



SOLAR PANELS AND SYSTEMS

JOHN MAXWELL, W0VG

DOUG SHARP, K2AD

DAVE MACIOROWSKI, WA1JHK

DR. WILLEM SCHREUDER, AC0KQ

TRISTAN HONSCHIED, NM0TH

The Winter Solstice - December 21, 2024

“The winter solstice is the day with the shortest period of daylight and longest night of the year, and when the Sun is at its lowest daily maximum elevation in the sky.”

Source: Wikipedia

So why are we learning about solar power on the shortest day of the year?



THEORY



History

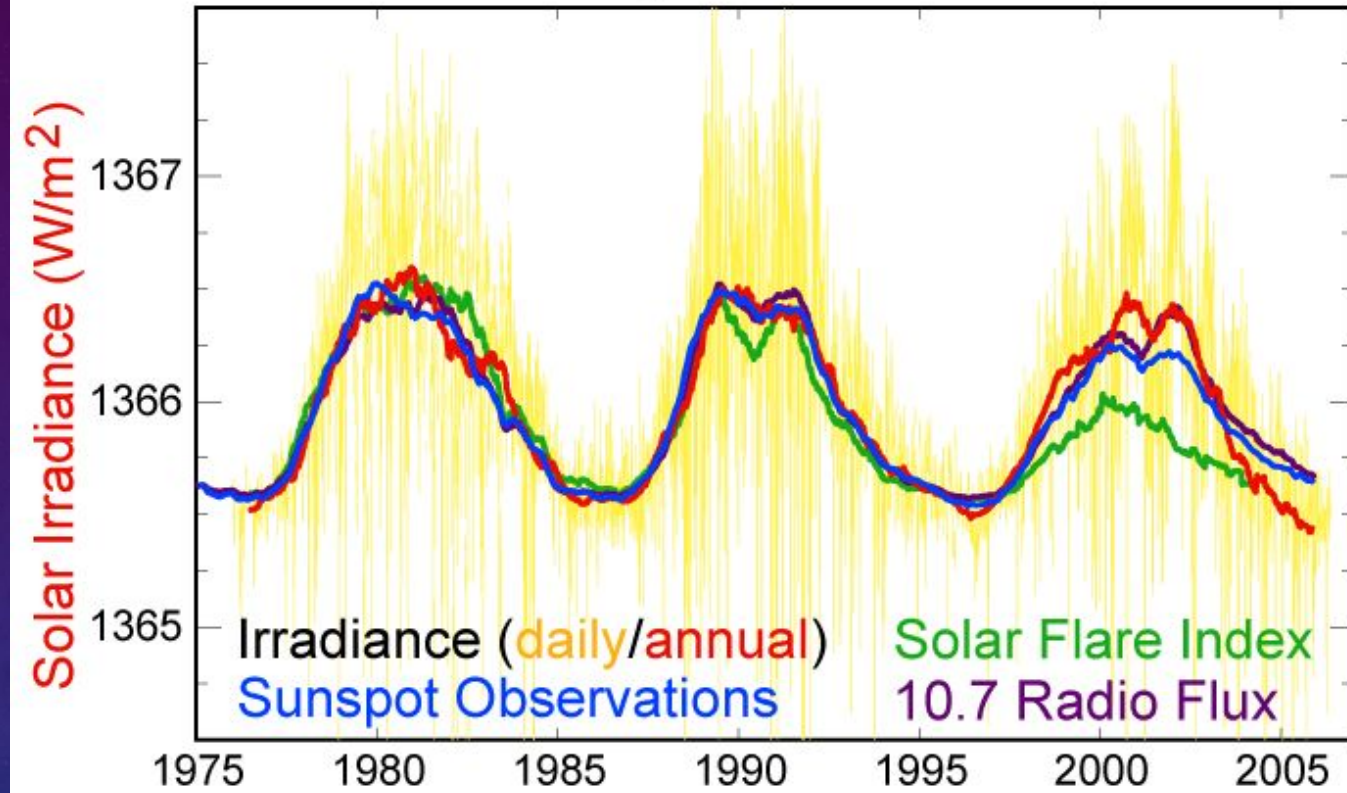
- 1839 Becquerel discovers *photovoltaic* effect in conductive solution
- 1887 Hertz investigates *photoelectric* effect
- 1905 Einstein explains photoelectric effect (2021 Nobel Prize in Physics)
- 1950s Bell labs creates semiconductor solar cells
- 1958 Vanguard 1 first solar powered spacecraft (100 mW)
- 1962 Telstar 1 commercial solar powered satellite
- 1970s Energy crisis increase interest in solar power



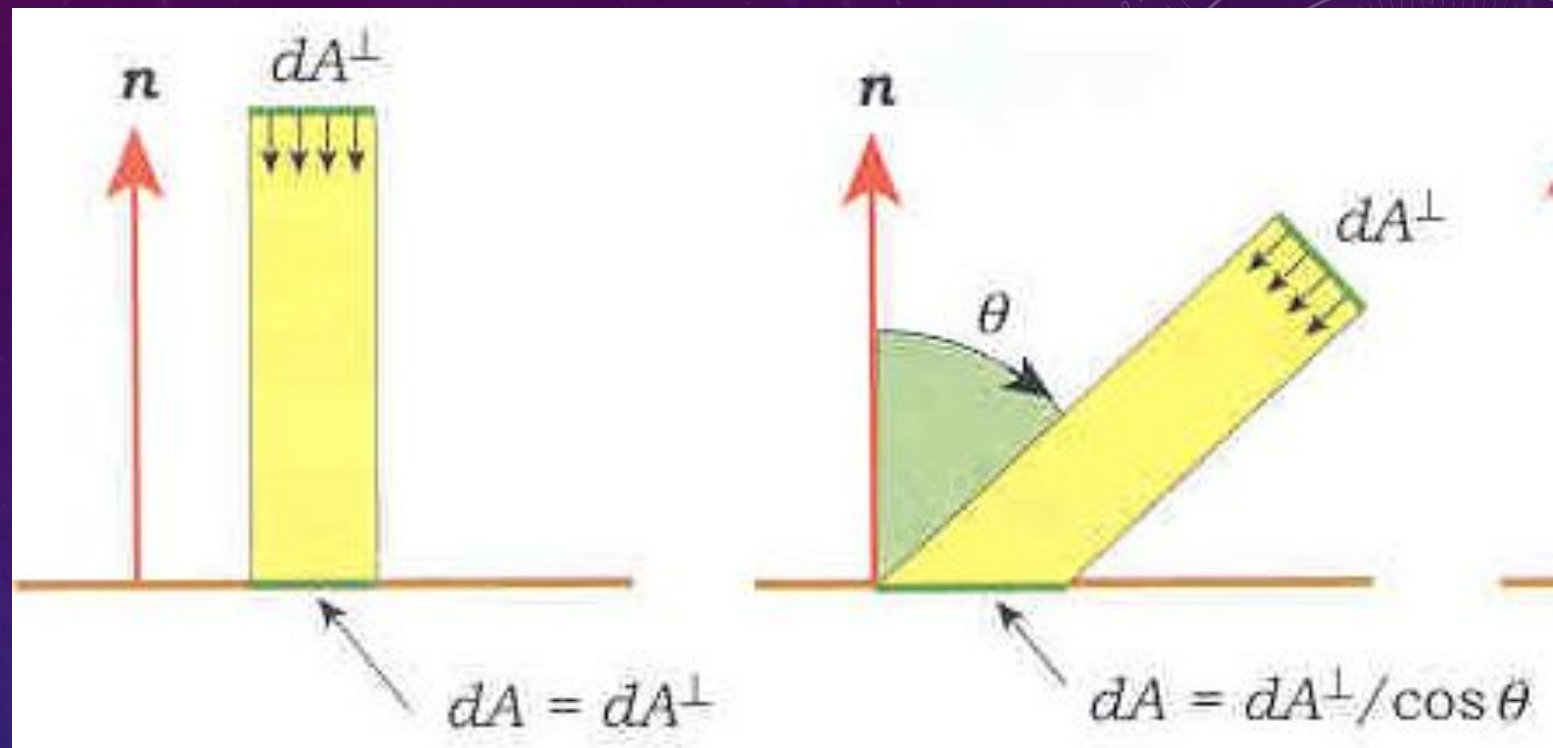
Theoretical limits 1

- Sun generates energy through fusion
 - Decreases $1/r^2$ with distance from sun
 - Fluctuates with solar cycles,
- Solar irradiance at top of atmosphere $\sim 1366 \text{ W/m}^2$

Solar Cycle Variations



Theoretical limits 2



- Solar irradiance at ground level $\sim 1000 \text{ W/m}^2$
 - Depends on cloud cover, dust, etc.
- Lambert's Law $I = I_0 \cos \theta$
- Power generation depends on cell efficiency



How PV (photovoltaic) Cells Work

- PV cells are the building blocks of a solar panel
- Silicon-based semiconductor (like a large, planar photodiode)
- Photovoltaic effect – light from the sun stimulates the flow of electrons



Solar Panel Technologies

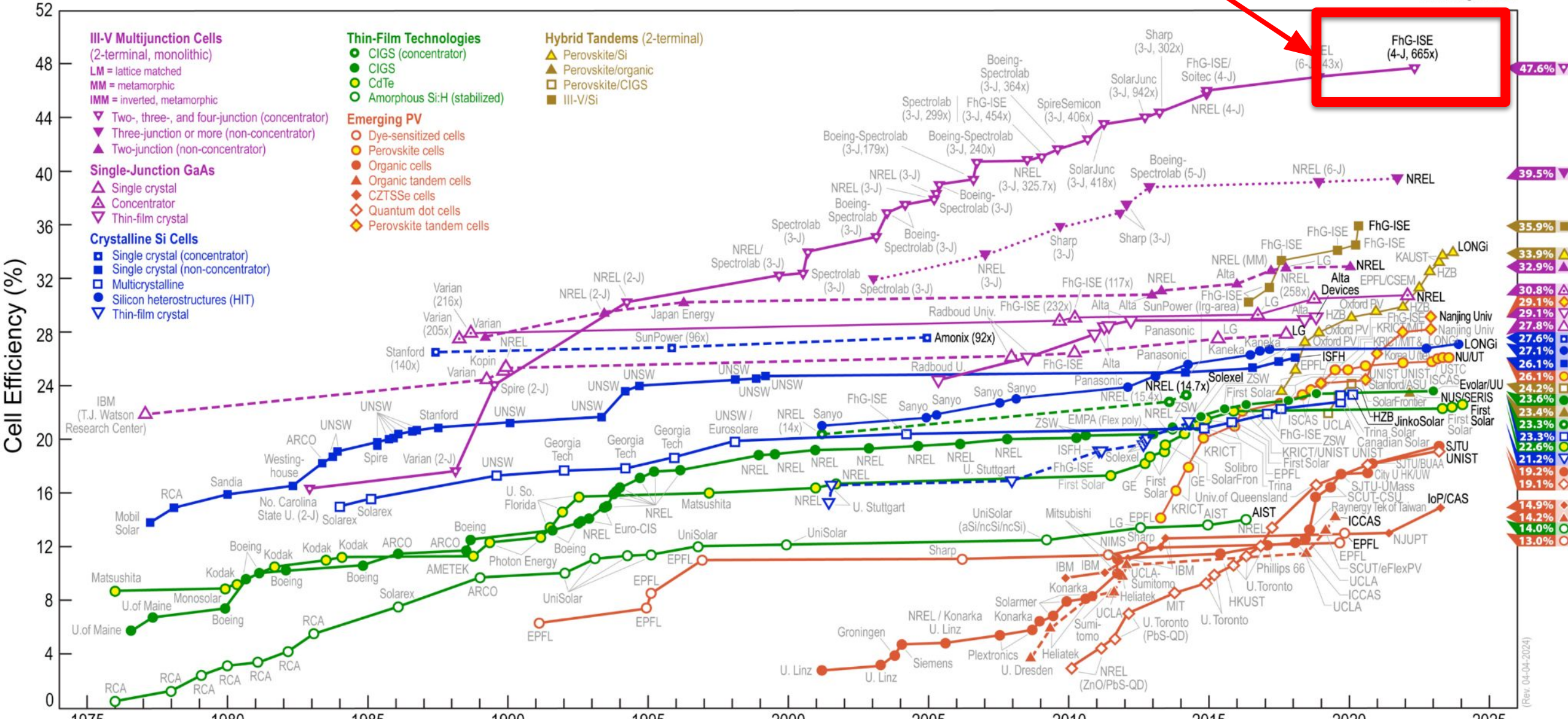
- Mono- vs bifacial
 - One vs two-sided panels.
 - Bifacial can collect extra light reflecting off ground, rising/setting sun
 - Monofacial suitable when mounted onto surfaces like roofs
- Mono- vs polycrystalline
 - Monocrystalline panels are more efficient (and more expensive)
 - Monocrystalline cells are octagonal-shaped



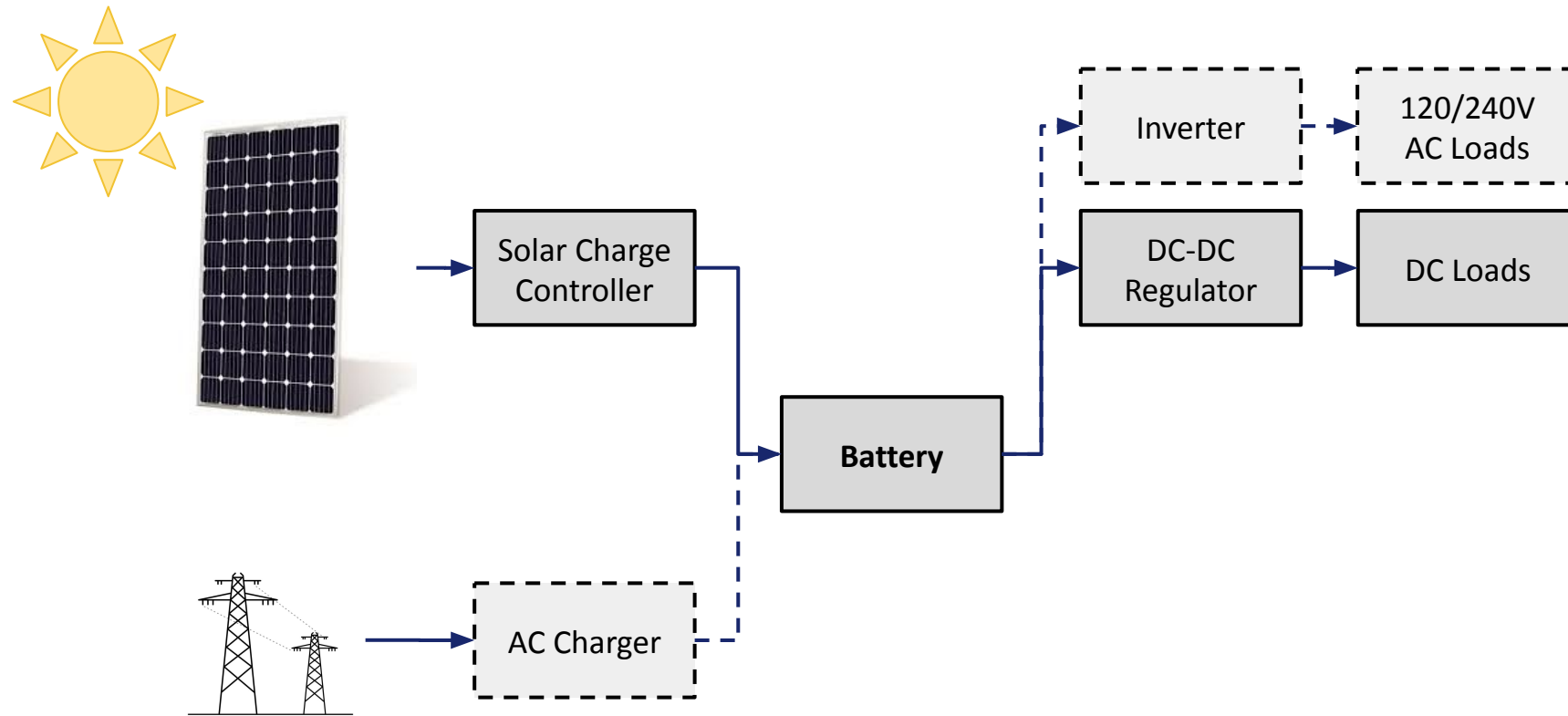
Panel efficiency evolution

47.6% efficiency!
(in a lab setting)

Best Research-Cell Efficiencies



High-Level Overview



Charge Controllers MPPT vs PWM



PWM controllers are smaller, lighter, and cheaper than their MPPT peers, they are ideal for non-essential loads in a simple environment (ie, go-box.) Essentially, any system that operates occasionally and doesn't tax the batteries much will be fine on a PWM charge controller.

However, any larger, high-demand, on or off-grid solar system supporting essential equipment or services should always be equipped with an MPPT controller. MPPT controllers sophisticated circuitry allows them to leverage maximum potential from large solar panel arrays and all common battery voltages.

If you have a critical need, stability and maximum production is being leveraged, a better MPPT controller is a must. MPPT generally assumes higher solar array voltages as well.



PWM Noise Considerations



In a critical environment as we usually operate on in the amateur radio world, PWM controllers can be significant square wave noise generators. This mostly stems from the less-expensive design of the PWM controller. If noise could be a concern to you, stick with the higher quality (and yes, more expensive) charge controller.

It's the old adage, "You get what you pay for."



Charge Controller Cost Considerations



If you're simply building a go-box to be used on a deployment, a simple PWM controller is likely the best, most cost-effective (and small) solution for your charging needs. If you are moving into a larger deployment for a repeater site or other critical infrastructure, spending some money for a unit that will be more robust for lightning, power reliability and charging would be worth your time.

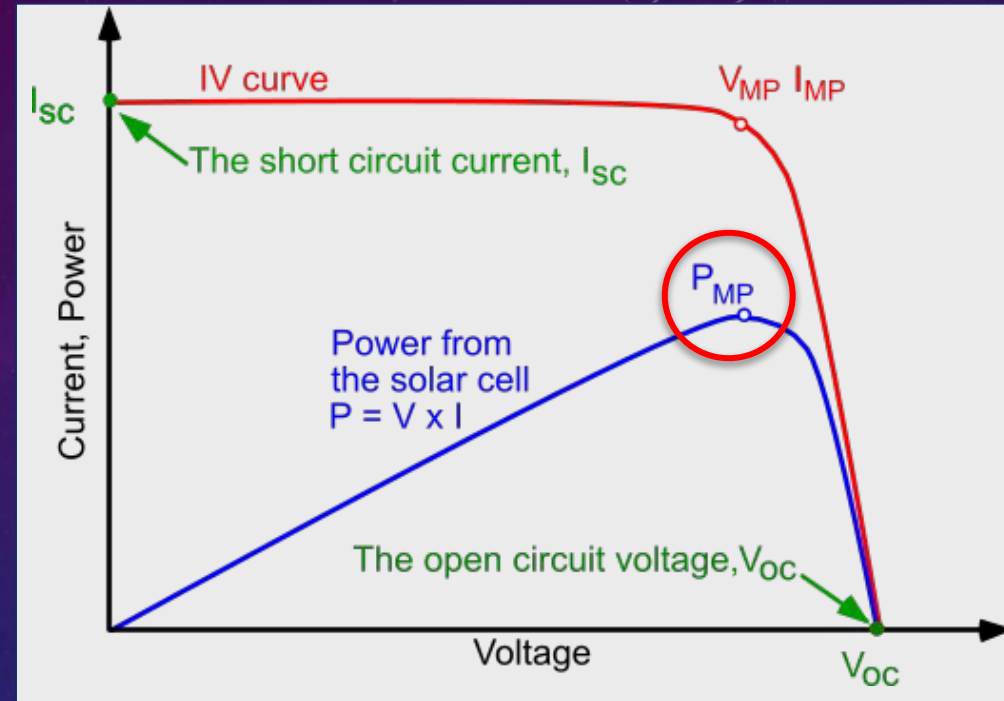
Reliability is paramount in deployed environments and definitely comes with cost.

We've used EPEVER Tracer, Outback Flex, Victron and Schneider Electric charge controllers and for the most part, they work fine. I have an EPEVER 80A (output current) charge controller in my RV which costs from \$300-350 on amazon. It's been pretty reliable but has its quirks.

We've also used Outback, Schneider and Victron in our site deployments and have been much more robust and are about 30% more for similar device specifications.

A loose analogy

- You'd never key up your radio into a short- or open-circuit
- You want a matched circuit where **power transfer is maximized**
- Charge controllers are analogous to antenna tuners –they adjust to help optimize your power draw from the solar panel.
- The amount of current you draw from a panel affects the voltage. MPPT controllers find the peak in the curve.



Power Budgeting – RV

Start with an Energy Use Audit to Measure Consumption

How to Size Solar and Batteries:

<https://www.youtube.com/watch?v=WXtp5F4Z0aI>

Easy RV Energy Audit:

<https://www.jayco.com/blog/prepped-for-solar/>

For DC, measure current draw using battery state-of-charge monitor or inductive current meter.

For AC, use a Power Watchdog

<https://www.amazon.com/gp/product/B07PMJ2K95>

Or Kill-A-Watt

<https://www.amazon.com/gp/product/B01MR6YK0C>

12V, DC Appliances	Amps	X Qty.	X Hours Run/Day	= Total Amp Hours
10 Watt Light	0.08			
15 Watt Light	1.25			
Water Pump	4			
12 Volt TV	3			
SC Fan*	4			
Furnace Fan*	8			
12 Volt Stereo	0.8			
Refrigerator	0.4			
Propane Alarm	0.21	1	24	
Other				

*Fan and furnace are not typically run at the same time.

120V, AC Appliances*				
AC Fridge	10			
TV	4			
DVD	3			
Satellite Dish	4			
Microwave	100			
Toaster	66			
Coffee Maker	60			
Blender	12			
Computer	25			
Laptop Computer	5			
Other				

*All amperage ratings are based on a 12 volt system.

**Fridge amps based on a 4.4 cubic foot fridge, running 12-hours/day.

Total amp hours per day

Power Budgeting – Simple Backup

Start with an Energy Use Audit to Measure Consumption

How to Size Solar and Batteries:

<https://www.youtube.com/watch?v=WXtp5F4Z0aI>

Sum Idle Loads Per Day

Add On-demand Loads



Power Budgeting

- Estimate How Much Sun Available Per Day
 - (Slides coming up on that.)
 - Allow for bad weather especially snow loads in the winter!
- Power Sources
 - Solar Panels – Roof Mount and Portable
 - Gas/Propane Generator
 - Wind
 - Other, e.g. Tow Vehicle



To Tilt or Not To Tilt

- A frequent debate when installing solar panels as part of a solar panel system is whether it is necessary to tilt the panels, by how much and how often does the angle need to be changed.
- A related question is whether to track or not to track. Tracking uses an AZ/EL mount so that the solar panel is always in position to accept the most solar insolation.

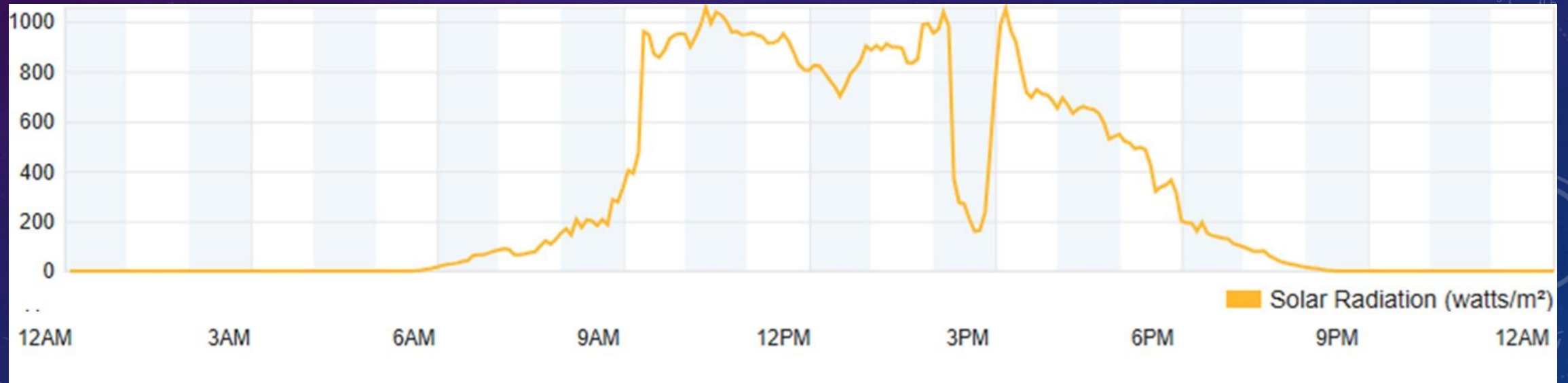
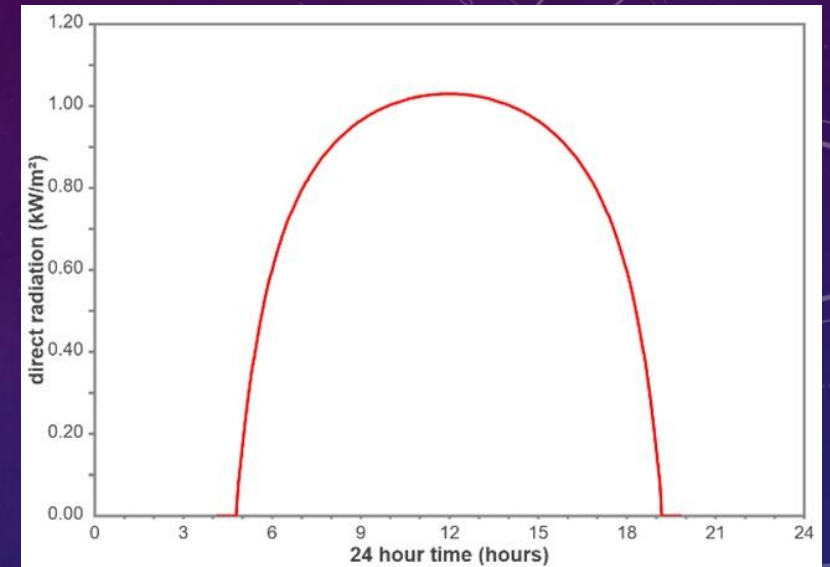


Solar Insolation

Watts per Square Meter (watts/m²)

Many common weather stations provide this data

Example: June 21, 2024, longest day of the year



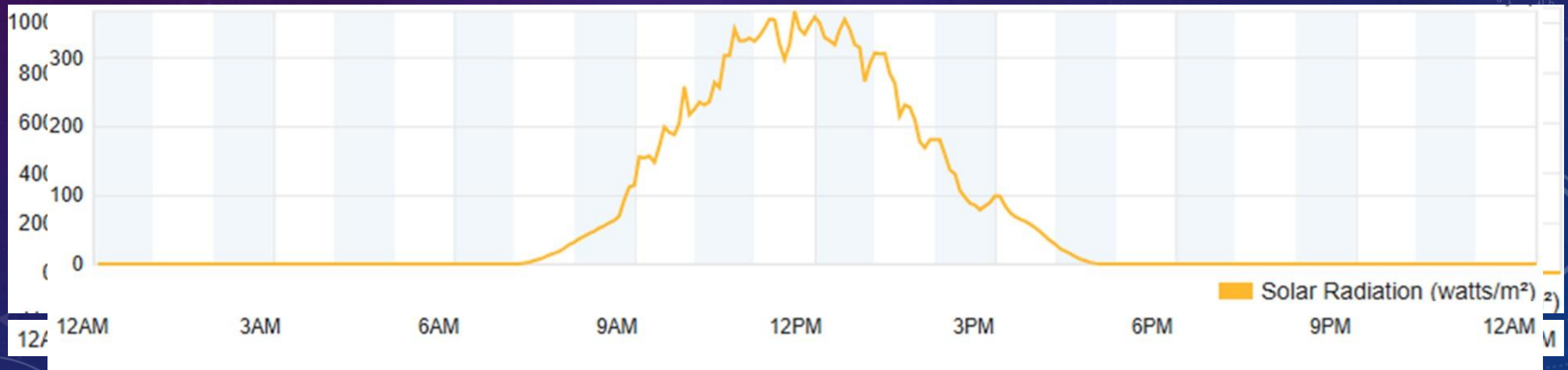
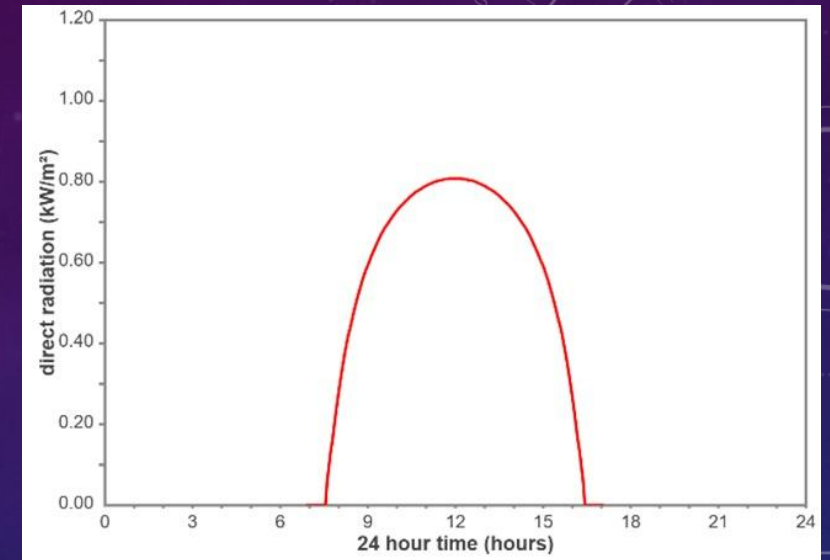
Source:

<https://www.wunderground.com/dashboard/pws/KCOLONGM397/graph/2024-06-21/2024-06-21/daily>

Solar Insolation

Watts per Square Meter (watts/m²)

December 12, 2024, almost the shortest day

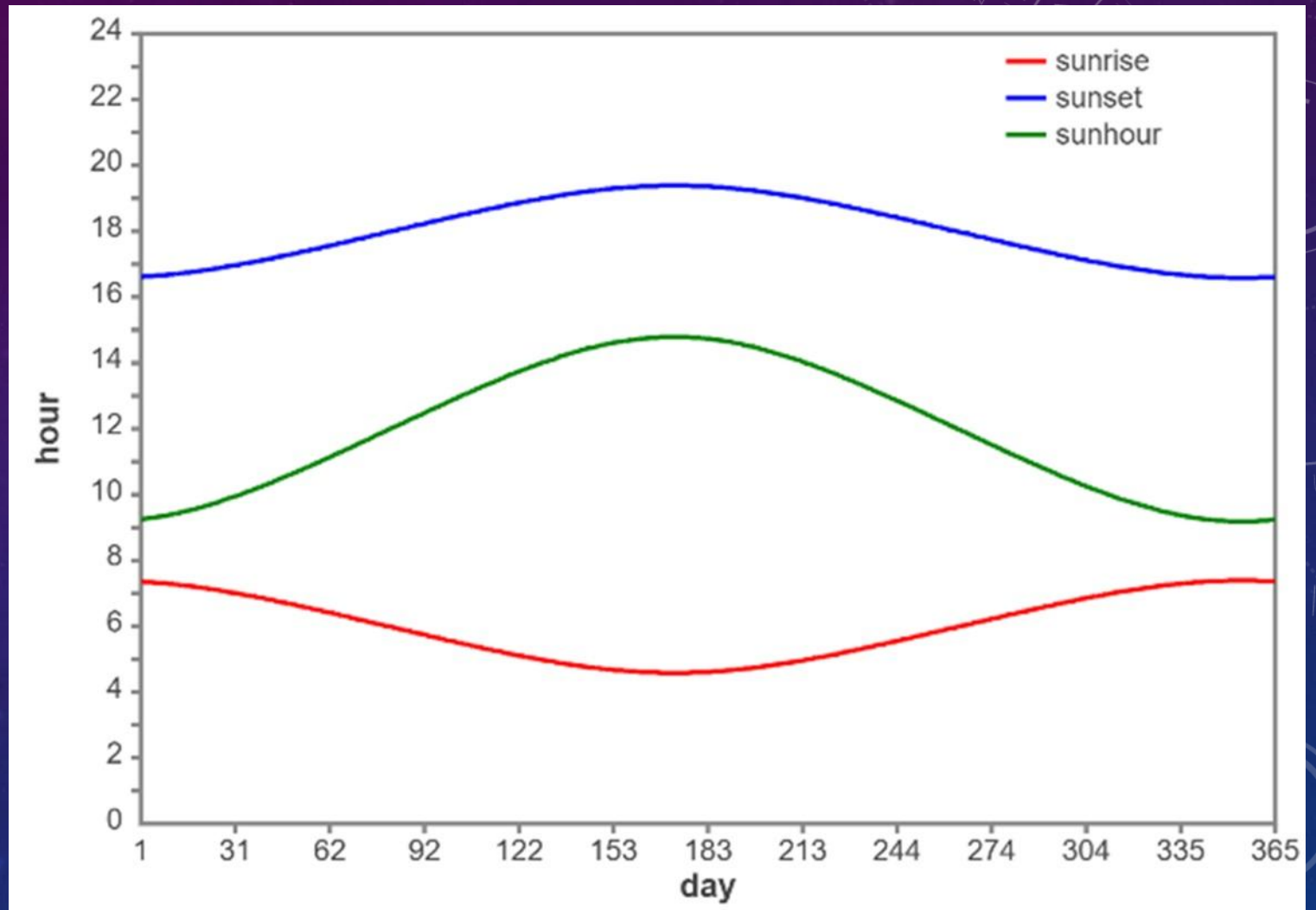


Source:

<https://www.wunderground.com/dashboard/pws/KCOLONGM397/graph/2024-06-21/2024-06-21/daily>

Solar Insolation

At 40-degrees latitude.
Hours of sun by day of year.

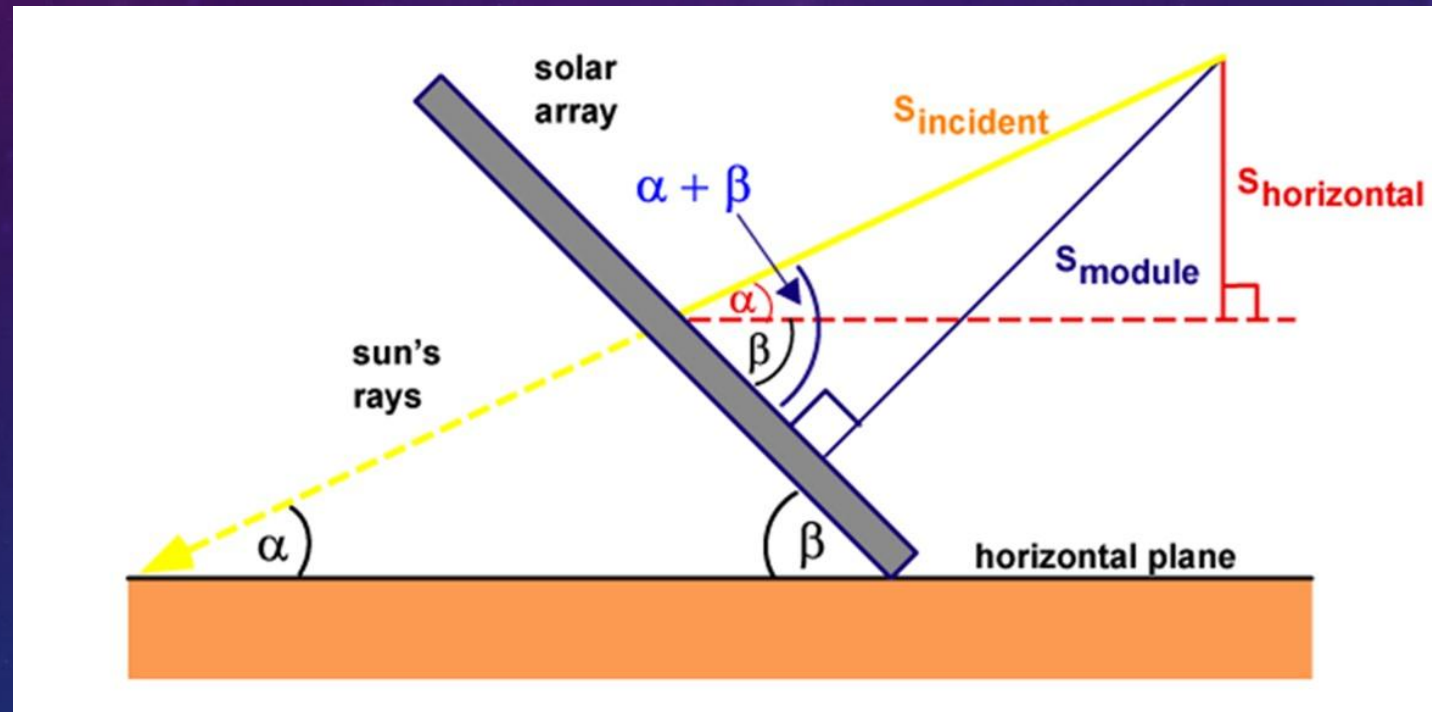


Source:

<https://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation>

Solar Insolation

Solar panel collection is most efficient when the sun is perpendicular to the panel's surface



Source:

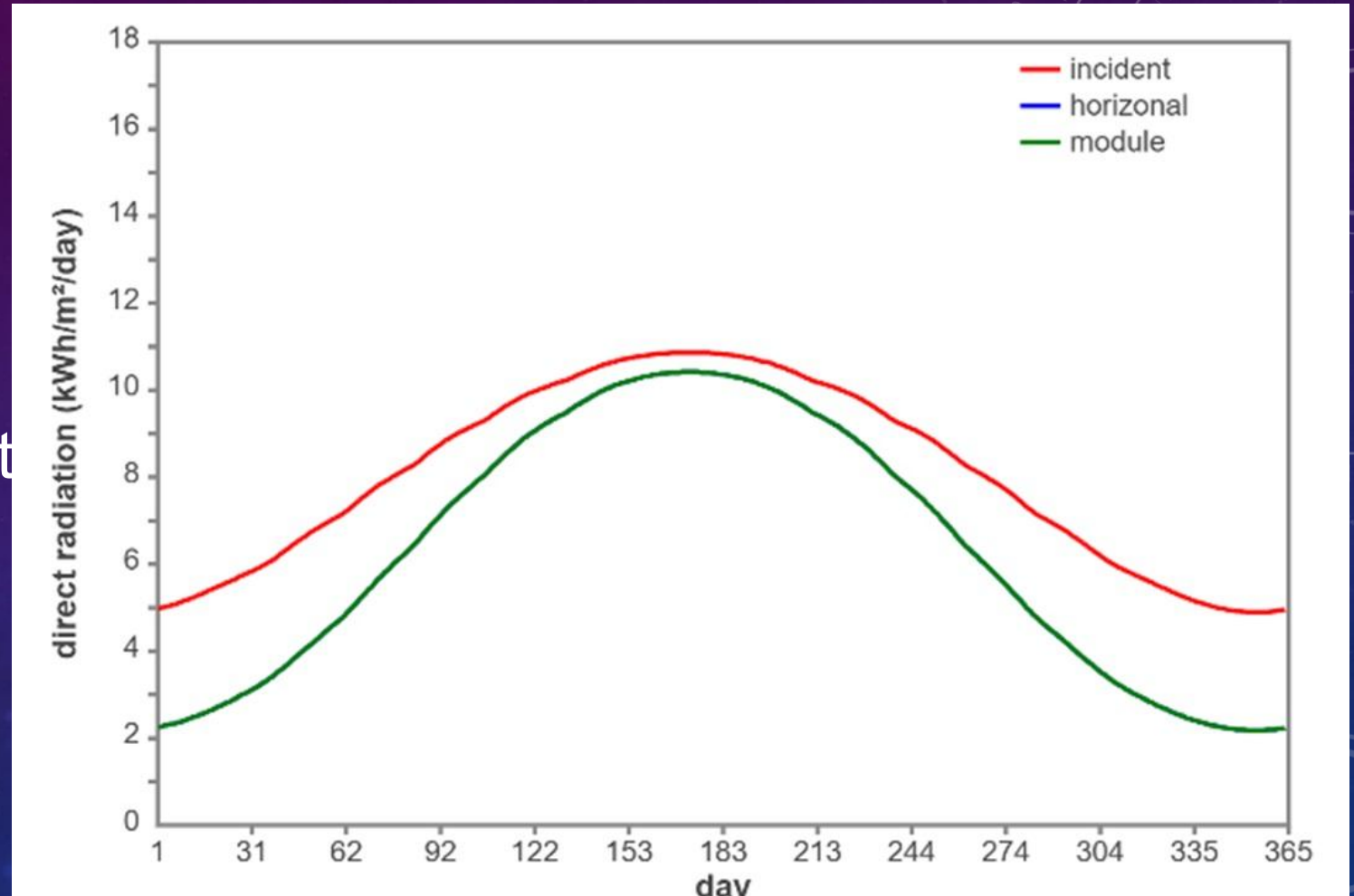
<https://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-on-a-tilted-surface>



Solar Insolation

How does Tilt Help?

Great in the summer, not so much in the winter.



Tilt = Horizontal

Source:

<https://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation>



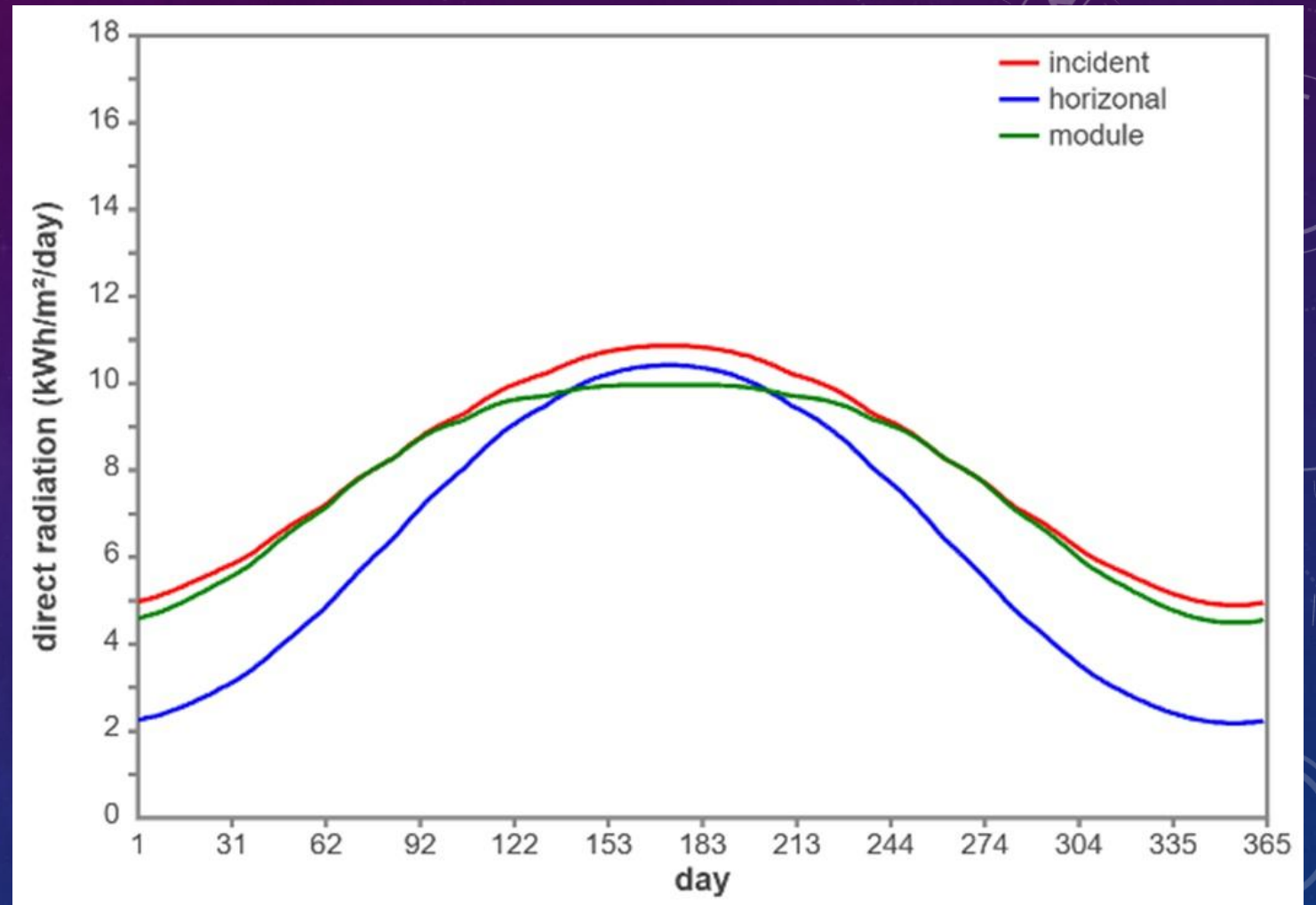
Solar Insolation

How does Tilt Help?

- Rule of thumb for Fixed Tilt:
Set Tilt to Latitude

Significant improvement
winter, minimal impact
summer

Try the model at the link,
below.



Tilt = 40-degrees

Source:

<https://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation>



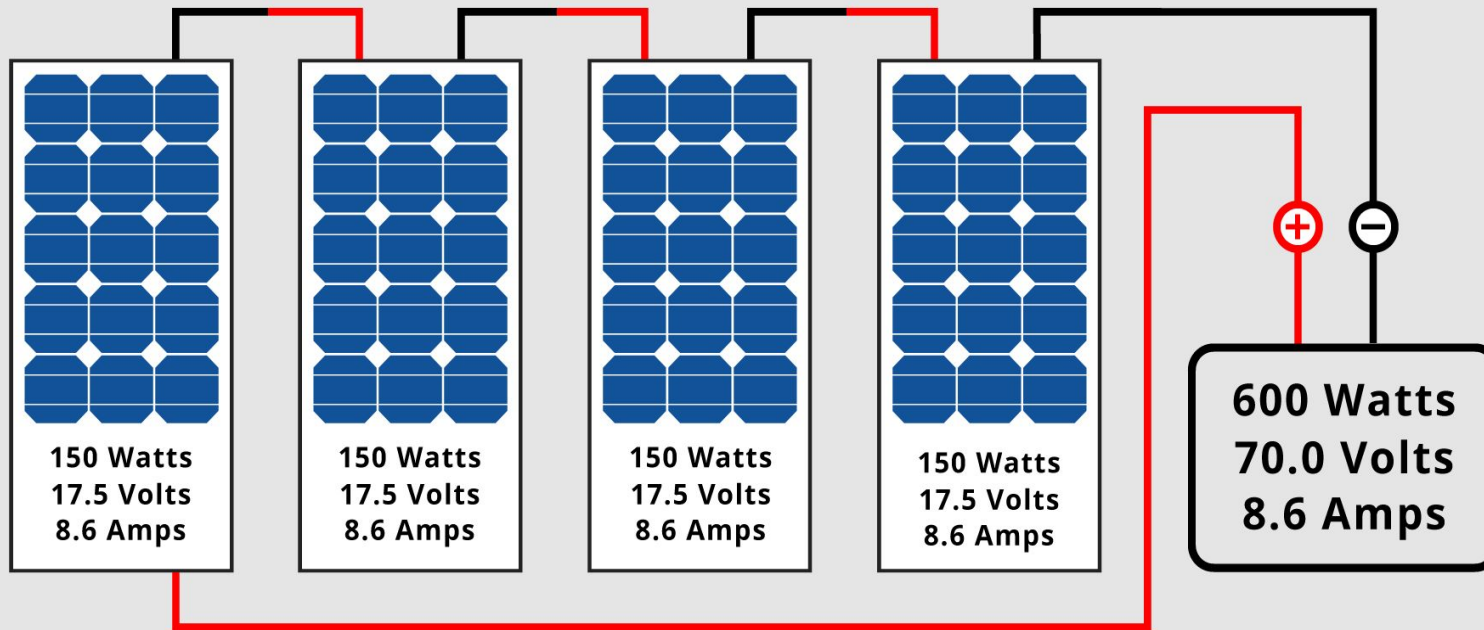
Series vs Parallel Arrays

- Many installations have more than one panel. How should they be wired together?
- Why should I use a series array? A parallel array?
- What do I need to consider?



Series Array

SOLAR PANEL WIRING **SERIES**



In a series array, the panel voltage is additive. In the case shown to the left, it will have 600W across 70V which is simply calculated:

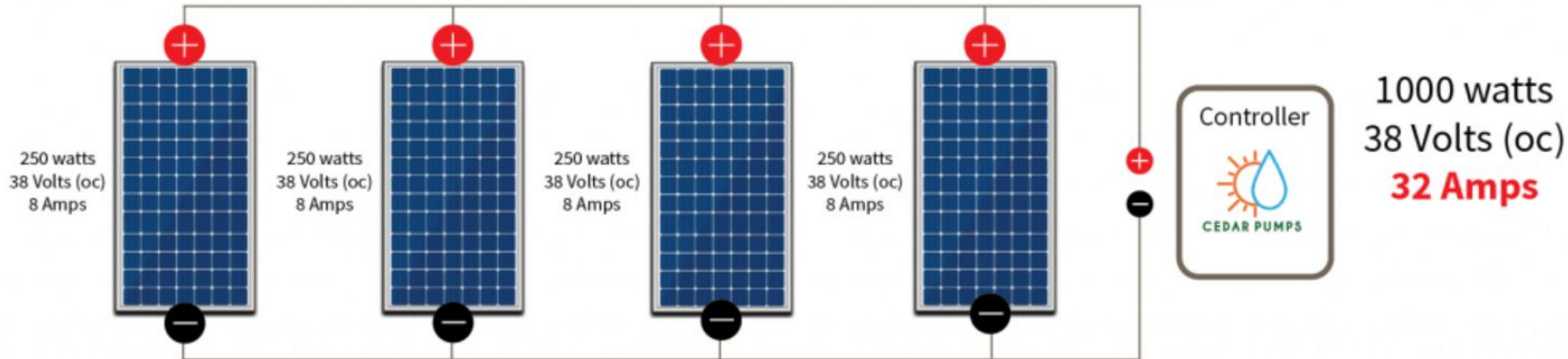
Watts/Volts=Amps or 8.57A

The wire size for this is 14AWG Stranded Solar Cable which provides some overhead! Wire is rated for 15A.

Parallel Array

Parallel Example

4 strings of 1 x 250w module. **Volts stay the same & Amps add up**



In a parallel array, the panel voltage stays the same, amperage is additive. In the case shown to the left, it will have 1000W across 38V which is simply calculated:

Watts/Volts=Amps or 26A

The wire size for this is 8AWG Stranded Solar Cable which provides some overhead! Wire is rated for 45A.

Copper isn't cheap! More voltage means less cost of wire.

For big arrays, copper will get EXTREMELY expensive.

Ref: <https://www.youtube.com/watch?v=b2H8vpj8rQg&t=4s>
<https://www.youtube.com/watch?v=KJ5zCY5EBEQ&t=3s>

Series+Parallel Array

In a series+parallel array the panel voltages in each series string add, the amperages add when the two strings are connected in parallel.

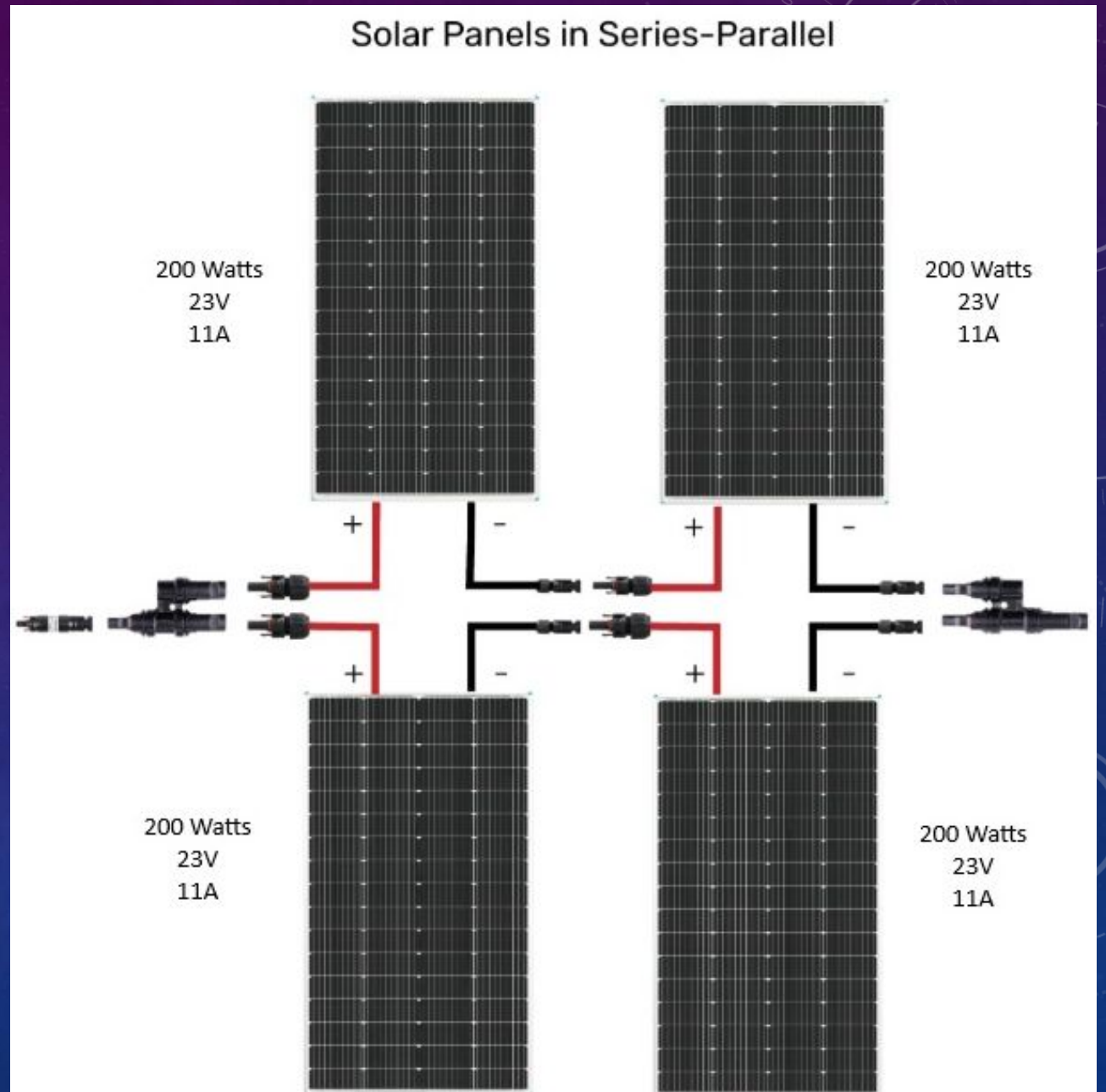
In the case shown to the right, it will have 800W in two series strings:

Each string is $23\text{V} + 23\text{V} = 46\text{V}$.

The two strings paralleled is $11\text{A} + 11\text{A} = 22\text{A}$.

The controller is presented with 46V at 22A @ 25C .

The wire size for this is 10AWG Stranded Solar Cable which provides some overhead! Wire is rated for 30A.



Solar Power Safety



- Solar arrays and battery banks **CAN** produce dangerous voltages and currents!
- Series arrays are often hundreds of volts
 - Insulation and switches must be rated for this (at DC).
- Even 48V battery systems can sting you
- Short-circuiting large batteries will violently vaporize metal and start fires
- **NEVER** backfeed your home electrical system without approved interlock devices on your main panel



Batteries

- Solar power is too unstable to use directly.
- Popular rechargeable battery types
 - Lead-acid based
 - Wet / flooded, Sealed / AGM
 - Starter vs deep-cycle vs marine
 - Lithium-based
 - Lithium polymer (Li-Po)
 - Lithium iron phosphate (LiFePO₄)
- Cost, operating environment, longevity, and safety are factors



Battery Chemistry Comparison

	Cost	Energy Density	Charge Temp.	Longevity	Safety	Notes
Lead-Acid, Wet/flooded	\$	Good	-4°F to 120°F	Shortest (2-3 years)	Risk of sulfuric acid spill if tipped, lead, off-gases H ₂ gas if overcharged	Great for large, stationary bulk storage banks. Freezes when battery is discharged.
Lead-Acid, AGM	\$\$	Good	-4°F to 120°F	Shorter (2-5 years)	Safest – sealed, minimal H ₂ off-gassing, but don't crack it open	Low-cost portable applications
Lithium Polymer	\$\$\$\$	Highest	32°F to 100°F	Higher (~5 years)	Prone to thermal-runaway (fire/explosion) if damaged or overcharged.	When low weight / high energy density is needed in conditioned environments, longer-term investment and payback
Lithium Iron Phosphate	\$\$\$\$	High	32°F to 100°F	Higher (~10 years)	More stable than Li-Po	Much lighter than Lead LiFePo ₄ has most cycles of all battery chemistries

Battery Charging

- Different battery chemistries have different charging requirements
- Buy the appropriate charger!
- Some batteries have integrated Battery Management Systems (BMS)
 - On-board charging circuitry (accepts a straight DC input)
 - Balancing the individual cells
 - Overcurrent / over-temp protection features
 - Read your battery's manual



Cheap charger that supports multiple chemistries and battery voltages

Battery Safety

- Number of battery-powered devices at home is growing
- Cases of battery fires (esp. Lithium) are climbing
 - Very hard to extinguish
 - In many cases, the suspected battery was NOT actively charging.



Battery Safety Tips

- Use the correct type of charger for your battery type.
- Add fuses to your battery pigtails.
- Buy batteries from reputable sources.
- Store and charge safely.
- Use protective enclosures and guard terminals.
- Dispose of batteries if damaged or unneeded
 - BatteriesPlus and many other stores will recycle them for free
 - Some auto parts stores take lead-acid batteries and give you a gift card!
 - Check if your town has a collection site





OFF-THE-SHELF PRODUCTS

Build your own system!




Solar Panels - New

- Cell Type
 - Monocrystalline
 - Polycrystalline
 - Bifacial
- Manufacturers
 - Santan solar - <https://www.santansolar.com/>
 - Renogy - <https://www.renogy.com/>
 - Many others

Monocrystalline and polycrystalline solar panels differ in the following ways:

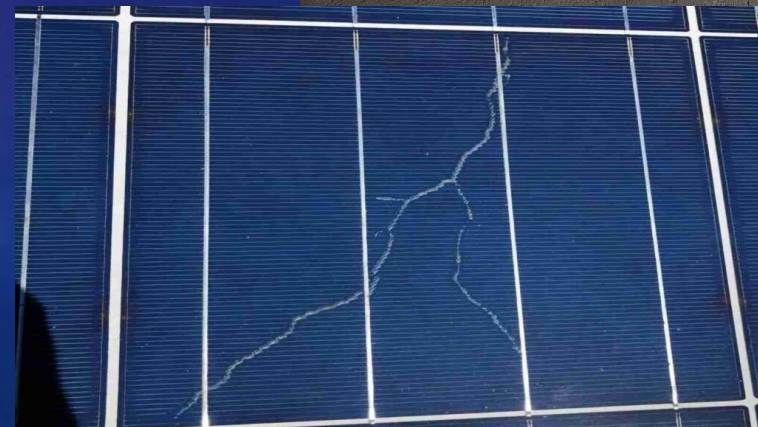
- **Appearance:** Monocrystalline panels are black and have rounded edges, while polycrystalline panels are blue and have a fragmented look. 
- **Efficiency:** Monocrystalline panels are more efficient, with an efficiency rating of 15–24%, compared to 13–16% for polycrystalline panels. 
- **Cost:** Monocrystalline panels are more expensive than polycrystalline panels. 
- **Manufacturing:** Monocrystalline panels are made from a single silicon crystal, while polycrystalline panels are made from multiple silicon crystals melted together. 
- **Lifespan:** Monocrystalline panels have a longer lifespan and manufacturers typically offer a 25-year warranty. 
- **Performance in the shade:** Monocrystalline panels perform as well as polycrystalline panels in the shade. 
- **Space:** Monocrystalline panels are better if space is limited. 

While monocrystalline panels are generally more efficient and perform better, polycrystalline panels are more affordable and have become more competitive due to technological advancements. 



Solar Panels - Used

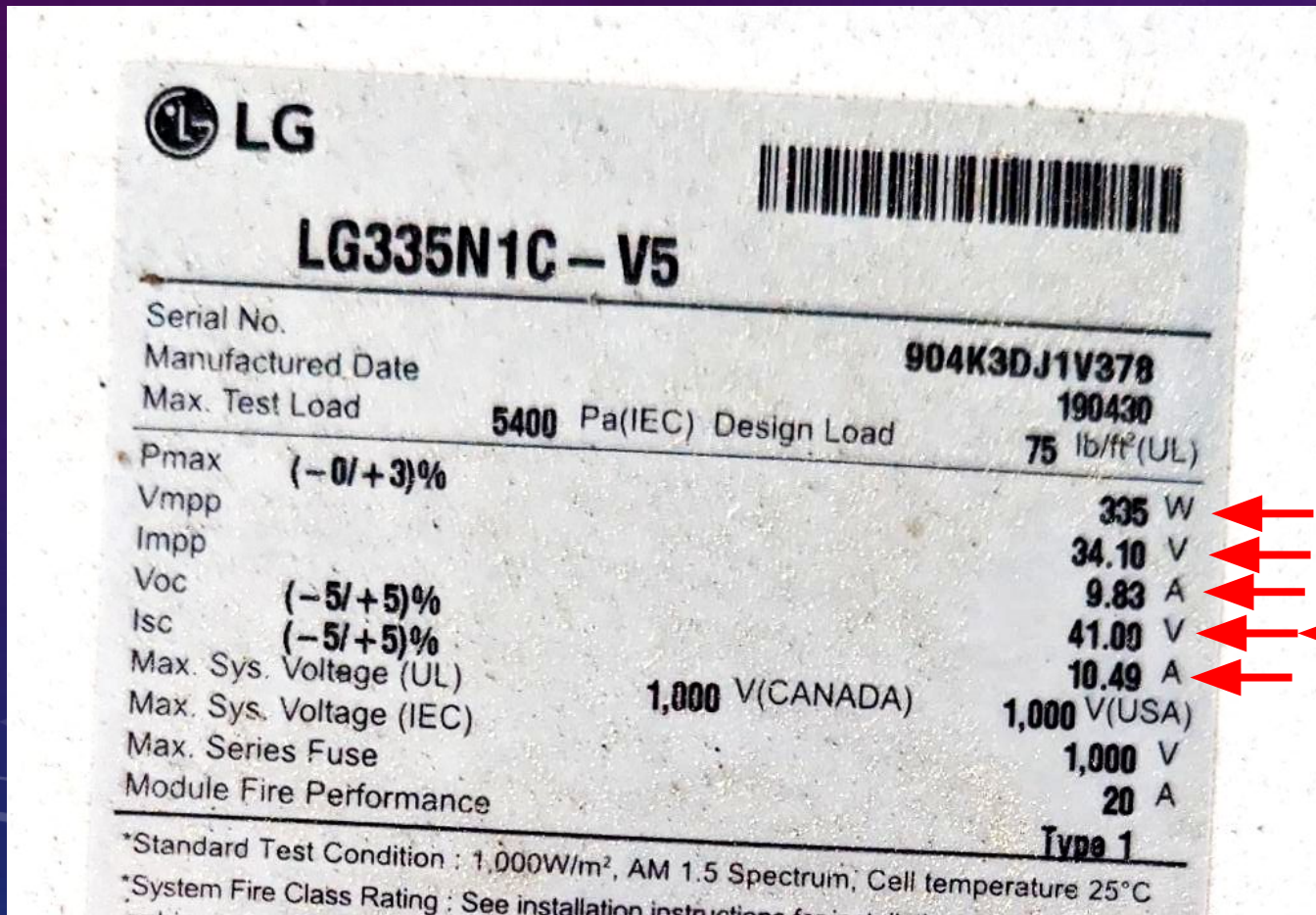
- Used panels?
 - Save a lot of money, but likely lower efficiency
 - Good deal if not space-constrained
 - Panels last decades if not damaged
- “Snail Trail” panels
 - Snail Trail are panels with cosmetic defects
 - Sold at a discount, but has insignificant impact on power output
- A few of many sources
 - Santan solar - <https://www.santansolar.com/>
 - Local surplus houses
 - Many others



*Top: Pallet of used panels on sale at Resource Central, Boulder CO
Bottom: Snailtail panel*



Reading Labels on Panels



- Pmax → max power output
 - $P_{\max} = V_{\text{mpp}} * I_{\text{mpp}}$
 - (maximum power point)
 - Drawing this much current yields the most power (in full sun)
- Voc → Open-circuit voltage (nothing attached)
 - Voc usually is a concern in the winter when the temperature of the system is very low. Voc can be up to 10% more than the summer operating voltage. This needs to be considered when sizing solar controllers max voltage!
- Isc → Dead-short current
- Max sys voltage → limits the number of panels in series
- All specs are at 25C
 - They go UP at colder temperatures!

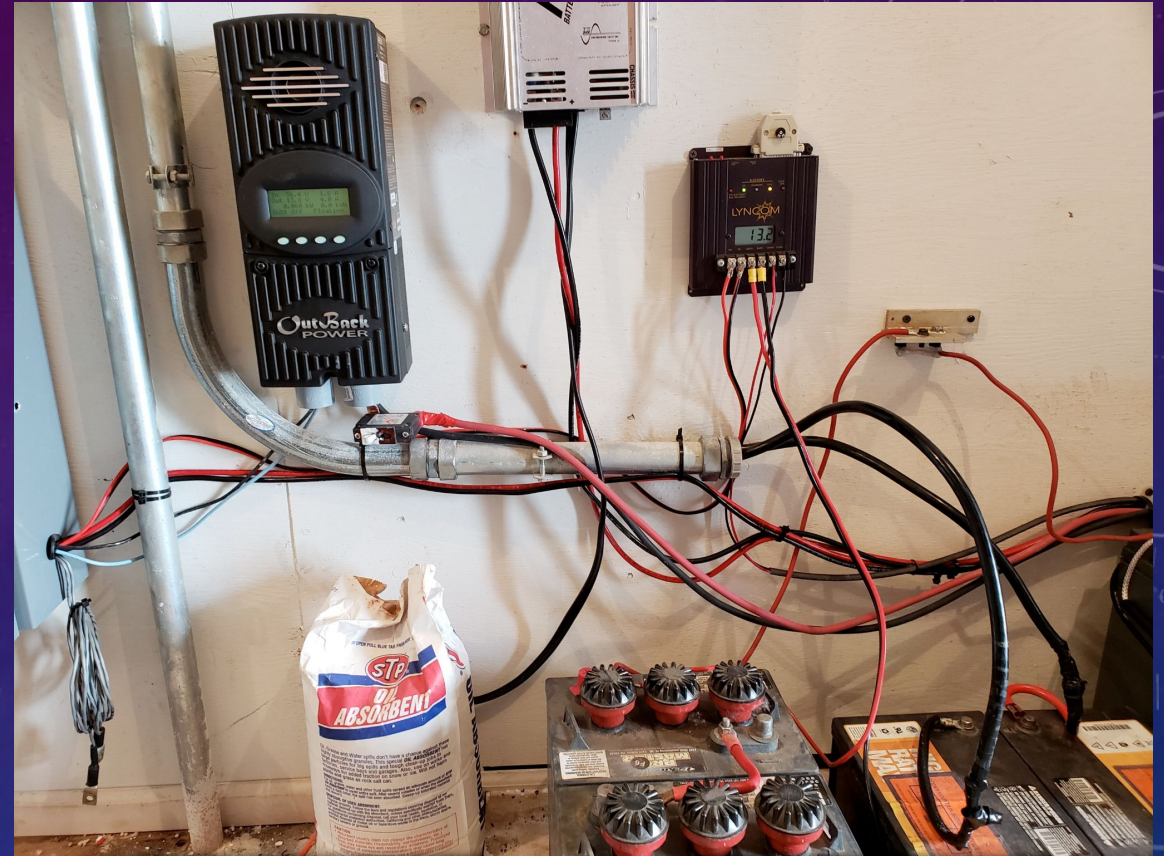
MC4 Solar Panel Connector

- Most panels have these.
- Individual positive and negative leads; easy to daisy chain in series.
- Waterproof, UV-resistant
- 600V or 1500V rating (newer versions)
- Buy a good quality crimp tool or solder
- They will arc if not properly attached



Charge Controllers

- Brands
 - Outback
 - EPEVER
 - Victron
 - Schneider Electric
- IP monitoring and telemetry is vital for remote sites



AC Inverters

- Victron
 - Outback
 - GoPower
 - Renogy
-
- Avoid EPEVER Inverters due to poor quality
-
- Grid Supplement
 - Some Inverters allow you to charge the batteries from the Commercial Grid when necessary



Batteries

LiTime LiFePO4 Batteries

Built-in BMS

Many capacities, physical sizes, BMS sizes and options

Optional Internal Heaters for Low Temperature Applications

Optional Bluetooth

Support Parallel Operation

10 Year Service Life

4000 cycles at 100% DOD, 6000 cycles at 80% DOD, 15,000 cycles at 60% DOD

<https://www.litime.com/>



Battery Form-factors



DC/DC Converter

Used in Multi-Battery Systems

Isolate Starter Battery from House Battery

Typically used to isolate the tow vehicle 12V power system from the 12V/24V/48V Lithium power system of a trailer.



Use properly-rated components!

- DC arcs more easily than AC. Your switch must be rated for DC voltages and currents!
- Low-quality crimps and connections lead to fires
- Use fuses and circuit breakers
- Aluminum or copper-clad aluminum cable is cheaper, but carries less current and fatigues easily

What do you do when the bad happens?

First shut off the electrical power

As needed use a ABC Powder or CO2

Don't use water!





PRACTICAL EXAMPLES



Small-scale Portable Setups

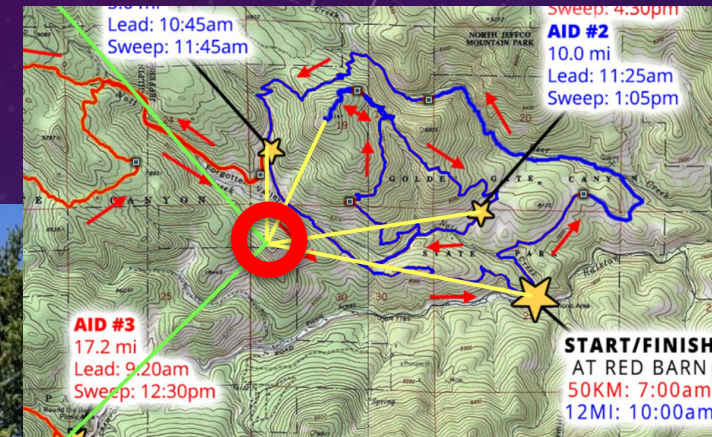
- Great for camping, SOTA/POTA, field day, ARES deployments
- Just like before: Solar panel + battery + load
- In-room demos



RMHAM at the Dirty30 Race

- **Problem:** Need to establish microwave links from multiple sites in a mountainous race course. Central location is a peak with no road access or any infrastructure.
- **Solution:** Deploy Chris, K0SWE, with solar, battery, and microwave gear
 - All hauled up via backpack.
 - 36-hour deployment to keep our communications network operational for the whole event.
 - Gear used: folding solar panels, charge controller, small batteries

<https://k0swe.radio/2021/06/13/dirty-30.html>



WA1JHK RV Trailer Solar Power

Goal

Provide off-grid operation for multiple days

Lighting, Starlink, Furnace, Fridge and Water Heater Controls

Not planning to run air conditioning

Minimal 120V appliances, mostly TV

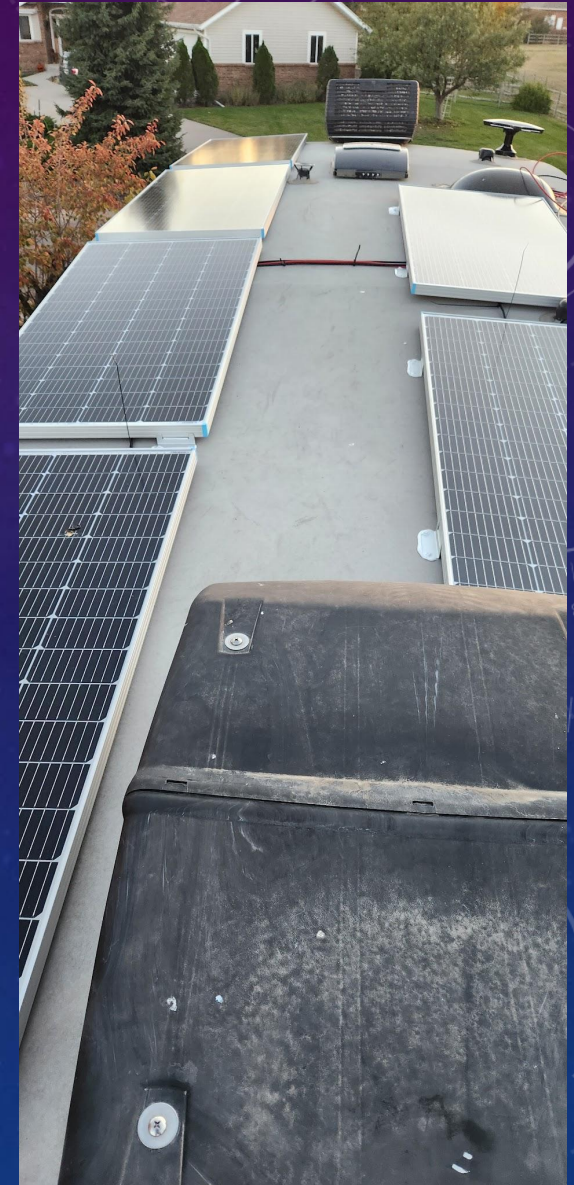
Considerations

Jayco Eagle HTX 26RLX 5th Wheel, 31 feet long

Limited roof space – drives panel dimensions

PV pre-wiring from the roof to the charger location is “somewhere”

PV pre-wiring from the roof is 8AWG stranded



WA1JHK RV Trailer Solar Power



Checking out the roof space.



Prewired PV connectors.

WA1JHK RV Trailer Solar Power

Where does the pre-wiring show up?



The pre-wiring is here somewhere.

Inductive wire tracer



Oh, there it is.



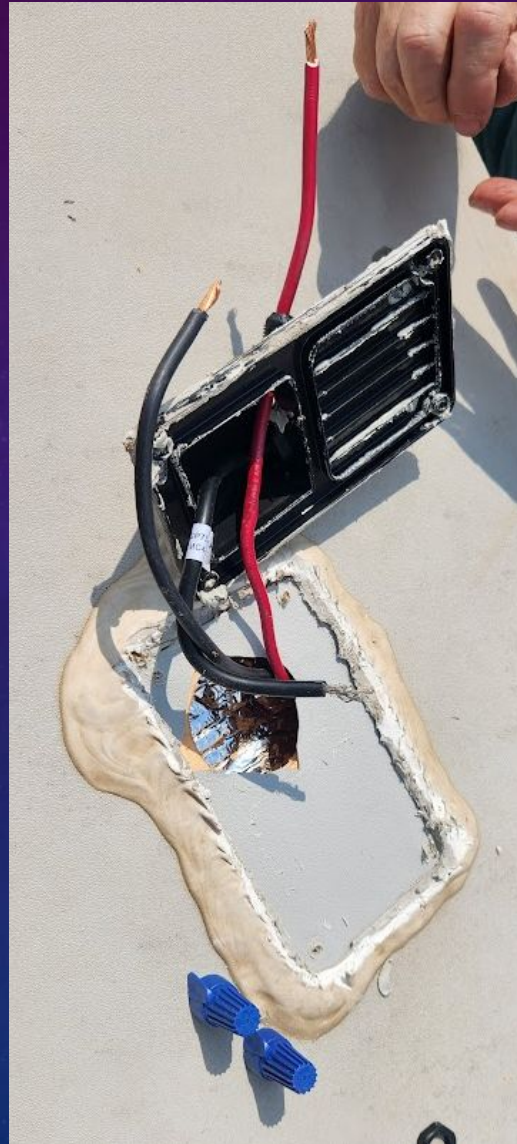
Spliced to feed to the front bay

WA1JHK RV Trailer Solar Power

Testing the Pre-wired Roof-Mount
PV Connection



Aren't those wires supposed to be connected?



Much Better.



WA1JHK RV Trailer Solar Power

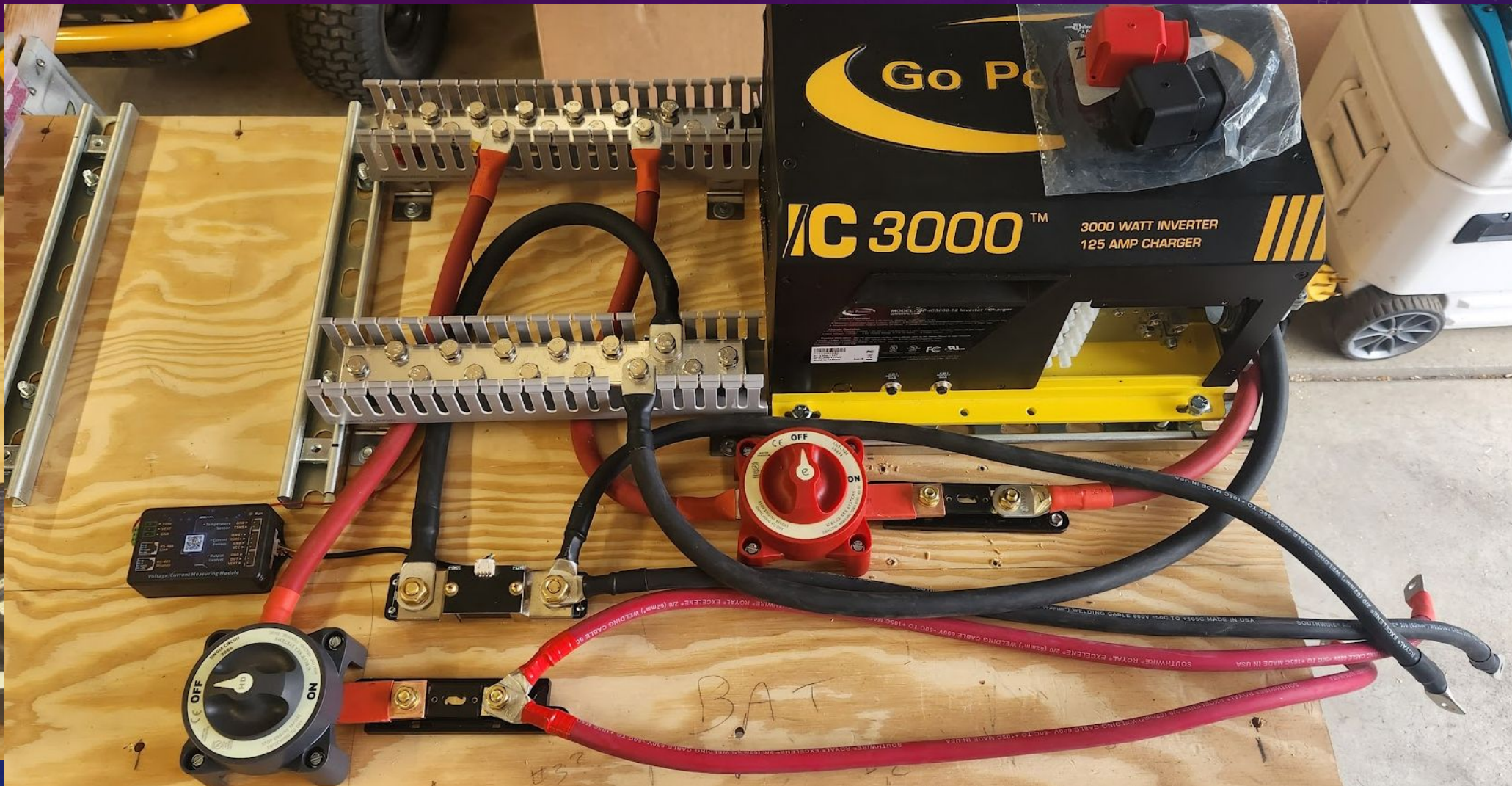


Plan it out



Get familiar with the State of Charge Monitor and the 200AH LiFePO4 Battery

WA1JHK RV Trailer Solar Power



Mount components on a backboard in the garage before installation.

WA1JHK RV Trailer Solar Power

Wiring the panels

3S+2P (3 Panels in Series String + 2 Strings In Parallel)

69V, 22.10A @25C to the MPPT Charger

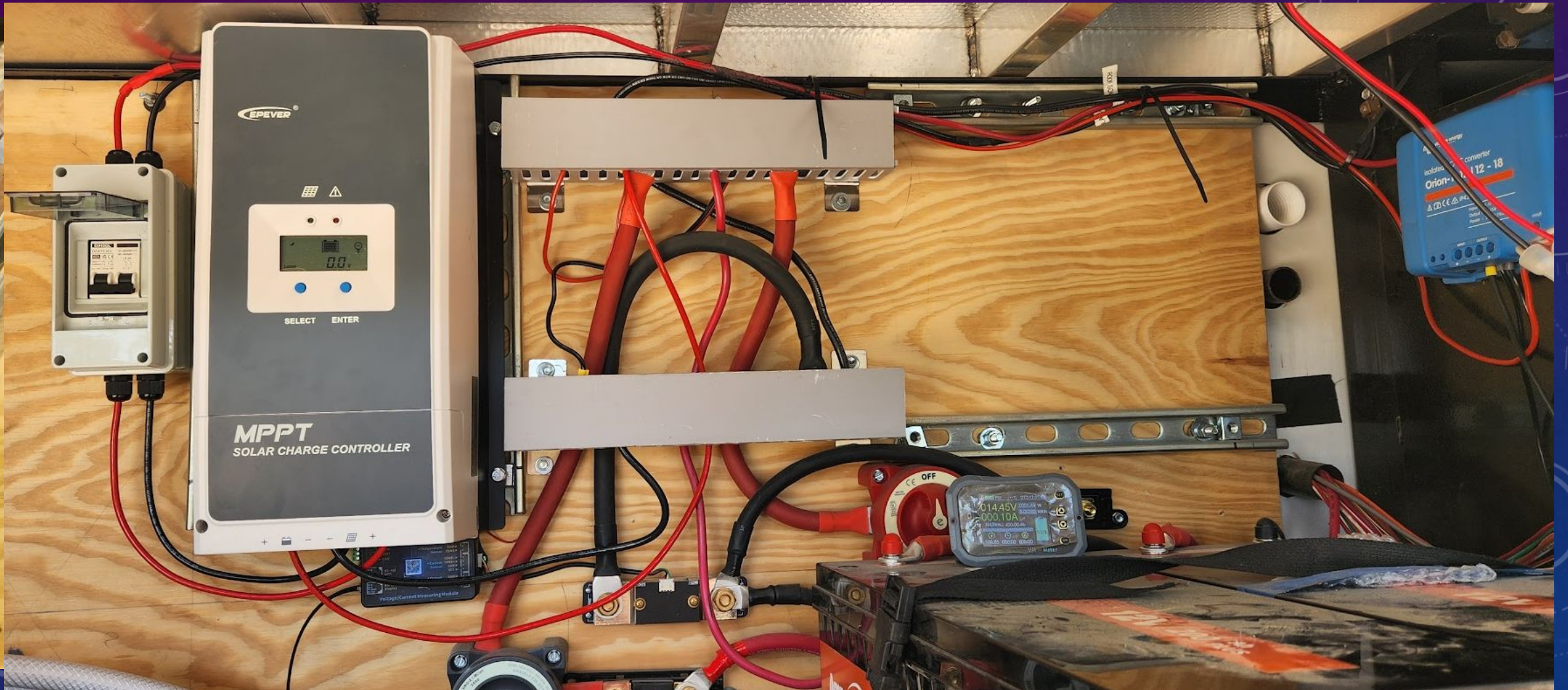
Pre-wiring from Roof to Front Bay is 8 AWG Stranded



RENOGY	
Module Type	RSP200D
Max Power at STC (P_{max})	200 W
Optimum Operating Voltage (V_{mp})	19.2 V
Optimum Operating Current (I_{mp})	10.42 A
Open-Circuit Voltage (V_{oc})	23.0 V
Short-Circuit Current (I_{sc})	11.05 A
Temp Coefficient of P_{max}	-0.37%/°C
Temp Coefficient of V_{oc}	-0.28%/°C
Temp Coefficient of I_{sc}	0.05%/°C
Max System Voltage	600 VDC
Max Series Fuse Size Rating	20 A
Fire Performance	Type I
Safety Class	Class II
Weight	12 kg (26.5 lbs)
Dimensions	1491x699x35 mm (58.7x27.5x1.4 in)
STC	Irradiance 1000W/m ² , T=25°C, AM=1.5



WA1JHK RV Trailer Solar Power



Front bay equipment mounted, wired, just missing the inverter. That's two 200AH LiFePO4 batteries.

WA1JHK RV Trailer Solar Power

References

Components

Solar Panels: <https://www.renogy.com/200-watt-12-volt-monocrystalline-solar-panel/>

MPPT Charger: <https://www.epever.com/product/tracer-an-50-100a-mppt-charge-controller/>

Inverter/Charger/Transfer Switch:

<https://gopowersolar.com/products/ic-series-3000-watt-inverter-charger/>

Switches, Circuit Breakers: <https://www.blueseas.com/>

PV Circuit Breakers: <https://www.amazon.com/gp/product/B0BLH5NZKB>

Information

<https://www.pveducation.org/pvcdrom/welcome-to-pvcdrom>

<https://www.youtube.com/@EXPLORISTlife>

<https://www.youtube.com/@EXPLORISTlife/playlists>

Solar panel voltage and current at very low temperatures

<https://www.youtube.com/watch?v=MxziHKvTRh8&t=498s>

RMHAM Bunkhouse Trailer

- 8x 245W Advance Solar panels (=1960W)



Two tilting arrays of panels

Mini-split heating and cooling

Shore power inlet, 120VAC outlets

RMHAM Solar Sites

- Mosquito (right)
 - Full-time solar power
 - Elevation: 13,500ft
- Breckenridge (below)
 - Supplemental solar + battery power due to unreliable AC supply
 - Older equipment, due for an upgrade



K2AD Home - “A MAN BUILDS HIS HOUSE; THEN HE DIES”

I may be building my solar system for a long time!

New QTH with 7 acres, in Unincorporated Weld County, no HOA, open sky view to the South

Goal: 20KVA to run the entire property off-grid with commercial backup





Q&A