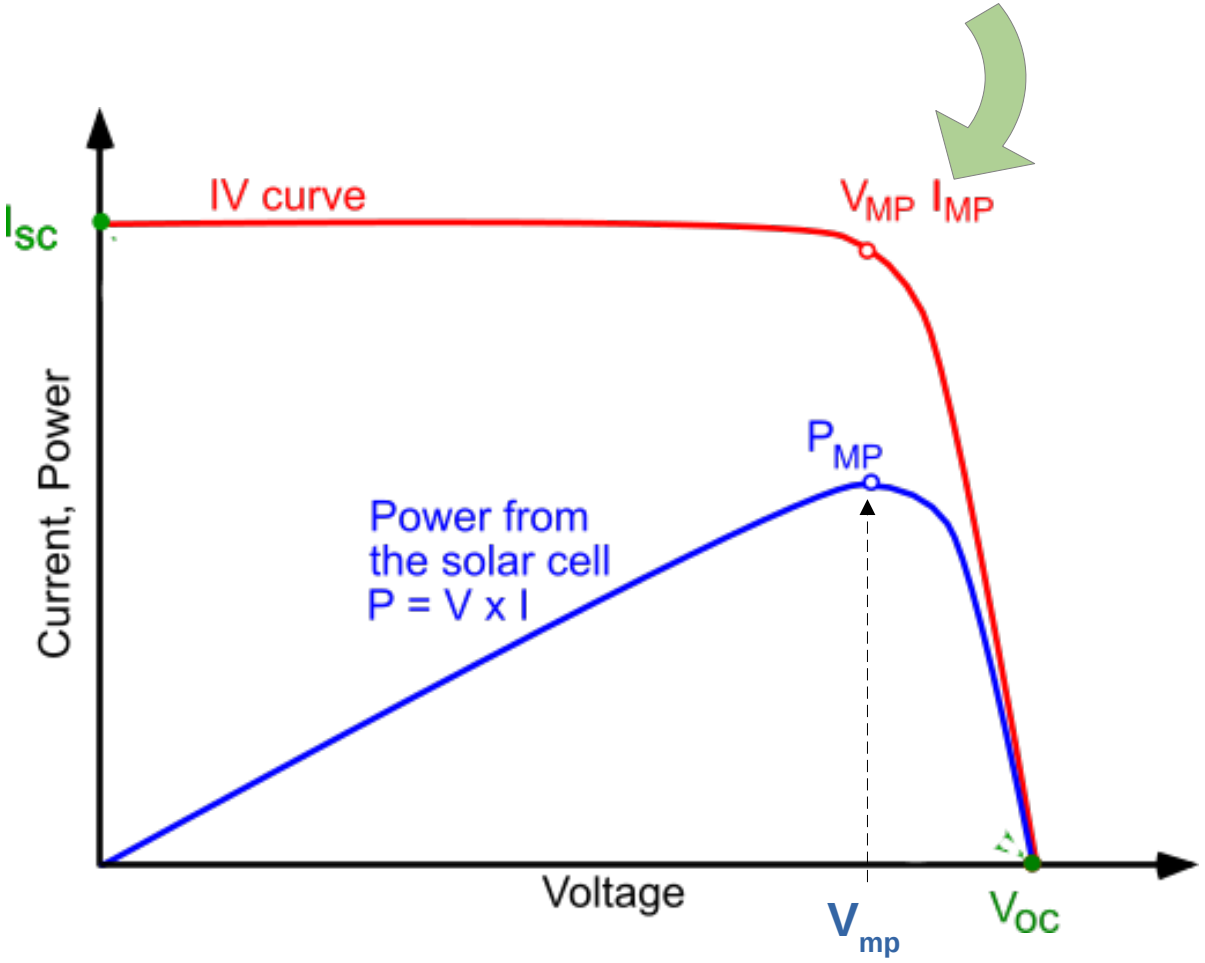
Charge Controllers

How does MPPT work?

Shape of this red curve (and hence the blue too) changes with temperature and illumination

Power = Current * Voltage

There will be a point at which the current * voltage (**blue line**) is a maximum. This is labeled P_{MP}



Charge Controllers

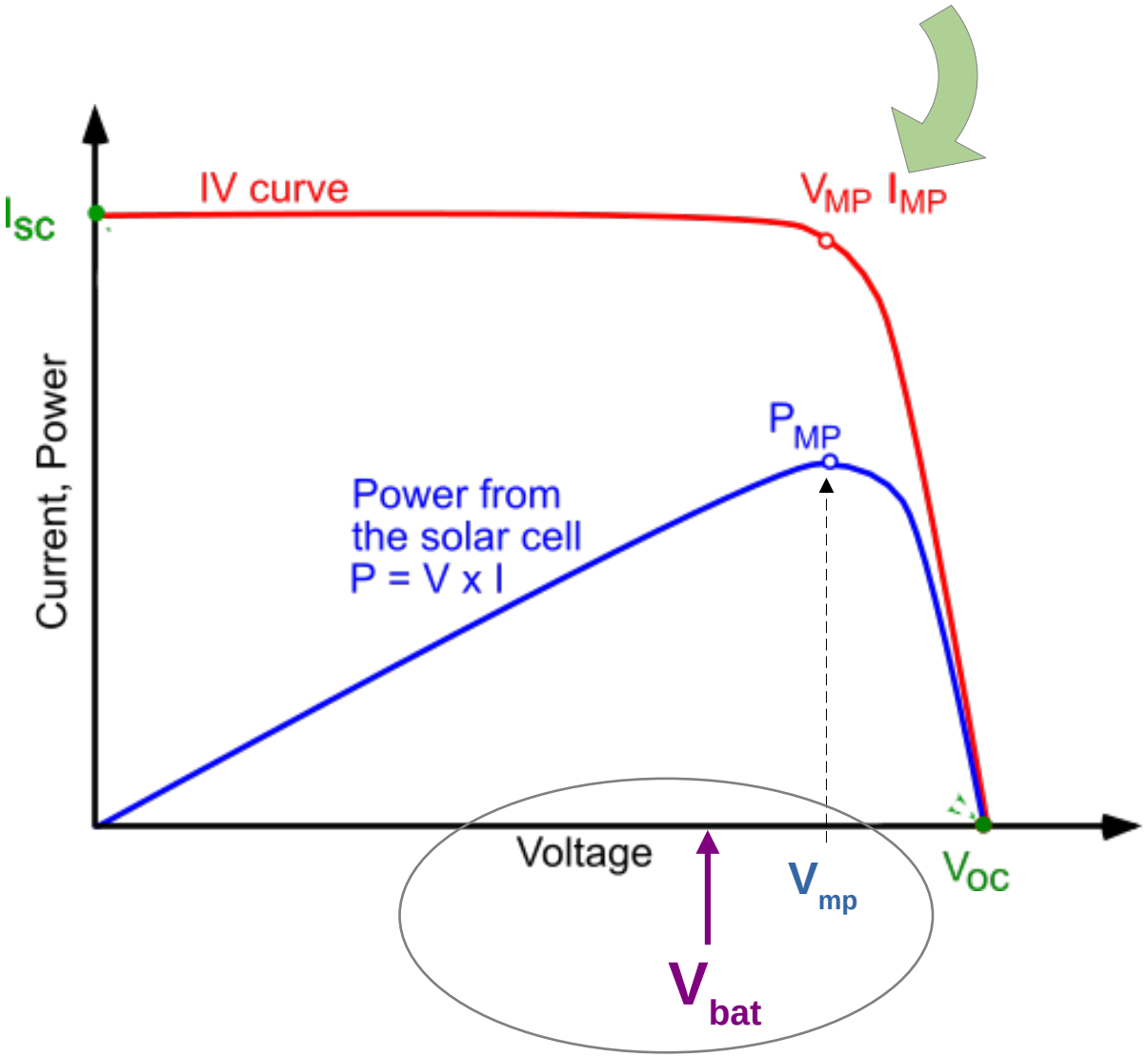
How does MPPT work?

Power = Current * Voltage

There will be a point at which the current * voltage (**blue line**) is a maximum. This is labeled P_{MP}

MPPT allows panel to operate at P_{MP} even when V_{bat} is not same as V_{MP}

Shape of this red curve (and hence the blue too) changes with temperature and illumination



Charge Controllers

Features to Pay Attention To

Voltage Rating Make sure that the controller is intended for your boat's DC system voltage (most commonly 12 V). Also ensure the controller is suited to the panel it is paired with (for 12 V systems, most common panels have V_{oc} = 17 V – 20 V range)

Current Rating The controller needs to handle at least the panel's I_{sc} (Short-circuit current).

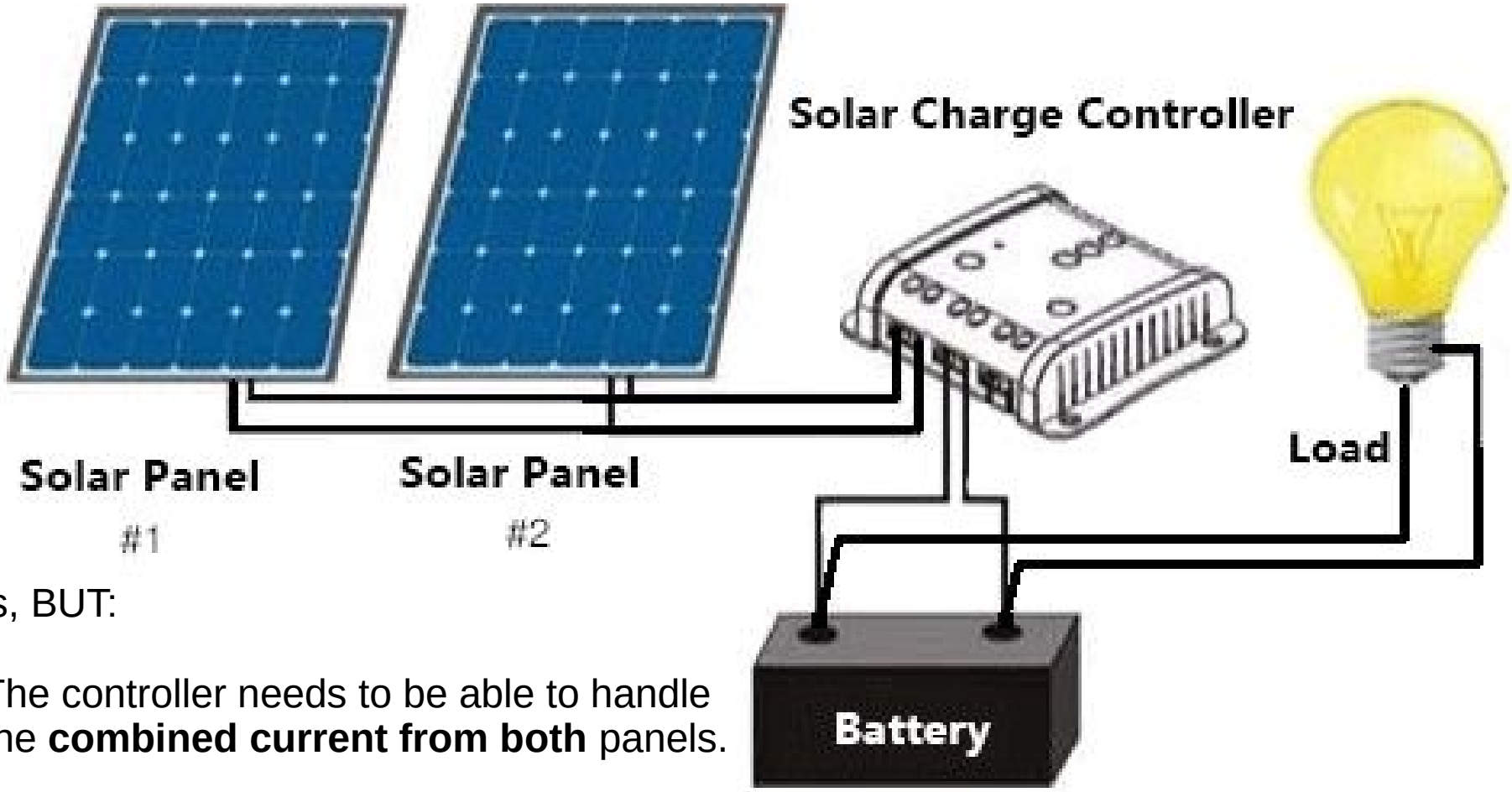
Battery Type Selection Many controllers allow selecting which battery type (e.g. Flooded Lead-Acid; AGM; Gel) they are connected to, for the proper charging voltages.

Battery Equalization Some controllers include a setting that performs battery equalization (which is suitable only for flooded lead-acid batteries).

Temperature Compensation Some controllers sense the temperature and adjust the charging voltages appropriately.

Charge Controllers

Can Multiple Panels share a Controller?

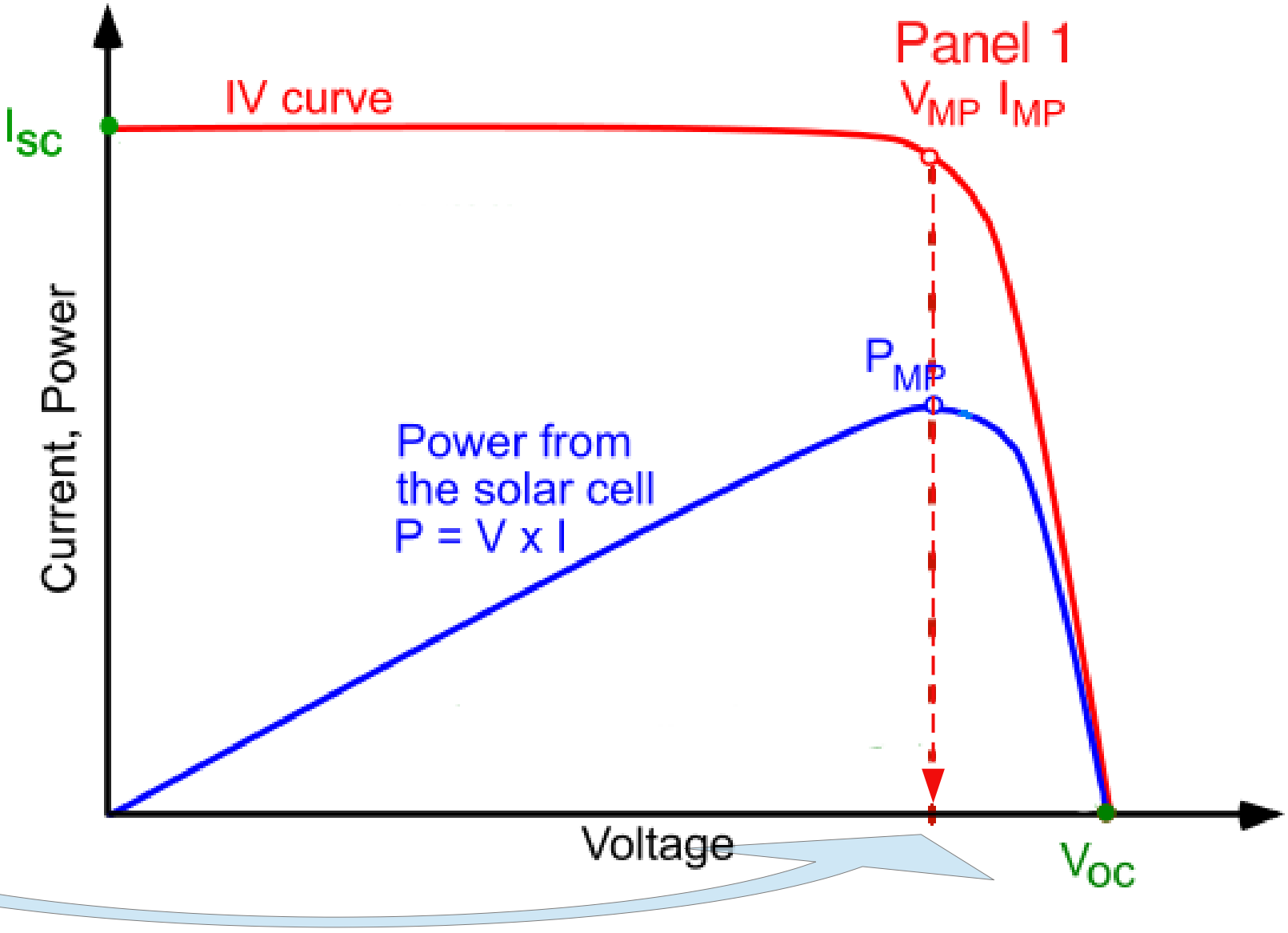


Yes, BUT:

- The controller needs to be able to handle the **combined current from both** panels.
- MPPT controller won't optimize performance unless both panels are **identical, and equally illuminated**.

Charge Controllers

Can Multiple Panels share a Controller?



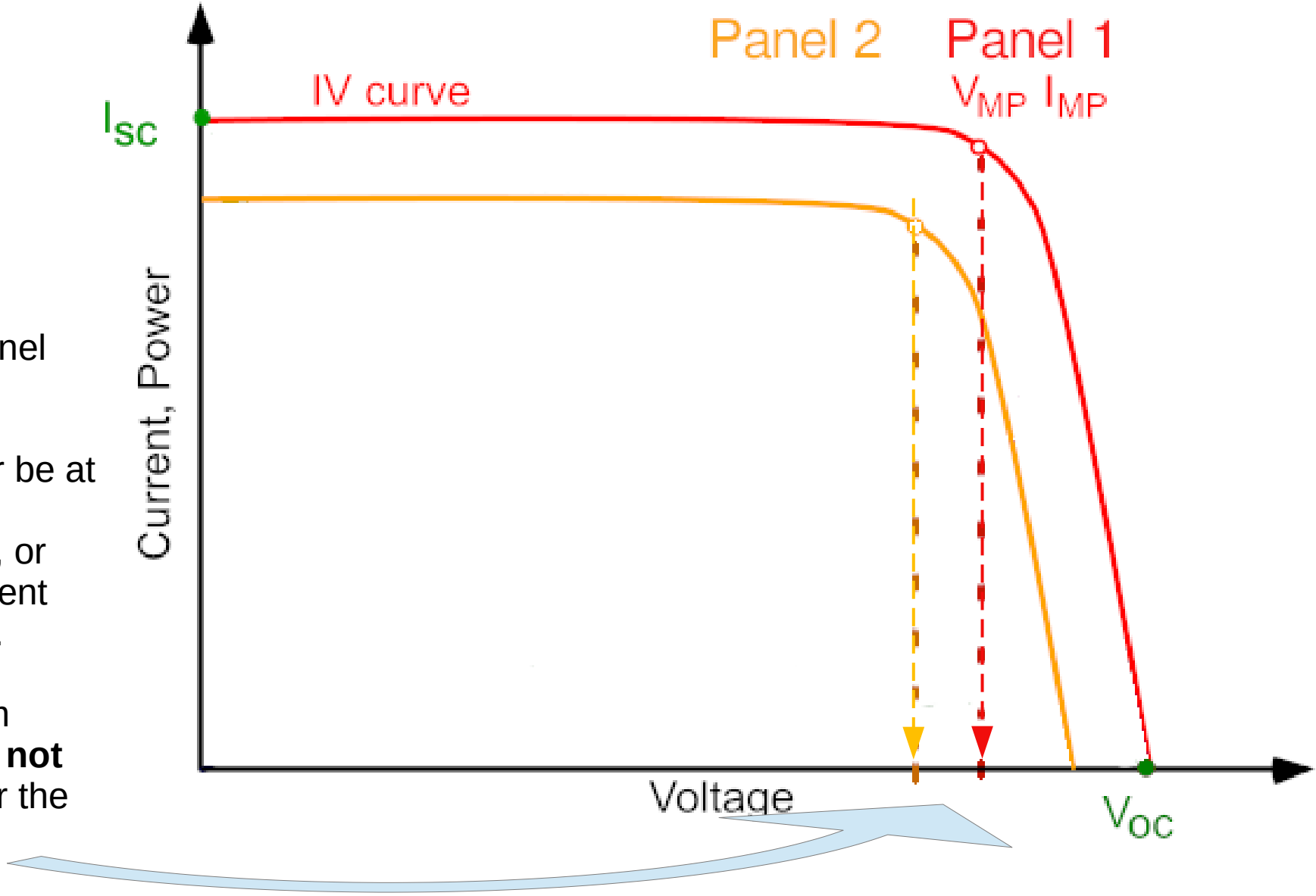
With **one panel**, the controller can find an operating point that maximizes power.

Charge Controllers

Can Multiple Panels share a Controller?

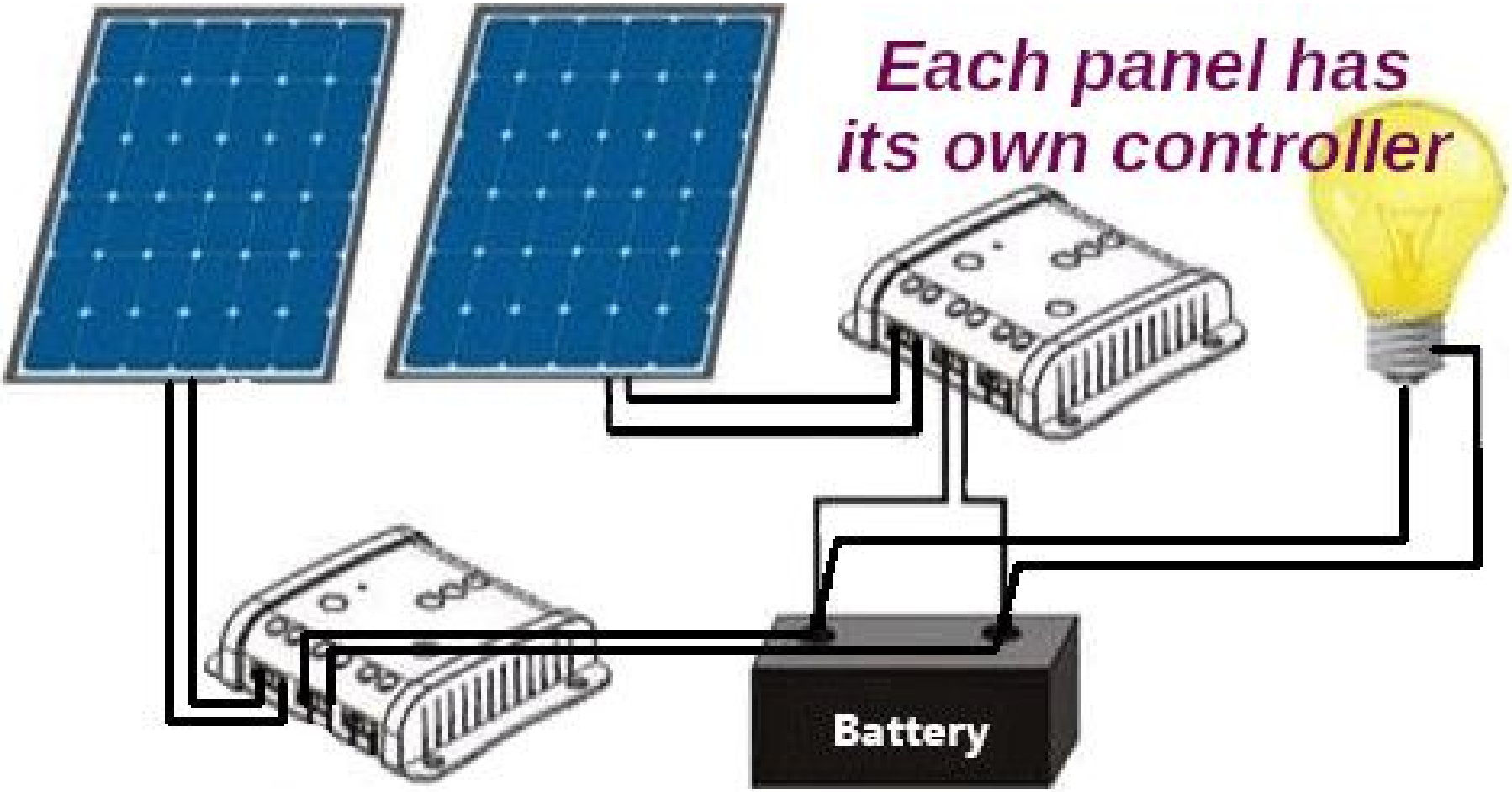
A second panel might be illuminated differently, or be at a different temperature, or even a different construction.

The optimum voltages are **not the same** for the two panels.



Charge Controllers

A More Efficient Arrangement



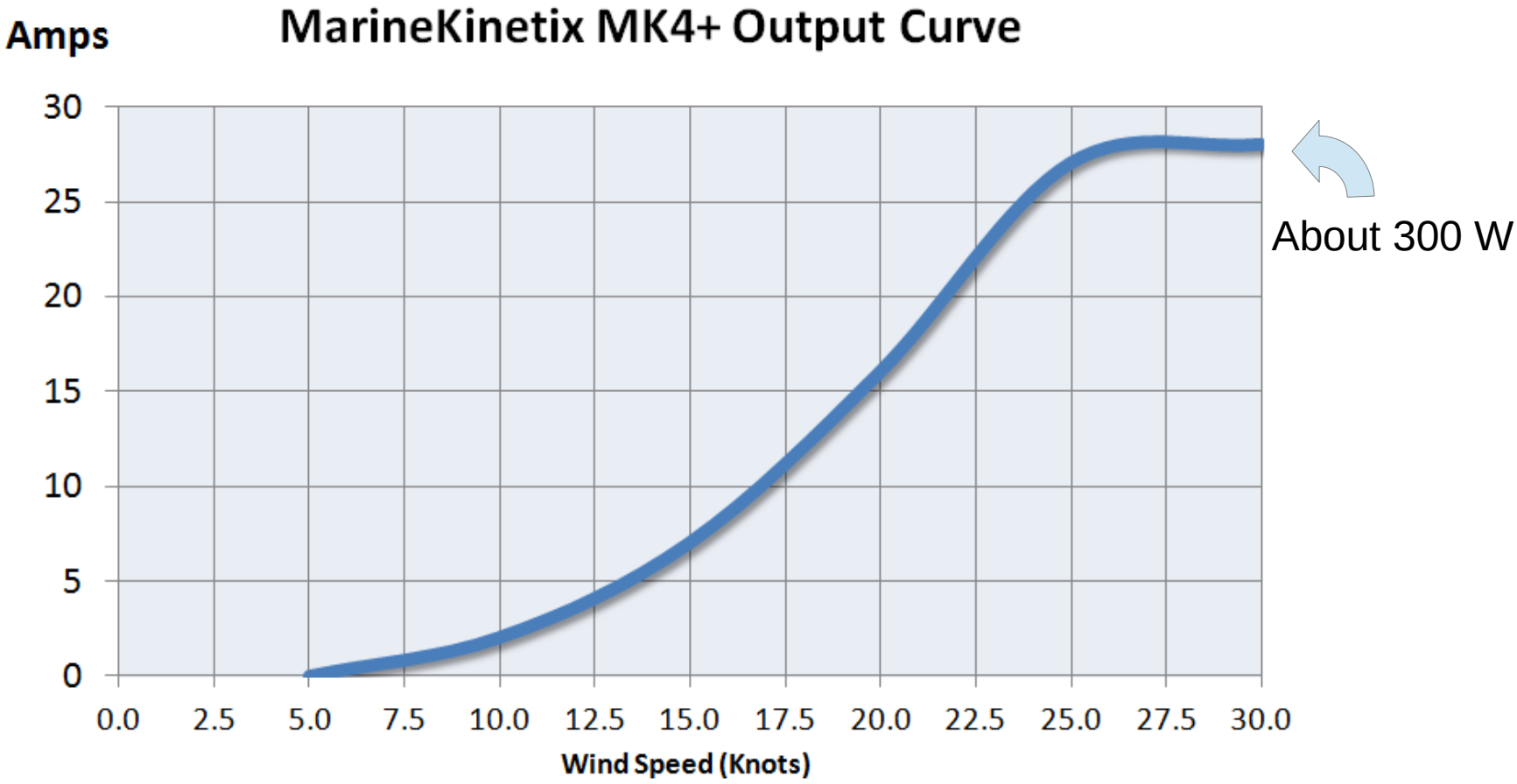
Each controller optimizes performance of its panel.
The panels need **not be identical, nor equally illuminated**.


Questions?
5 min break...

Wind Generators

Potential to generate lots of power

- Wind can blow 24 hrs/day; solar limited to 5-16 hours/day;
- Wind is energy-dense: power proportional to speed, cubed



Wind Generators

Comparisons to Solar

- Wind generators have moving parts – will need maintenance

  Warranties are usually in the 1 – 5 year range. Bearings will wear out. Blades may be damaged by striking objects.

- Not Silent. However, some models are quite good (e.g. MarineKinetix is rated at 35 dB @ 5m @ 10 knots (comparable to a fridge))

  A good strategy is to check marinas and anchorages for different models so you can hear the difference. Some manufacturers publish ratings, and there are comparative reviews available.

- Wind **can** be a good complement to solar: cloudy days can be windy, and sunny days can be calm. It depends heavily on where you cruise and in what seasons. *e.g.* in Trade-wind tropical areas the wind is quite reliable, while Pacific NW coast is pretty calm in summer.

Wind Generators

Factors to think about

- **Mounting** needs to be considered **before** you buy (just like with solar). There needs to be safe clearance for the rotating blades.

  Weight varies widely too: e.g. 17 lbs (MarineKinetix) compared to 37 lbs (Eclectic Energy)

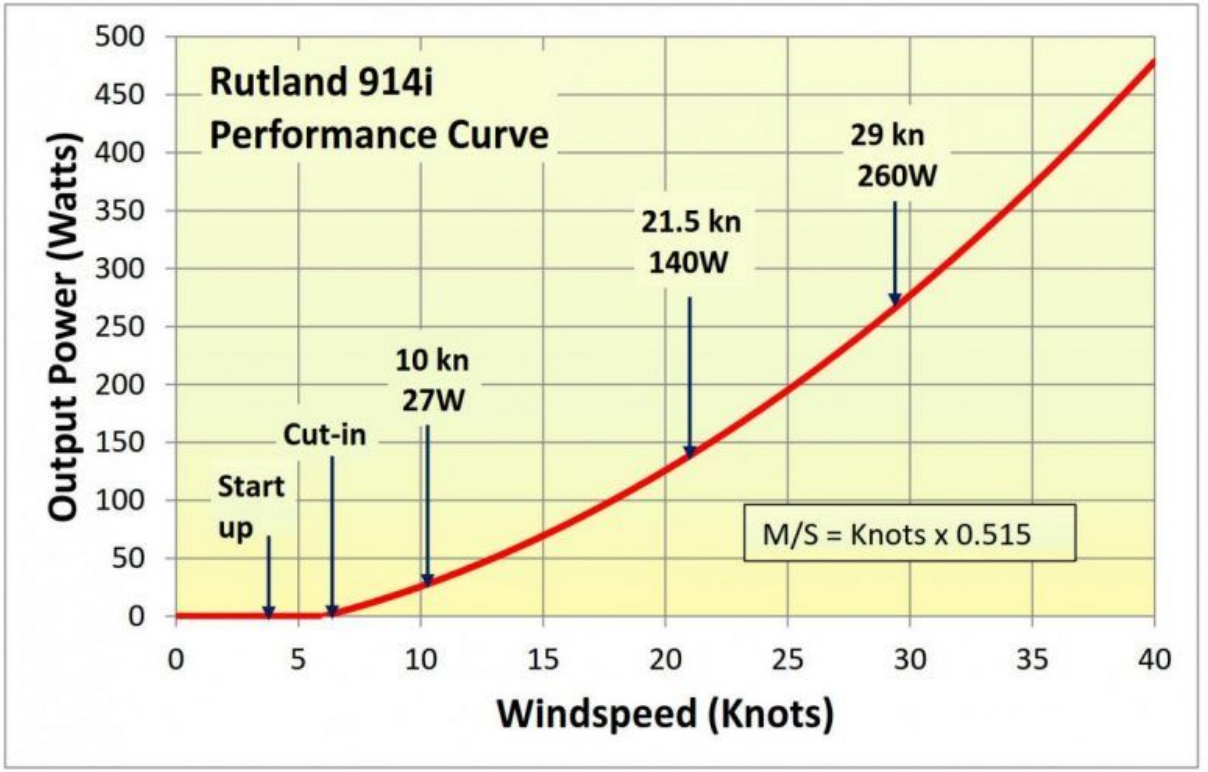
- **Braking** methods in high winds vary for different models: some are automatic, some are manual. Check the manufacturer's rating for maximum operating wind speed **and** for maximum safe wind speed.

Wind Generators

Factors to think about

- The **charge controllers** vary widely for different models. Some are a basic ON/OFF at a voltage setpoint. Some are not-included with the generator. Some have load-dumping (routing excess power to resistors). This can be useful e.g. if you have a hot-water tank.

There are a few that include connections for solar panels too (e.g. Rutland 914). If they have that plus MPPT, that could be desirable.



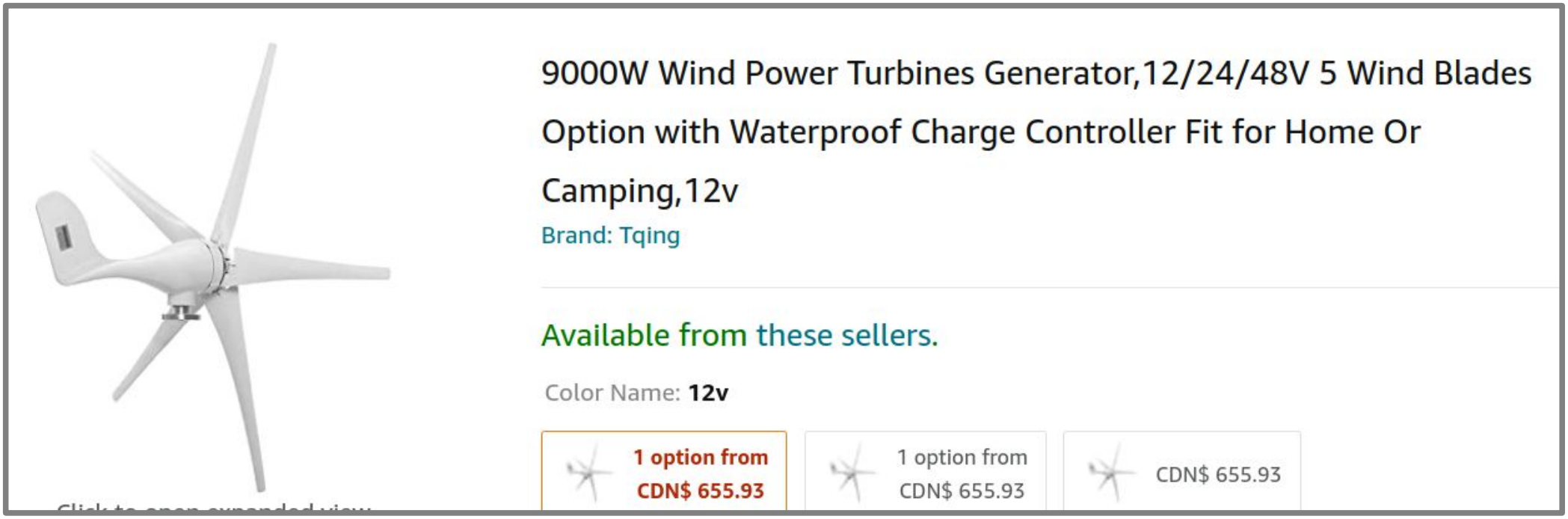
Wind Generators

Watch out for...

- Beware of models not designed for the marine environment or that have unusual claims.

This one is about 1/2 the price of established marine versions, and mentions only Home/Camping use.

I am **very skeptical** about the 9000W claim: that is a current of 9000 / 12 = 750 Amps !!!



Wind Generators

Ballpark Costs

($CAD, not including mounting)

- Rutland 914i $1245
- MarineKinetix MK4+ $1897
- Eclectic Energy D400 $2900
- Air Breeze $1739
- Silentwind 400 $2240

Compare these to cost of solar panels: approx $1 / Watt (also not including mounting)

Water Generators

Quick Overview

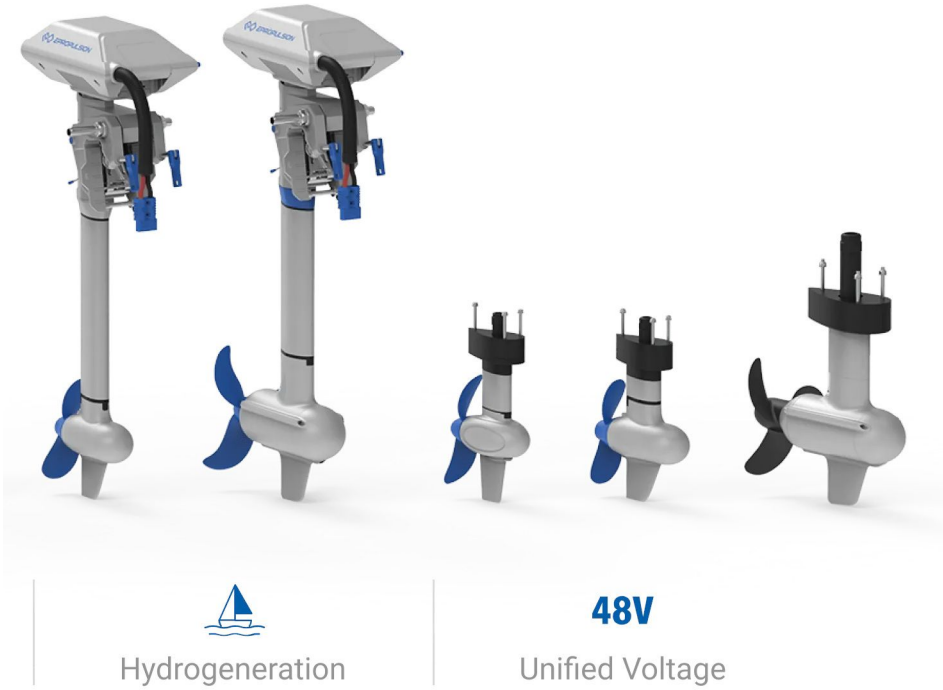
- An impeller submerged in water spins as the boat moves, which turns a generator.
- The impeller is either mounted on a pivoting leg (like an outboard) or tethered to the generator with a special rope. Trailing-type impellers are occasionally lost to large fish.
- Can produce around 100 - 600 Watts
- As electric engines become more popular on sailboats, decent hybrid propulsion+generation systems are being developed.

Water Generators

Combined Propulsion / Generation Units

Torqeedo

Thunderstruck



ePropulsion

Water Generators

Factors to Consider

- May slow the boat by 1/4 to 1/2 knot unless the wind is strong.
- Towed type can be less permanently-installed than most wind/solar systems.
- In trade winds, can generate 24 hours/day
- Can collect debris in water; may need clearing
- Darrell Nicholson's (*Practical Sailor*, Aug 2017) closing comment *"But right now, I think solar, then wind still reign in the world of ship-board alternative energy."*

Water Generators

Watt & Sea 600 review

- 150 W at 6 knots; 600 W at 12 knots
- $US 6000

Currents
16 Oct 2021
S/V Gargoyle


Questions?

Fossil-fuel Generators

Some reasons to have a generator

- **Emergency charging backup**, where the primary energy source is solar or wind
- To **avoid putting additional wear** on the primary engine, for vessels with insufficient solar or wind capacity
- For **higher-power loads** that the vessel's existing inverter and battery combination can't handle.

Fossil-fuel Generators

Factors to Consider

Which fuel? *Diesel* is much safer to carry, and most boats are already equipped with the tanks, jerry cans, filters and pumps to handle it. *Gasoline* generators are common and less expensive. *Propane* generators are becoming more popular, and while their fuel is hazardous, it is also one that most vessels carry.

> Calculate a power-budget to figure out how powerful a generator you want, and how much fuel you will need to carry.

Prices start at around $600, up

Champion Power Equipment 100574 4000-Watt RV Ready Digital Hybrid Inverter Generator with Dual Fuel Technology

Brand: Champion Power Equipment

4.5 ★★★★½ 104 ratings

Price: CDN$ 1,872.52 & **FREE Shipping**

Get a **$5 promotional credit** on reload of **$100 or more** to your Amazon.ca Gift Card Balance.

New (2) from CDN$ 1,872.52 + FREE Shipping

Style: **4000-Watt + Dual Fuel + Manual Start**

Fossil-fuel Generators

Factors to Consider

- How **Quiet** is it?

Normal conversation at 1m is about 60 dBA

6 dBA increase sounds about 1.5 times louder.

Model	Noise Rating
A-iPower Yamaha SC2000iV	58 dBA @ 50% @ 7m
Hyundai HY2000si	50 dBA @ 25% 59 dBA @ 100%
Honda EU2200i	48 dBA @ 25% @ 7m 57 dBA @100% @ 1.5m
Champion 4000W Hybrid	64 dBA @ 7m

- **Radio Frequency Interference (RFI)**. Most generators are quite noisy from a radio perspective – affecting the whole anchorage. Unfortunately, manufacturers don't publish their measurements.

Fossil-fuel Generators

Factors to Consider:

- **Does it include 12V output?** Some (e.g. Honda EU2200i) have 12 VDC output in addition to 115 VAC. However, it may not be possible to use both at the same time – check the specifications carefully.

- **How To Connect To It?** Can be permanently-wired to your vessel's AC system (a good choice for larger generators that will want a dedicated operating location anyway). Consult with a qualified marine electrician for this. Another option is to use an extension cord and just plug in your individual loads – this is the easiest option for infrequent emergency use.

  If tying into your vessel's AC system, you will need to properly deal with grounding, overload protection, and methods to switch between shore power, generator power, and battery/inverter power.

- **Environmental Impact** Burning fossil fuels, disposing of used oil are undesirable.

Fuel-cell Generators

Consume Methanol, Produce Electricity

Converts chemical energy of Methanol + Oxygen into electrical energy without interim stages and with high efficiency.

Methanol comes from a fuel cartridge, while oxygen is taken from the air.

Besides electricity, byproducts are heat, water vapour, and carbon dioxide.

Fuel-cell Generators

Consume Methanol, Produce Electricity

- EFOY generators come in 3 sizes: 80, 140, 210. The model 80 produces 40 W output (remember that this can be 24 hrs/day) and weighs only 6.5 kg.
- Model 80 costs about $3600 (Jan 2022) Model 210 costs about $7200.
- Methanol is supplied in 5, 10, 28 and 60 litre plastic containers. EFOY does not recommend using any other source of methanol.
- Methanol consumption is about 0.9 litres per kW·Hr. For a 12V system, this is about 92 A·Hr per litre. A 5 litre cartridge costs $90, so your fuel cost is about $0.20 / A·Hr.
- Output power drops linearly at about 25% per 3000 hrs.
- The generators can charge all types of 12V lead-acid batteries, plus $LiFePO_4$ and some Li-ion.
- The latest models come with a Bluetooth interface so you can monitor their performance using your smartphone.


Questions?

Energy Budget

Energy Budget

A way of checking whether your electrical system can provide enough power to meet your desires.

Energy Budget

1st Law of Thermodynamics
NoFreeLunch

Energy Budget

Electrical Energy **In** = *Electrical Energy* **Out**

How do we measure Electrical Energy?

Watt • hours or **Amp • hours**

Technically more correct.

BC Hydro uses this (kW•h)

Less proper, as it assumes a fixed voltage.

Battery Manufacturers usually use A•h

Energy Budget

Example: measure Energy use of **Nav Light**

Nav Light consumes 1.5 Amps (measured with meter)

multiply by 12.0 Hours (daily usage)

18.0 A•h per day

If we wanted to express this in Watt Hours, we multiply by the voltage (12 V):

18 A·h * 12 V = 116 W·h

Energy Budget

Daily Consumption

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Totals			

Daily Production

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Totals			

- In a spreadsheet, total up all your electrical loads.
- On a separate section total up all your energy producers.

The difference between the two totals is your energy suplus / deficit. This surplus / deficit will fill or deplete your batteries.

Energy Budget

Daily Consumption

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Nav Light	1.5	12	18
Windlass	75	0.02	1.5
Fridge	3	10	30
Totals			

Daily Production

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Solar Panel	3.5	8	28
Wind Gen	8	2	16

Tips:

- Focus on your major energy consumers
- Measure, or use manufacturer’s specs to determine Current
- Estimate your daily Usage time.
- You may need separate budgets for **At-Anchor** and **On-Passage**

Energy Budget

Daily Consumption

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Nav Light	1.5	12	18
Windlass	75	0.02	1.5
Fridge	3	10	30
Totals			**49.5**

Daily Production

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Solar Panel	3.5	8	28
Wind Gen	8	2	16
			44

Add up your electrical Consumption and Production.

If your consumption is greater than your production, this amount of energy is taken from your batteries daily. It **must be replaced** (plus a little bit more, to account for losses), otherwise your **batteries will eventually run flat**.

Energy Budget

Daily Consumption

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Nav Light	1.5	12	18
Windlass	75	0.02	1.5
Fridge	3	10	30
Totals			**49.5**

Daily Production

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Solar Panel	3.5	8	28
Wind Gen	8	2	16
			44

What can we do with an Energy Budget?

- ➔Choose a size for your House Batteries
- ➔Estimate how long you can cruise under various scenarios
- ➔Estimate engine run-time daily/weekly/monthly

Energy Budget

Let's pretend it's a cloudy day...

Daily Consumption

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Nav Light	1.5	12	18
Windlass	75	0.02	1.5
Fridge	3	10	30
Totals			**49.5**

Daily Production

Item	*Current [A]*	*Usage [h]*	*Energy [A*h]*
Solar Panel	3.5	2	7
Wind Gen	8	2	16
			23

In this example, we have a daily deficit of about 27 A·h. If our battery bank is 200 A·h capacity, it will be totally empty in 200 / 27 = about 7 days.

So a good way to think about it is: how many days do I need to run my boat under various conditions (e.g. cloudy days) before I have to resort to other charging methods (e.g. engine). Then size your batteries accordingly.

Energy Budget

Sizing Your House Batteries

1. Decide on # of days you want to power your boat without needing external / supplemental charging
2. Multiply # of days by the daily deficit in your energy budget
3. The answer is the **minimum** battery bank capacity

Example:

5 days between running engine
Daily **Production 30 A·h**
Daily **Consumption 75 A·h**

$$5 * (75 - 30) = 5 * 45 = \mathbf{225\ A{\cdot}h}$$

Days * **Deficit** = **Minimum Battery Bank Capacity**

Energy Budget

Additional Sizing Thoughts...

Minimum Battery Bank Size does not take into account factors such as avoiding fully discharging the batteries (more on this later).

You may want to make allowances for **reduced Production** (e.g. extended cloudy periods) or **reduced Consumption** (e.g. energy-saving measures like timed-sleep-mode on radar). Play with the spreadsheet values to get a feel for different scenarios.

Energy Budget

External / supplemental charging is any form of charging you want to reduce or avoid, like running the engine, plugging into shore power, or running a generator.

Estimating Supplemental Charging Time

1. Calculate your daily deficit
2. Divide deficit by your external / supplemental charging rate
3. The answer is the **hours / day** you need supplemental charging

---

Example:

Daily **Production 30 A·h**
Daily **Consumption 75 A·h**
Alternator Output 40 A

(75 – 30) / 40 = 45 / 40 = **1.13 h** (1h 8m)

Deficit / Charge Rate = Daily Run Time

Energy Budget

Additional Charge Time Thoughts...

You don't need to perform the calculated charging every day, however you need to eventually make up for any lost charging time. (recall that Battery Bank size determines how long you can go without charging)

Charging rate can be difficult to estimate, as it is rarely constant and is affected by multiple factors (more on this later).

Approaches that reduce your charging time are worthwhile, by reducing engine run time, for example. These approaches include smart chargers, alternator upgrades, etc.

A common misconception is that **adding more battery capacity** will balance your energy budget. No – it will just **allow you to wait longer before charging** becomes necessary.

Balancing Your Budget

- Consume Less Power

  LEDs, upgrade Fridge insulation, avoid Inverters, etc

- Reduce the On-time

  Transmit less often, Shorten laptop use, Raise fridge temperature

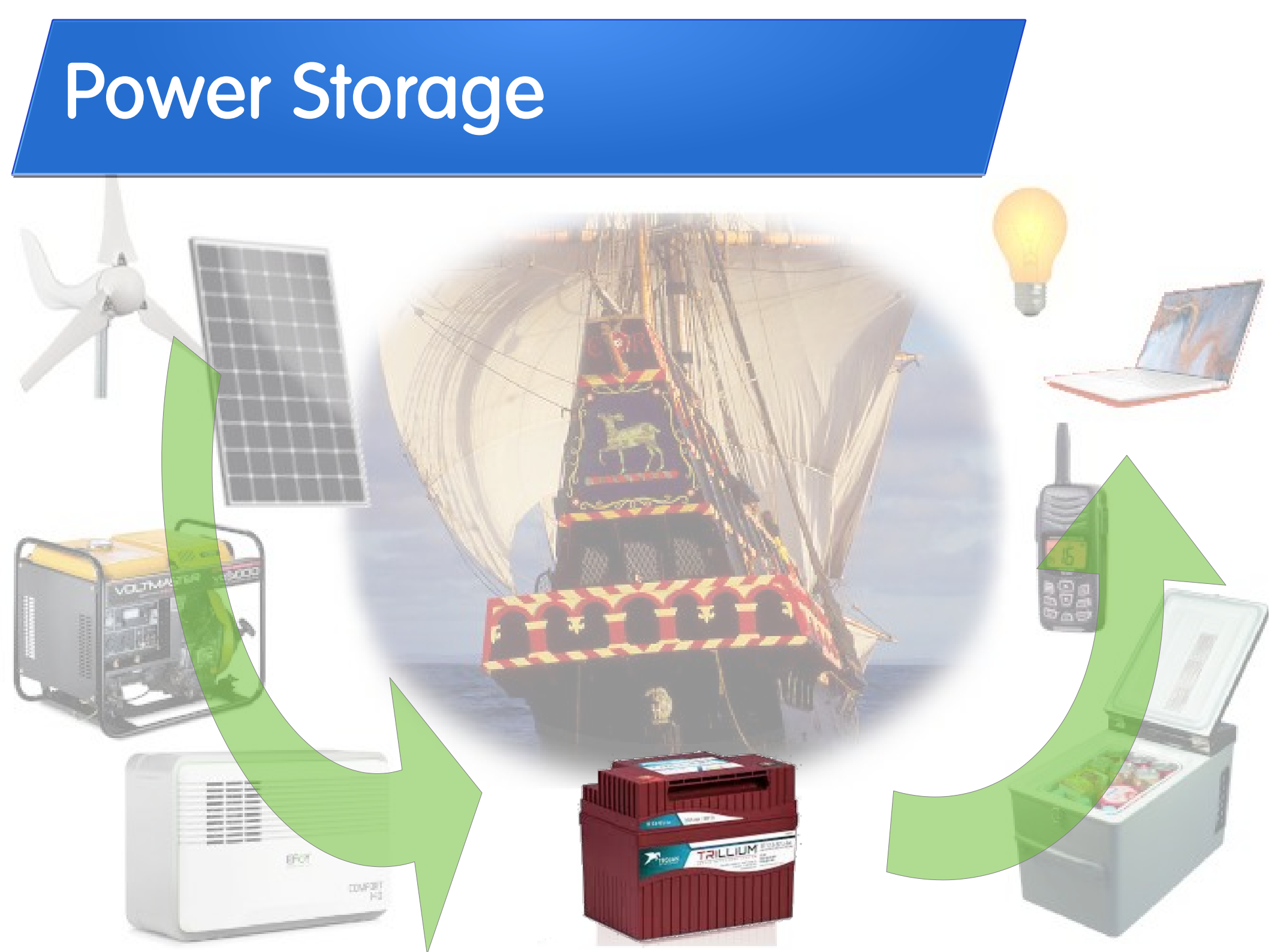
- Add More Generating Capacity

  Bigger alternator, more solar panels, etc.

  Multi-modes may help (e.g. Wind + Sun)


Questions?

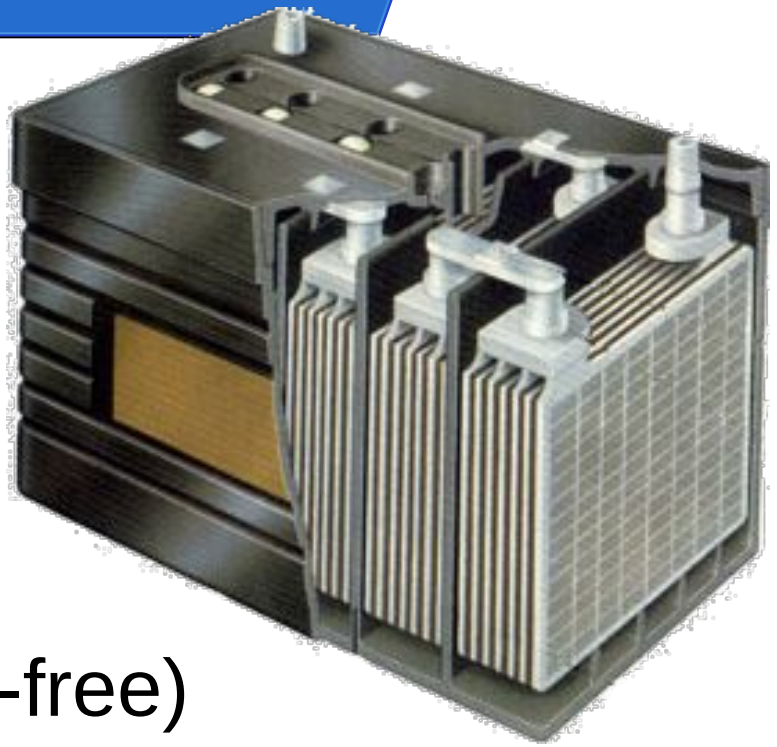
Power Storage



Battery Types

Lead-acid

Lead-alloy plates, immersed
In sulphuric acid electrolyte



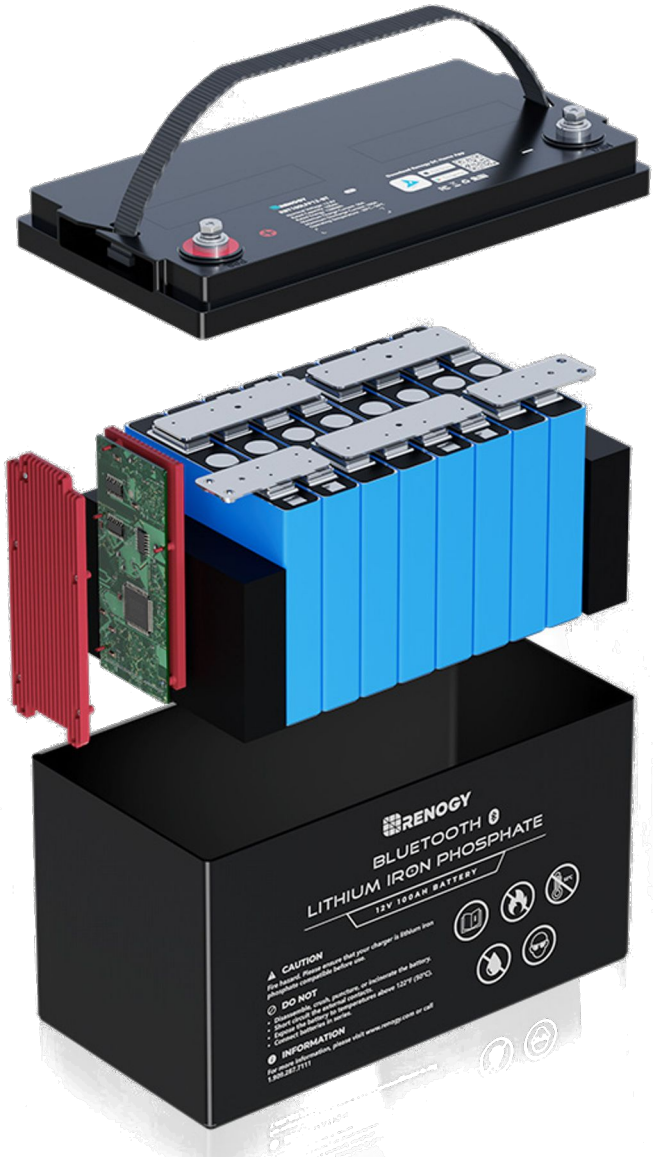
- **Flooded**
- **Sealed** (SLA, maintenance-free)
- **Absorbed Glass-Mat** (AGM, spill-proof)
- **Gel** (also spill-proof, electrolyte is in gel-form)

Battery Types

Lithium-ion

Lithium Iron Phosphate

($LiFePO_4$ or LFP)



There are many other Lithium-ion chemistries, such as Lithium-ion Polymer (LiPo) used in phones, etc.

These other Lithium-ion types are not recommended for main boat storage batteries.

Battery Recycling

Lead-acid **Good existing infrastructure**

Lithium **Developing, especially in EU**

Li-Cycle Canadian company, with spokes in USA and Norway

Battery Materials (Black Mass)

Mixed Copper/Aluminum

Lithium Carbonate

Cobalt Sulphate

Manganese Carbonate

Nickel Sulphate

Battery Terminology

Capacity amount of energy a battery can store. Usually reported in A·h

Charge / Discharge Rate amount of current passing in / out of battery. Reported in A, or as a fraction of battery's capacity. E.g. Drawing 10 A from a 100 A·h capacity battery discharges it at 0.1C

Depth of Discharge percent of total capacity that has been pulled from the battery. e.g. 80% DoD on a battery means 20% of its total capacity remains.

Series connecting batteries in series adds the voltages, but the A·h capacity remains the same.

Parallel connecting batteries in parallel leaves the voltage the same, but adds the A·h capacity.

Battery Terminology

Cell Balancing A battery is a collection of cells connected in series and/or parallel. Slight variations in construction and environment cause individual cells to differ in their DoD. Cell balancing reduces these differences.

Battery Life how long a battery lasts, expressed as time or # of cycles, before it's capacity drops to a defined percent of original. It can be hard to compare Battery Life claims, as different manufacturers define the end-of-life differently and test under different conditions.

Battery Management System circuit(s) that protect a battery's cells from harmful conditions (e.g. over-temperature, over-current, over-discharge, etc.) The BMS can be outside or inside the battery. The BMS also performs cell-balancing.

Lead-Acid Batteries

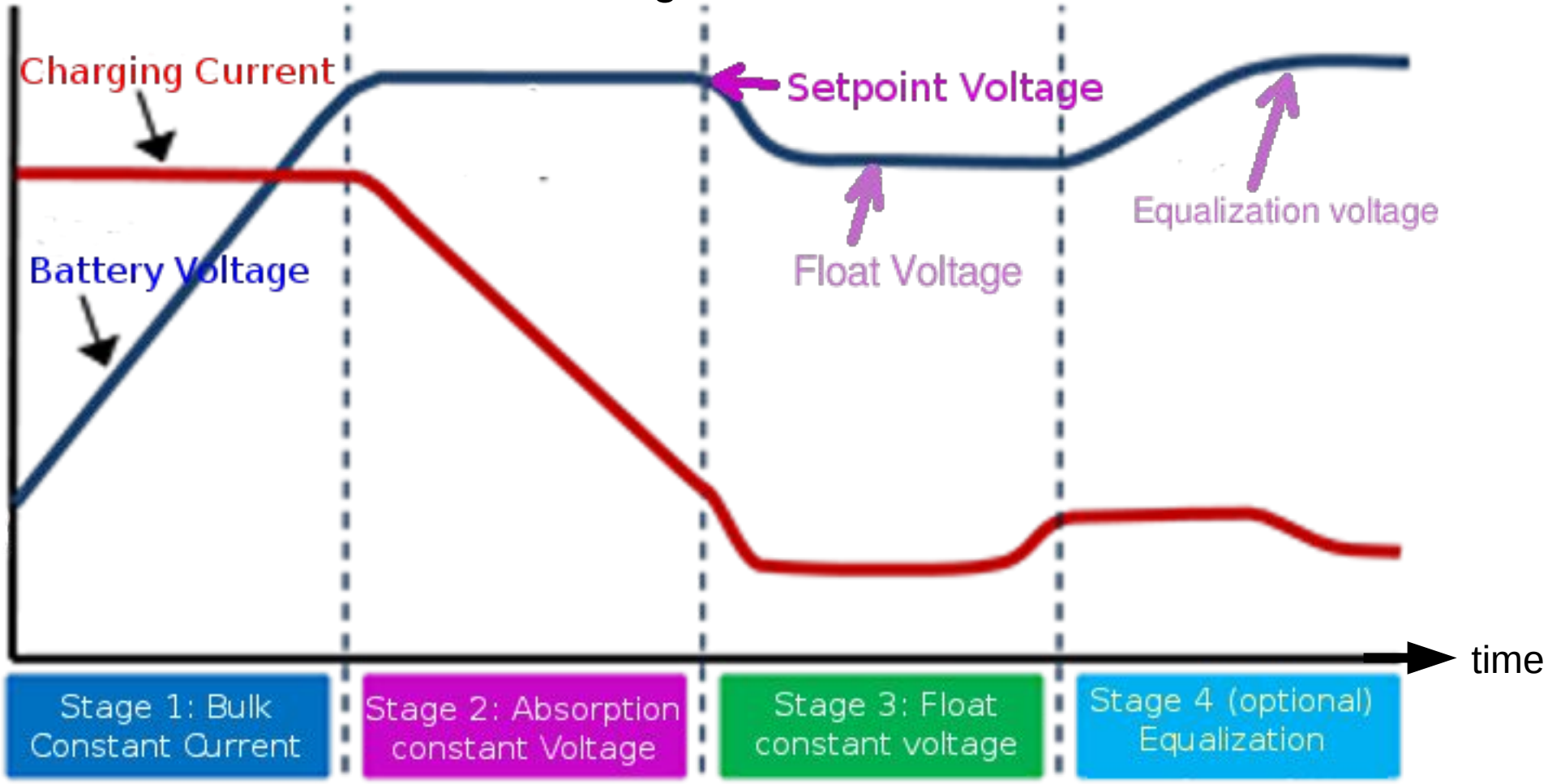
- Most common battery chemistry
- Recommended **Charging Profile** usually has 3 stages:
  - ***Bulk***, or ***Absorption***. High constant current until battery voltage reaches setpoint (differs for different types of lead-acid battery)
  - ***Topping***, ***Acceptance***, or ***Saturation***. Maintains voltage at setpoint until current drops to 3-5% of total capacity
  - ***Float***, or ***Maintenance***. Drops the charging voltage to approx 13.5 V and maintains it at this constant level.

Different types of Lead-acid batteries have slightly different charging profiles

Lead-Acid Batteries

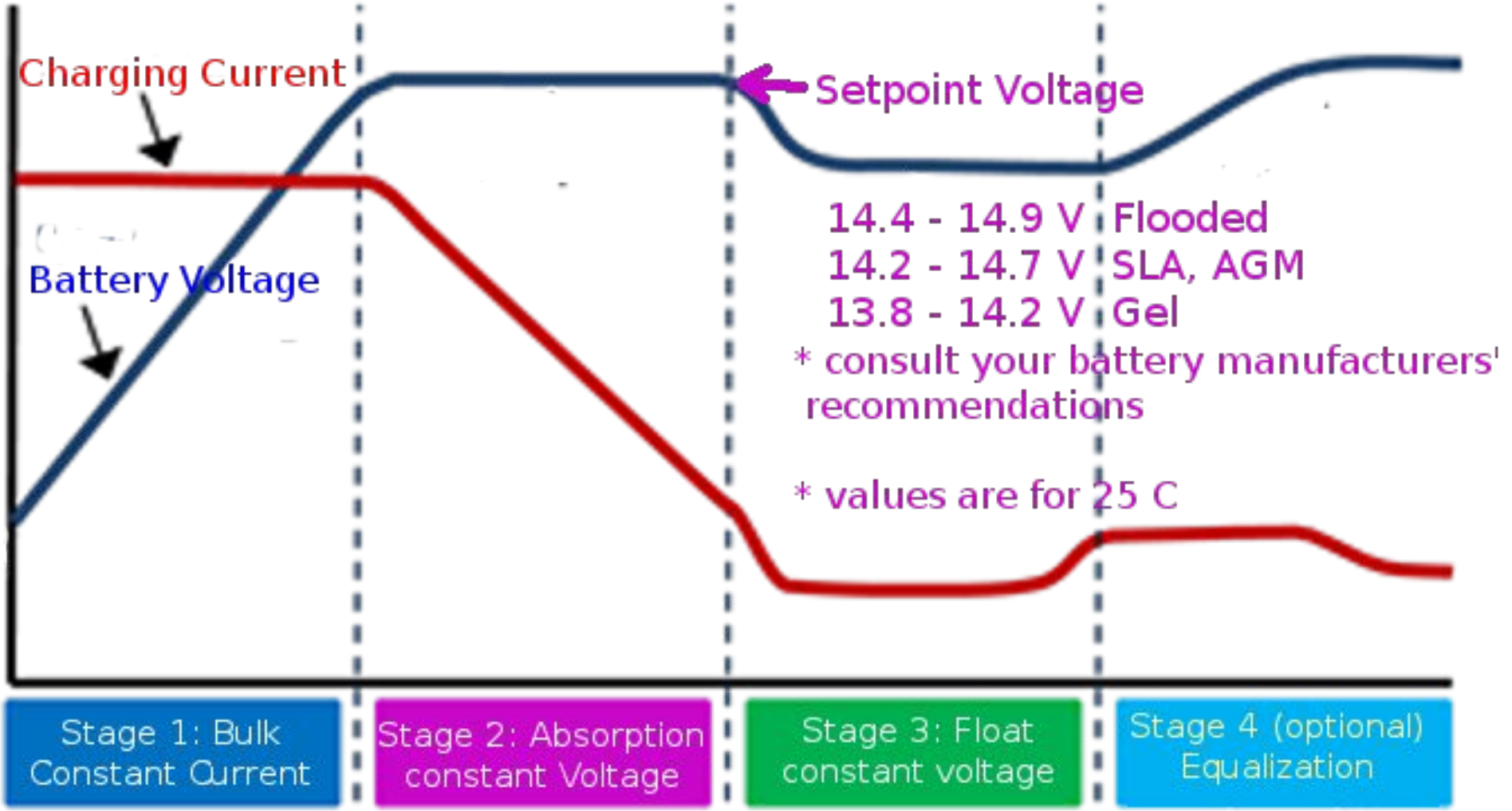
Chargers have 2, 3, or 4 charging stages

First 2 stages are usual for a stock alternator. 3rd or 4th stages are seen on Smart Chargers.



Lead-Acid Batteries

The different charging voltages make it tricky to mix different battery types. Ensure your charge controllers treat your batteries properly.



* Don’t Equalize sealed batteries, as you won’t be able to replace any lost water

Battery State-of-Charge

Measure resting (i.e. no loads) battery voltage

Generally valid for lead-acid batteries. Battery manufacturer, age, electrolyte condition affect values.

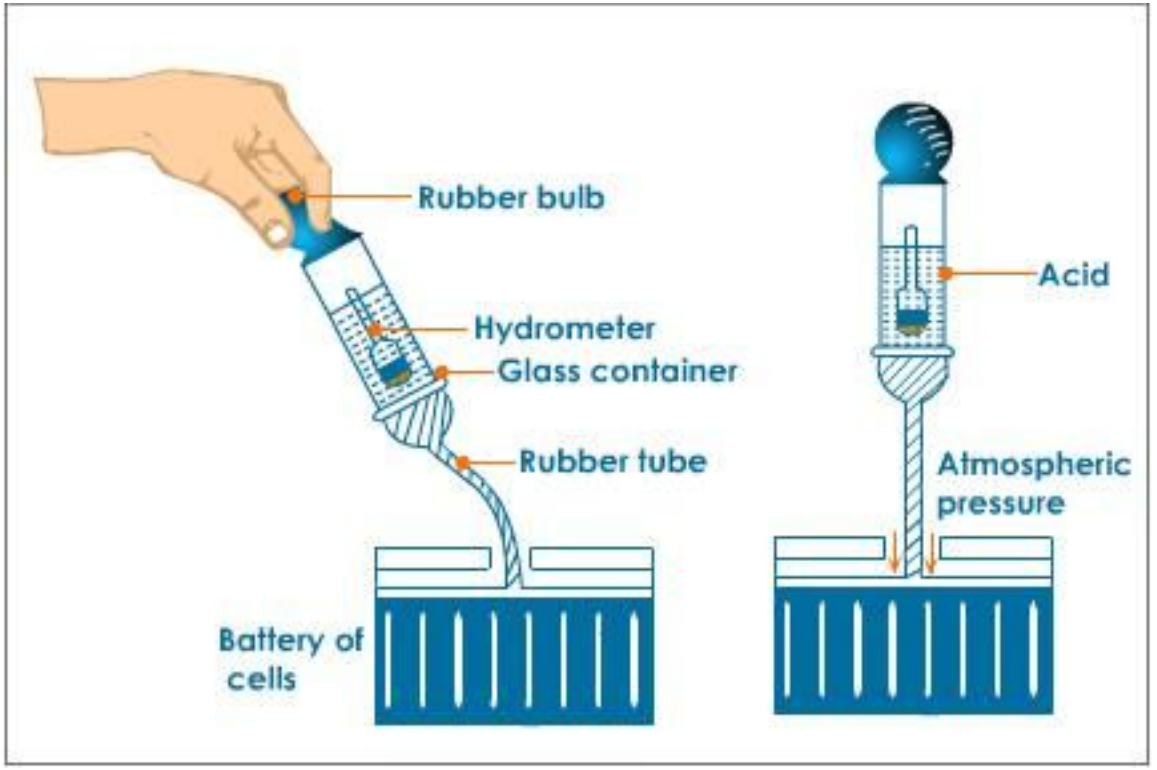
- **Temperature** affects battery voltage. As temperature rises, voltage drops. Correction factor is approx -0.018 V/°C for a 12V battery.

Many but not all charge controllers adjust for temperature.

State of Charge	12 Volt battery	Volts per Cell
100%	12.7	2.12
90%	12.5	2.08
80%	12.42	2.07
70%	12.32	2.05
60%	12.20	2.03
50%	12.06	2.01
40%	11.9	1.98
30%	11.75	1.96
20%	11.58	1.93
10%	**11.31**	**1.89**
0	**10.5**	**1.75**

Battery State-of-Charge

If you have a flooded (i.e. not sealed) battery, you can **test the concentration** of sulphuric acid using a **hydrometer**. It gives an accurate indication of the condition of each battery cell (compartment).



Lithium Batteries

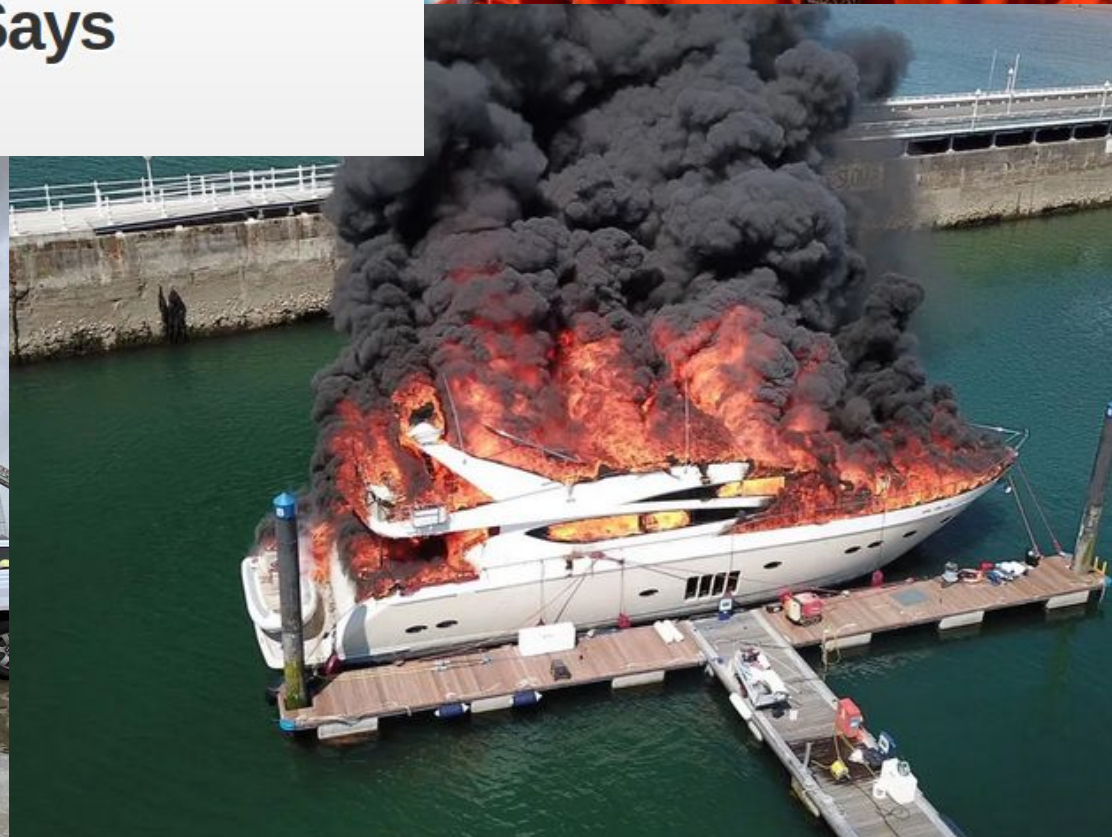
- **Higher energy density:** more A•h for a given physical size
- **Lighter weight** for a given size
- **Longer lifespan**: 2000 to 4000+ charge cycles (*vs. a few hundred for lead-acid*)
- Lower discharge rate during storage
- More finicky about charging profile
- More expensive

Safety - Fire

More recently, we see a lot of interest and analysis of high-profile **boat fires where lithium batteries are believed to be involved.**

Fire a Growing Risk to Shipping Because of Lithium-ion Batteries, Allianz Says

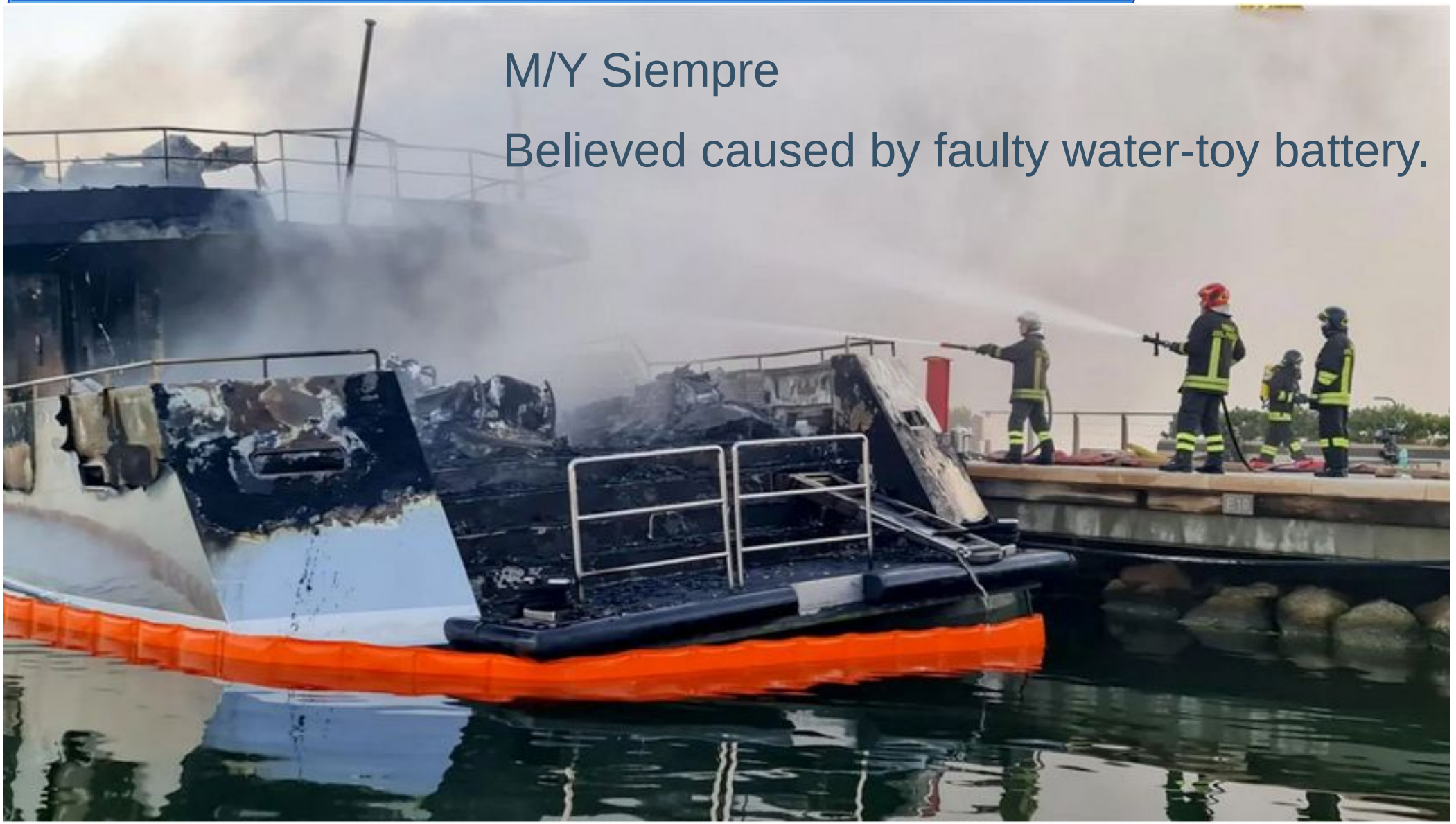
By Jim Sams | September 2, 2022



Safety - Fire

M/Y Siempre

Believed caused by faulty water-toy battery.



Emergency services work to put out the flames on board *Siempre*. The accident report suggested that the cause of the blaze may have been a faulty water toy battery · Credit: Vigili del Fuoco

Safety - Fire

“The proverbial problem children in this story are the high-energy LiPo variant (lithium-ion-polymer) portable batteries,” he says. “The ones that consumers can take out of the driven equipment and handle, charge, then reinstall for use. I am not so concerned about engineered hard installations.”

Captain Herb Magney, consultant with First Look, Inc., speaking for a group of concerned insiders representing insurance, yacht management, manufacturers and yacht captains, who have been working on a response to the threat of lithium battery fires on yachts.

https://www.boatinternational.com/yachts/news/yacht-fires-lithium-ion-batteries

Safety - Fire

“In the case of Siempre, there were two electric surfboards, an electric hydrofoil surfboard and two electric underwater scooters on board at the time of the fire.”

“...fire was likely to have been a faulty lithium-ion battery for the owner’s water scooter, or a fault in its power socket. Crew were aware of a problem with both items, having previously repaired scorching inside the socket. And they were awaiting instructions on disposing of the faulty battery, keeping it in a locker for safety.”

Lithium Batteries

Several different Lithium chemistries

- **Lithium Iron Phosphate** ($LiFePO_4$) is safest: it doesn't exhibit thermal runaway, and if an adverse event occurs that causes venting, the fumes are less hazardous.

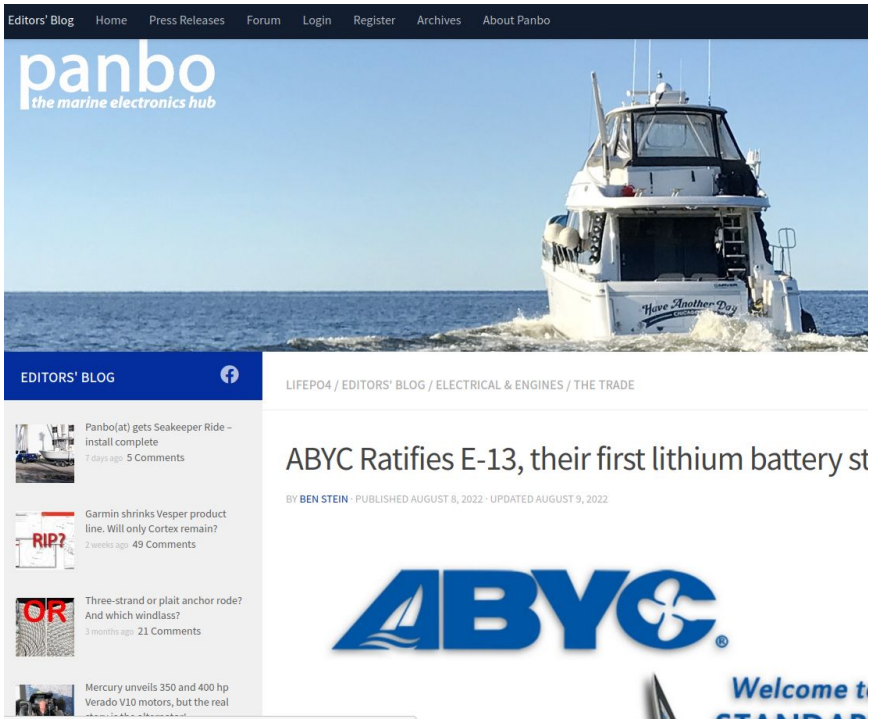

Lithium Safety

https://www.youtube.com/watch?v=07BS6QY3wI8
Physically puncturing LiFePO4 Battery

Several observations:

- **Lithium Iron Phosphate** will burn, after severe physical abuse
- Less ‘spectacular’ than LiPo
- Would get similarly undesirable results by puncturing a propane tank or a lead-acid battery
- Important to follow best practices when installing batteries on vessels – for physical protection, venting, fire protection, etc. See *ABYC E-13* standard.

Lithium Safety



Highlights:

- E-13 is a standard for lithium ion batteries. Includes many chemistries, including lithium cobalt oxide (LiCoO2), lithium manganese oxide (LiMn2O4), lithium iron phosphate (LiFeP04), lithium nickel manganese cobalt oxide (LiNiMnCoO2), lithium nickel cobalt aluminum oxide (LiNiCoAlO2), and lithium titanate (Li4Ti5O12).
- "I firmly believe that of the currently available chemistries, LiFePO4's safety characteristics make it the only logical choice on recreational boats."
- Lithium battery systems shall be installed and used in accordance with manufacturer's recommendations.
- Lithium batteries are not subject to routine electrolyte leakage or routine release of gas

https://panbo.com/abyc-ratifies-e-13-their-first-lithium-battery-standard/

Panbo – edited by Ben Stein

Lithium Safety

E-13 leaves battery restraint up to the manufacturers' reccomendations

13.6.4.1 Batteries shall be installed in locations and restrained in such a manner that they will be protected from shock, vibration, or movement according to the battery manufacturer's recommendations.

NOTE: Lithium ion battery manufacturers may have stricter battery restraining requirements than those specified in ABYC E-10, Storage Batteries, and 33 CFR 183.420 for lead acid batteries.

13.6.4.2 In the absence of the battery manufacturer's recommendations, batteries and battery banks shall be restrained to prevent any visible movement in the conditions under which the vessel is intended to be operated.

E-13 section 7: A BMS is required, and adds

NOTES:

1. *An alternative power source is recommended for critical systems (e.g., engine starting, propulsion, navigation lights, etc.) that may be affected if a BMS shuts down the battery. The alternative power source can be another lithium ion battery.*
2. *If a shutdown condition is approaching, a battery system should notify the operator with a visual and/or audible alarm before disconnecting the battery from the DC system.*
3. *BMS(s) may suddenly and unexpectedly disconnect a battery from loads and charging sources.*

https://panbo.com/abyc-ratifies-e-13-their-first-lithium-battery-standard/

Lithium Safety

ABYC E-13 Section 13.8 requires manufacturers supply info on:

- cell chemistry and design,
- safety hazards, features, and requirements
- electrical and environmental operating limits
- charging, serial and parallel connection restrictions
- battery restraining requirements
- effects of external heat and fire, fire suppression requirements
- recycling information

Ben commented that he was impressed by BattleBorn's manuals – they are a good example of documentation.

https://panbo.com/abyc-ratifies-e-13-their-first-lithium-battery-standard/

Lithium Safety

Final thoughts, from Ben:

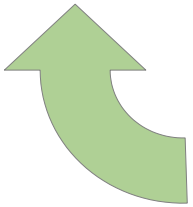
"Overall, I believe $LiFePO_4$ is safer than the lead-acid based batteries we've been installing in boats for many decades. $LiFePO_4$ batteries have safety mechanisms in place to shut themselves down if they exit their SOE [Safe Operating Envelope]. Lead Acid batteries don't. The failures I've seen with $LiFePO_4$ batteries are more graceful than the failures with FLA."

"But, the batteries do store a tremendous amount of energy. Without proper installation and care there is an inherent danger things can wrong with all that energy."

https://panbo.com/abyc-ratifies-e-13-their-first-lithium-battery-standard/

Lithium Batteries

- Lithium batteries have **different charging profiles** than lead-acids: require dedicated charging & monitoring circuits
- Some manufacturers have designed **drop-in replacements** for 12 V lead-acid batteries, by including the *charge-regulating*, *thermal monitoring*, and *cell-balancing* functions into the battery housing



BMS – Battery Management System

Events & Education

Feb 08 - Vancouver Club Night - New Zealand Aboard Traversay III

Feb 12 - Our Planetary System From a Sailor's Perspective

Feb 18 - Offshore Charting and Dead Reckoning

Feb 18 - Making and Storing Power at Sea

Feb 25 - Celestial Navigation

Feb 25 - Weather Strategies for the Inside Passage

Lithium House Battery - Impressions After One Year

Barb Peck & Bjarne Hansen

HOKU PA'A

NIAGARA 35

March 25th, 2021

Currents, March 2021

Move Over, Lead-acid !

Lithium Drop-in Batteries

- $1145 CDN for a 100 A•h lithium battery (Jan 2022, http://www.wegosolar.com/ in Chemainus BC). Cost now better than lead-acid, **if** you factor in 10X longer cycle life.
- Due to electric car market, technology is rapidly advancing. Expect costs to drop, similar to how solar panels are now < 1/10th the cost of 15 years ago.

Lithium Drop-in Batteries

Specs for Trojan Trillium 110 A·h

- 30 lbs, similar in size to 6V Golf-Cart lead-acid, but ½ the weight
- Recommended charging voltage 14.4 – 14.8 VDC

TROJAN BATTERY COMPANY

DATA SHEET

TRILLIUM
TROJAN INTELLIGENT LITHIUM

MODEL	TR 12.8-110 Li-ion
VOLTAGE	12.8V
NOMINAL CAPACITY	110Ah (1,400Wh)
CASE	PC/PBT Resin Blend, IP67 Enclosure, UL94 V-0
BATTERY	Deep-Cycle Lithium Iron Phosphate
COLOR	Maroon
CYCLE LIFE	>5,000 Cycles @ 80% DOD*
INTELLIGENCE	Integrated Microprocessor, State of Charge Gauge, Integrated Contactor, Current Sensor, Fuse

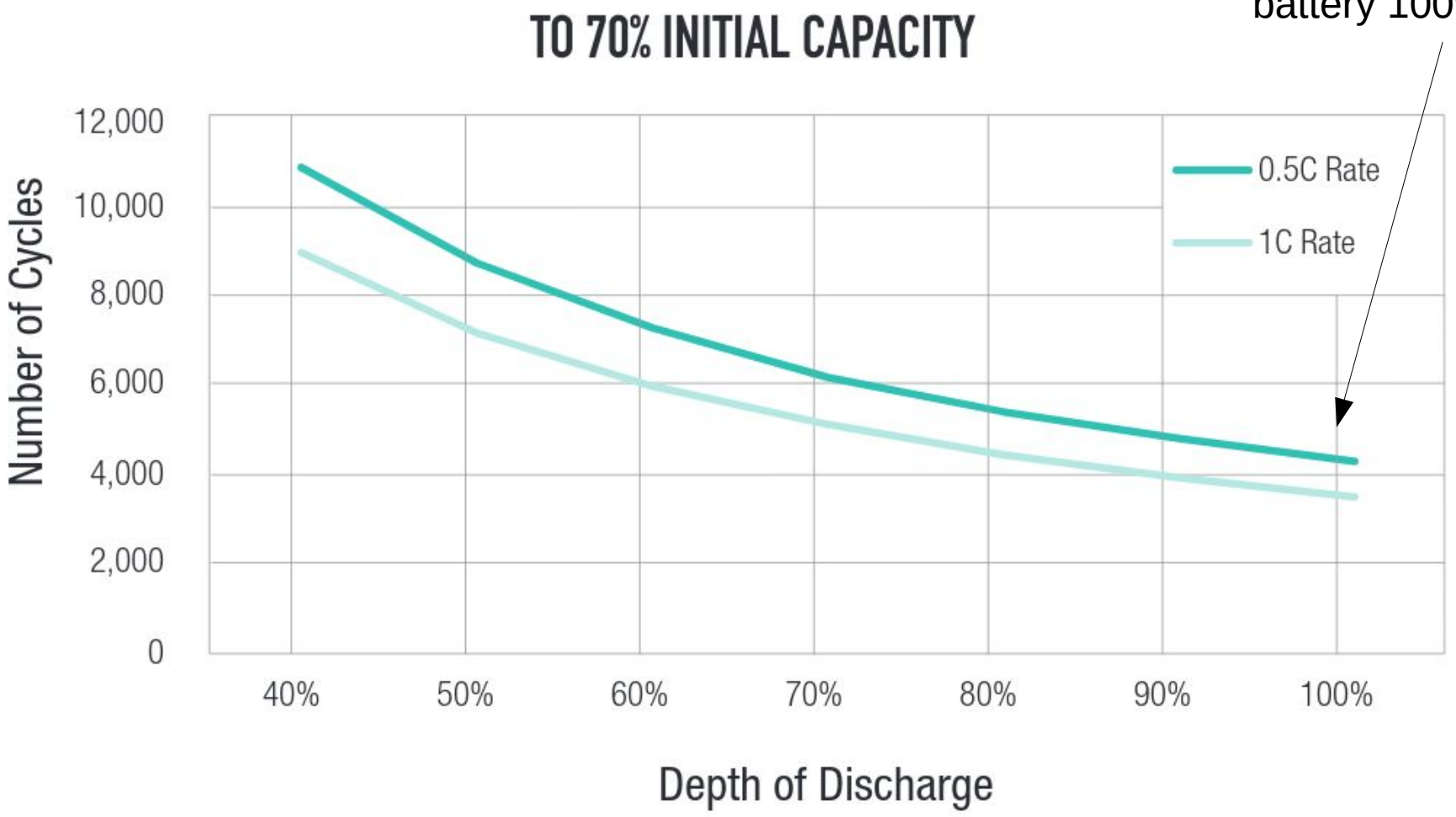
DEVELOPED IN THE USA

12.8 VOLT

Lithium Drop-in Batteries

Specs for Trojan Trillium 110 A·h

4000 cycles is 11 years, every day draining the battery 100% !!!



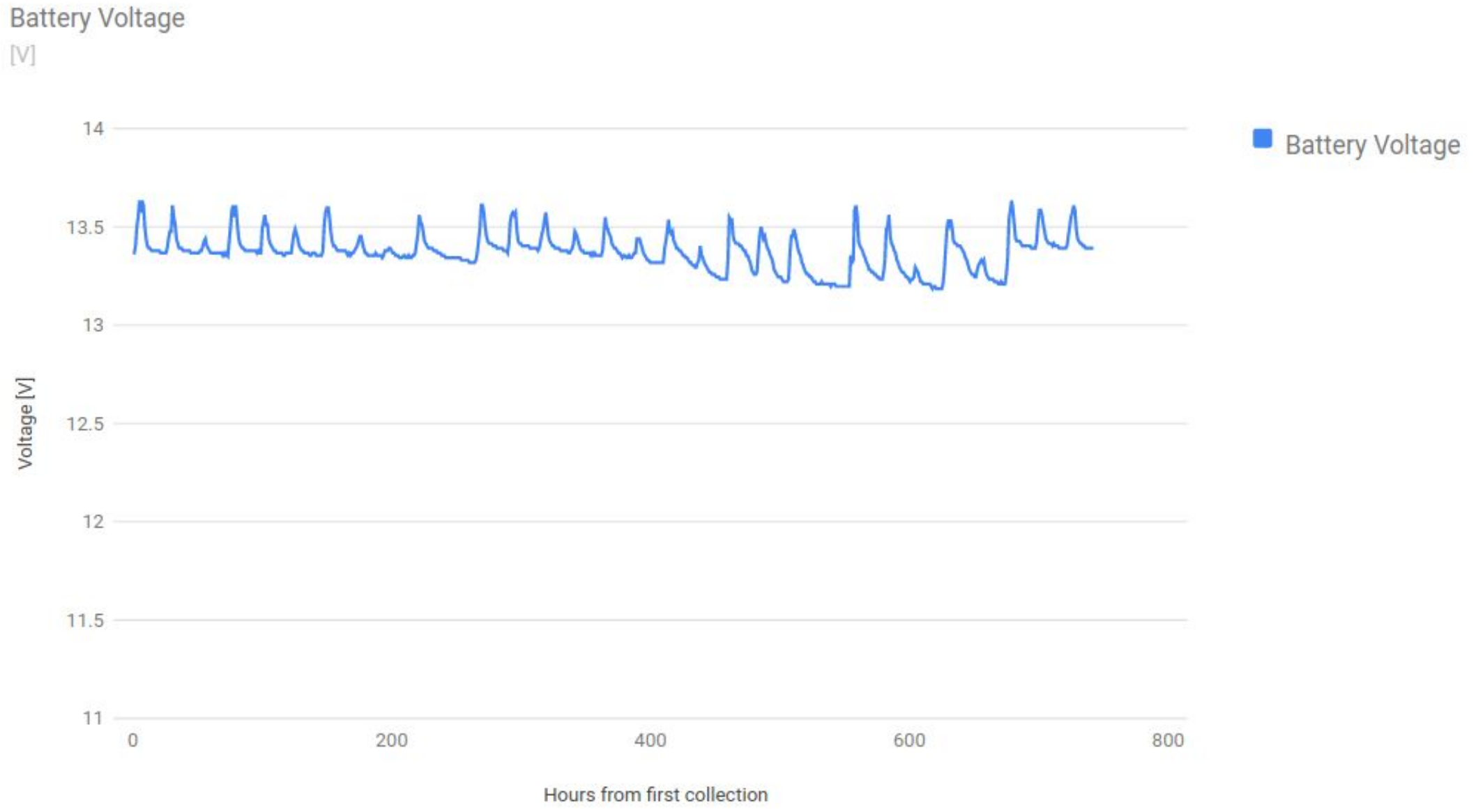
Lithium Batteries

Additional Factors to Consider:

- When looking at the capacity (A·h) remember that regularly **using 80% to 100% of that capacity is OK**, unlike with lead-acid batteries where only ~50% capacity is usable if you want to preserve lifespan.
- For safety, only choose Lithium batteries with **built-in Battery Management System** / protection, from reputable manufacturers.
- Check the battery's **charging specifications** carefully, and ensure all your charge controllers (solar, wind, alternator, etc) are compatible.

Lithium Battery Differences

Resting, Charging Voltages Likely Different from Pb-acid



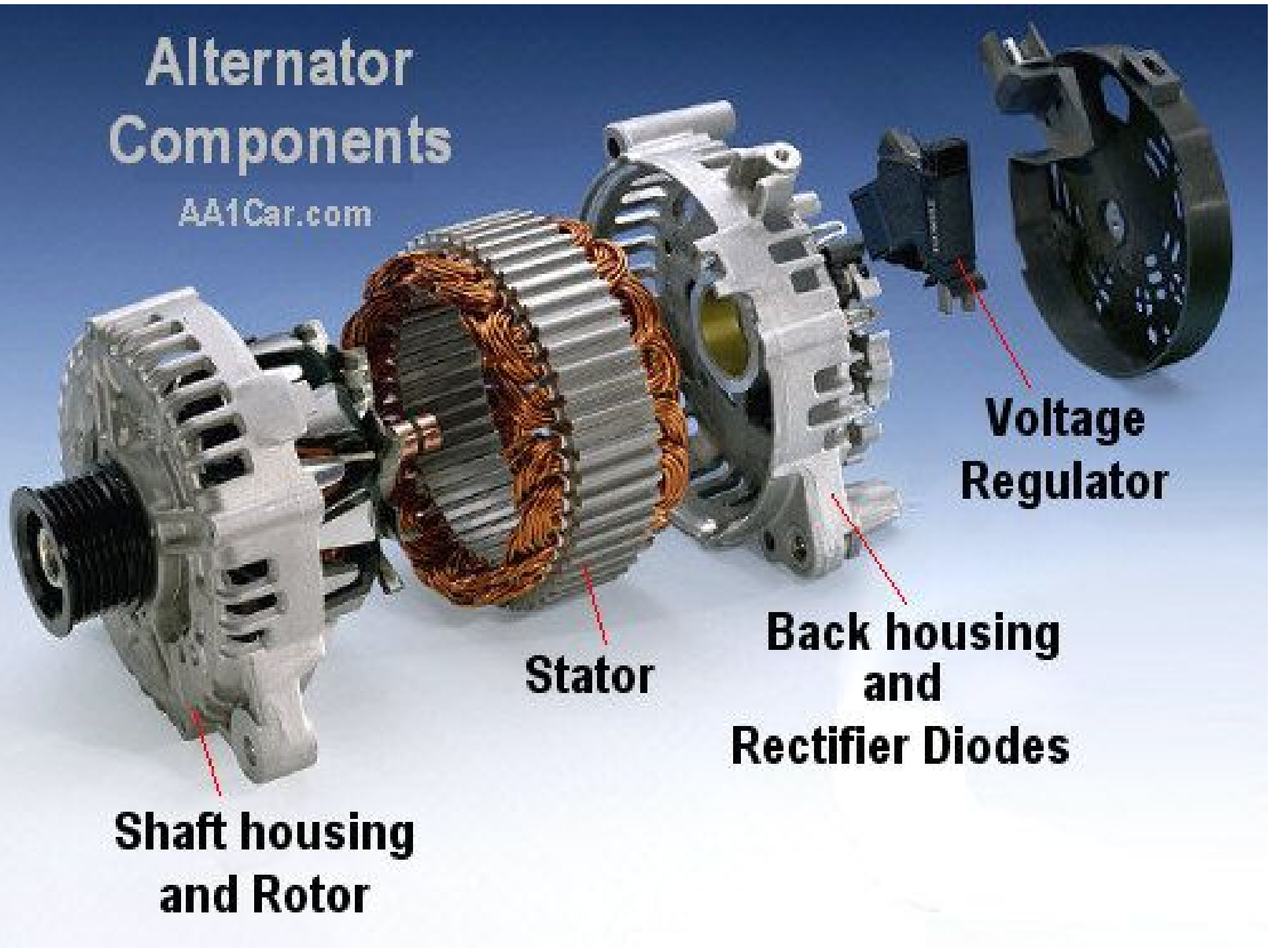
Lithium Batteries

If you replace your lead-acids with lithium batteries, you may need to **upgrade your alternator charging system**.

The much higher charging rate of a lithium battery will increase the load on your alternator. You may need to do one or more of:

- Increase cooling air flow,
- Beef up the alternator belt and pulleys,
- Change the alternator's charge controller, or
- Change the alternator

A nice benefit of the higher charge rate is shorter engine run-times.


Alternator
Components
AA1Car.com
Voltage
Regulator
Stator
Back housing
and
Rectifier Diodes
Shaft housing
and Rotor

Lithium Battery Differences

Additional Points to Consider:

- The built-in Battery Management System (BMS) will **shut off** discharging when the lithium battery is depleted. This happens **instantaneously**, without warning. So, monitor the charge state of your batteries to not be surprised.
- The BMS will also shut off charging when the lithium battery is full. Again, this happens instantaneously. If you are charging via alternator, then the sudden drop in current can cause a voltage spike which may destroy your alternator's charging regulator (if it is not protected). (Recall the warning on battery switches "Do not turn off while engine running")

  The above situations may be a good argument for keeping your lead-acid engine starting battery. It won't die without warning, and it can absorb the surge from the alternator when charging of the house batteries shuts off. Mixing lithium and lead-acid does have implications for your battery paralleling and charging strategies though.

Carbon-Foam Batteries

- Greater Depth-of-Discharge (DoD) than regular Pb-acid: **1150 cycles at 80% DoD**
- Better low-temperature (below 0C) performance
- Similar weight to Pb-acid
- Long term float-charging not recommended

Firefly / Oasis brand

74 lbs 6 year Warranty
$799 for 116 AHr 12 V G31 model (Jan 2022)

Silicon Dioxide Batteries

- **SiO_2 or Lead-Crystal** batteries have a non-liquid electrolyte; orientation of battery doesn't matter.
- Greater Depth-of-Discharge (DoD) than regular Pb-acid: **2800 cycles at 50% DoD**
- Low-temperature performance to below -30C
- Max charging rate is higher than regular Pb-acid, at 0.25C (*i.e.* 25% of battery capacity, so a 100 A·h battery can charge at 0.25 * 100 = 25 A). This is lower than the 1C rate of carbon-foam (Firefly) and $LiFePO_4$
- Similar weight to Pb-acid
- Similar to AGM in chemistry and construction

100 A·h battery was $538 in Jan 2019
(could not find more recent Cdn price)

Detecting Problems

Best way to notice a problem with your charging components is to install a battery monitor. After living aboard for a few weeks, you will learn the ‘normal’ voltages and currents for your boat. When readings deviate, there may be a problem.

Detecting Problems

Many Lithium batteries now include monitoring as part of the BMS.

Smart Lithium-Iron Phosphate Battery 12 Volt 100Ah

SKU: RBT100LFP12S-CA

~~CAD $1,099.99~~ CAD $684.99 Free shipping*


Questions?

Resources

Batteries - Info

- https://batteryuniversity.com/learn/article/charging_the_lead_acid_battery lots of useful info about lead-acid batteries
- https://www.trawlerforum.com/forums/s3/carbon-foam-batteries-1-year-later-26233-2.html
  experiences with Carbon-foam batteries
- https://panbo.com/marineelectronicsforum/general-discussion/firefly-battery-quality/ experiences with Carbon-foam batteries
- https://www.pysystems.ca/recommended/firefly-oasis-battery-carbon-foam-agm/ Jeff Cote (Pacific Yacht Systems, Vancouver) good presentation about various batteries
- https://azimuthsolar.ca/reviews-resources-research/silicon-dioxide-lead-crystal-batteries/
  description of SiO2 (lead-crystal) batteries
- https://dragonflyenergy.com/lithium-marine-batteries/ vendor (Dragonfly) providing good overview of Lithium batteries
- https://www.yachtingworld.com/gear-reviews/lithium-boat-batteries-upgrade-electrics-128151 2020 discussion of Lithium batteries in vessels. Note that some of the references to lithium batteries are of the lithium-manganese-cobalt (LiMNC) chemistry, which differs from the lithium-iron-phosphate LiFePO4 that is more common in the drop-in-replacement market.
- https://currents.bluewatercruising.org/articles/lithium-house-battery-impressions-after-one-year/ Report on our experiences with a lithium house battery on Hoku Pa'a
- https://files.gwl.eu/inc/_doc/LFP_Guide_ENG.pdf General $LiFePO_4$ info

Resources

Suppliers

- https://volts.ca Canadian distributor of batteries, solar panels, chargers, etc
- https://ca.renogy.com Another Canadian distributor of batteries, chargers, etc
- http://www.wegosolar.com/ Chemainus, BC distributor of solar products

Solar Panels

- https://news.energysage.com/monocrystalline-vs-polycrystalline-solar/ Good description of differences between mono- and poly-crystalline panels.
- https://www.futurity.org/bifacial-solar-cells-panels-power-2237612/ and https://www.pnas.org/content/116/48/23966 Articles about two-faced solar panels
- https://www.canadiansolar.com/ Canadian manufacturer of solar panels

Charge Controllers

- https://zhcsolar.com/solar-charge-controller-guide/ Extensive information about charge controllers.

Wind Generators

- https://store.marinebeam.com/marinekinetix-mk4-marine-wind-generator/ Good article discussing various design features of wind generators. It is selling a particular model, but the concepts are applicable to all.
- https://www.sailingtoday.co.uk/gear/gear-on-test/wind-generators-buyers-guide/ A review of mostly British wind generators, but gives good guidance on what to look for

Resources

Towed Generators

- https://www.practical-sailor.com/blog/towed-water-generators-are-they-worth-it Short article by Practical Sailor editor Darrell Nicholson (2017) about towed generators
- https://www.bwsailing.com/cc/2016/03/the-latest-in-water-generators/ Review article on water generators
- https://www.sailingtoday.co.uk/gear/gear-on-test/hydrogenerators/ Another review article on water generators

Fossil-fuel and Methanol Generators

- https://generatorgrid.com/boat/ Review of portable gasoline generators
- https://forums.qrz.com/index.php?threads/inverter-generators-and-rfi.523804/ A Ham's comments on RFI from gasoline generators. There are some specific good/bad models mentioned in the comments. Also see https://qsl.net/nf4rc/2019/InverterGeneratorSolutions.pdf
- https://www.pysystems.ca/resources/tech-talk/efoy-fuel-cells/ Comprehensive article about the EFOY methanol fuel cells by Jeff Cote at Pacific Yacht Systems. Same website also has good blogs and videos about other electrical system topics.
- https://panbo.com/testing-the-efoy-comfort-fuel-cell/#lightbox-gallery-0/1/ Review article of EFOY with good photos of installation and comments about getting fuel.

Resources

Vessel Wiring Standards

- http://www.ancorproducts.com/en/resources/abyc-standards has a good summary of ABYC standards as they apply to wiring
- ***Transport Canada Construction Standards for Small Vessels (2010)*** Section 8 deals with Electrical Systems. Majority of content is harmonized with ABYC standard E-11. This is the cheapest (i.e. free) reference source for electrical standards on small vessels.
- http://www.blackfinforums.com/sites/default/files/10/attachments/abyc-e-11.pdf ABYC Publication **E-11 AC And DC Electrical Systems on Boats *(2008)*** *note that ABYC has issued a 2012 edition but it is not readily available without a membership/subscription to ABYC.
- https://webstore.iec.ch/publication/709 IEC 60092-507:2014 Electrical Installations in Ships – Part 507: Small Vessels. Gives requirements for the design, construction and installation of electrical systems in small vessels. Requires purchase to download.
- https://www.boatus.com/expert-advice/expert-advice-archive/2021/february/analyzing-onboard-fire-claims Boat US report on causes of boat fires based on analysis of insurance claims.

Alternators

- Alternator manufacturer's troubleshooting manual. Balmar has good ones online (https://balmar.net/operation-manuals/) that can be useful even if you have another brand of alternator.

Our Website

- https://2bsailing.ca Our website with details of Hoku Pa'a and our cruises. In the info section you'll find copies of this and other presentations.

Resources

Books

- *Marine Electrical and Electronics Bible,* John C. Payne, 1998
- *Boatowner's Illustrated Handbook of Wiring,* Charlie Wing, 1993
- *Boatowner's Illustrated Electrical Handbook,* Charlie Wing, 2006
- *The Boatowner's Guide to Corrosion,* Everett Collier, 2006

Glossary

- **Positive** – the part of a circuit that supplies current. It has a higher voltage (pressure) than the negative part of a circuit. Positive connections are often identified with a **+** symbol or are coloured red.
- **Negative** – the part of a circuit into which current flows. It has a lower voltage than the positive part of a circuit. Negative connections are often identified with a **–** symbol or are coloured black.
- **Voltage Drop** – the electrical ‘pressure’ decreases in a circuit when following the current from the positive terminal towards the negative. This drop is caused by resistance and is equal to V = I * R, where V is the voltage drop, I is the current, and R is the resistance in that portion of the circuit.
- **Barrel Connector** – crimp-style connector intended to join two wires
- **Ring Terminal** – connector ending in a hole, usually held down by a screw
- **ABYC** – American Boat and Yacht Council, who publish safety standards for USA vessels but commonly applied in other countries
- **TC –** Transport Canada, who publishes safety standards for Canadian vessels. Their requirements are largely aligned with ABYC
- **UL** – Underwriters Laboratories. A safety standards agency, similar to CSA.

Glossary

- **LED** – Light Emitting Diode. An efficient solid-state light bulb.
- **Fuse** – a protective device that opens a circuit when excess current flows
- **Circuit Breaker** – functions like a fuse, but is resettable
- **Multimeter** – a handheld device for measuring voltage, current, resistance, etc.
- **Open Circuit** – a circuit that does not have a continuous path for current to flow.
- **Short Circuit** – an unintentional closed path for current to flow, allowing it to bypass the normal path. Can allow excess current to flow, leading to fire.
- **Series Connection** – a connection in which the current is required to flow through all parts in sequence. Used for example when measuring current.
- **Parallel Connection** – a connection in which the current has multiple paths to flow. Used for example when measuring voltage.
- **AWG** – American Wire Gauge. A measure of how thick a conductor is. Another way of specifying wire size is by its cross-section in mm^2.
- **Voltage, Current, Resistance, Power**. The four main electrical parameters we are concerned with. See presentation for details.

Thanks for your attention !