Photovoltaics

Conversion of light to electricity

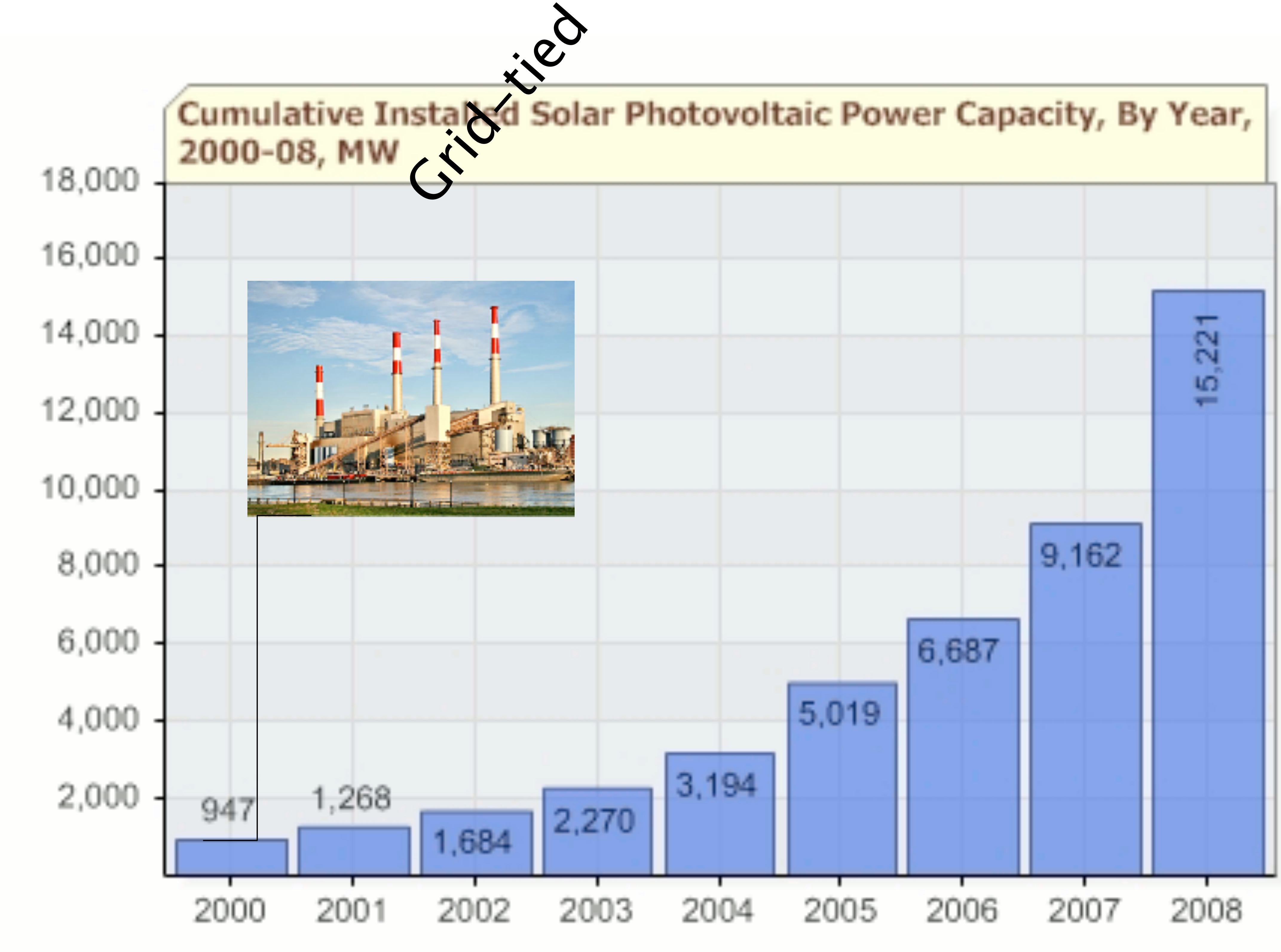
Energy
ITP / NYU / Feddersen

TODAY:

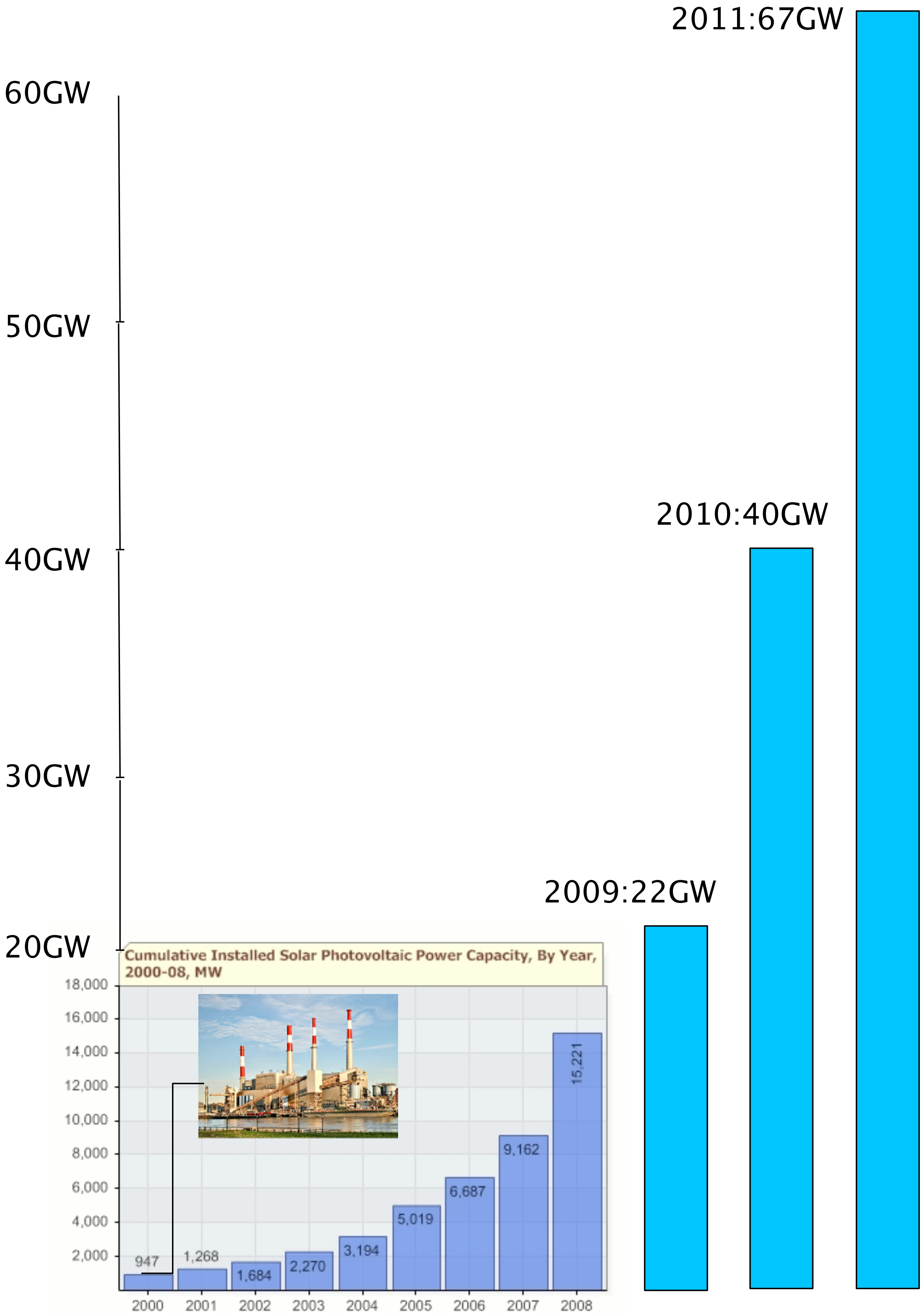
- Why is solar important?
- What exactly is photovoltaic (PV) solar?
- How does PV work?
- Preview: How can I plan a small/medium/large solar project?

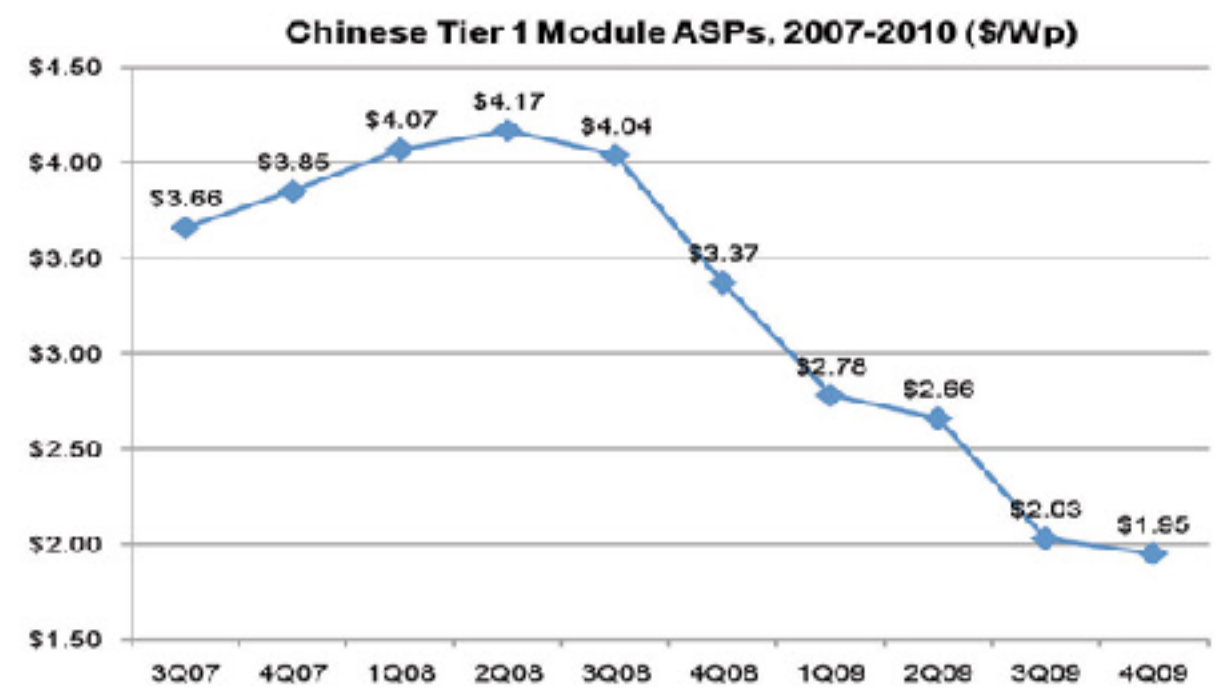
WHY SOLAR?


Energy directly from the sun, powering a
GLOBAL TRANSFORMATION
happening right now



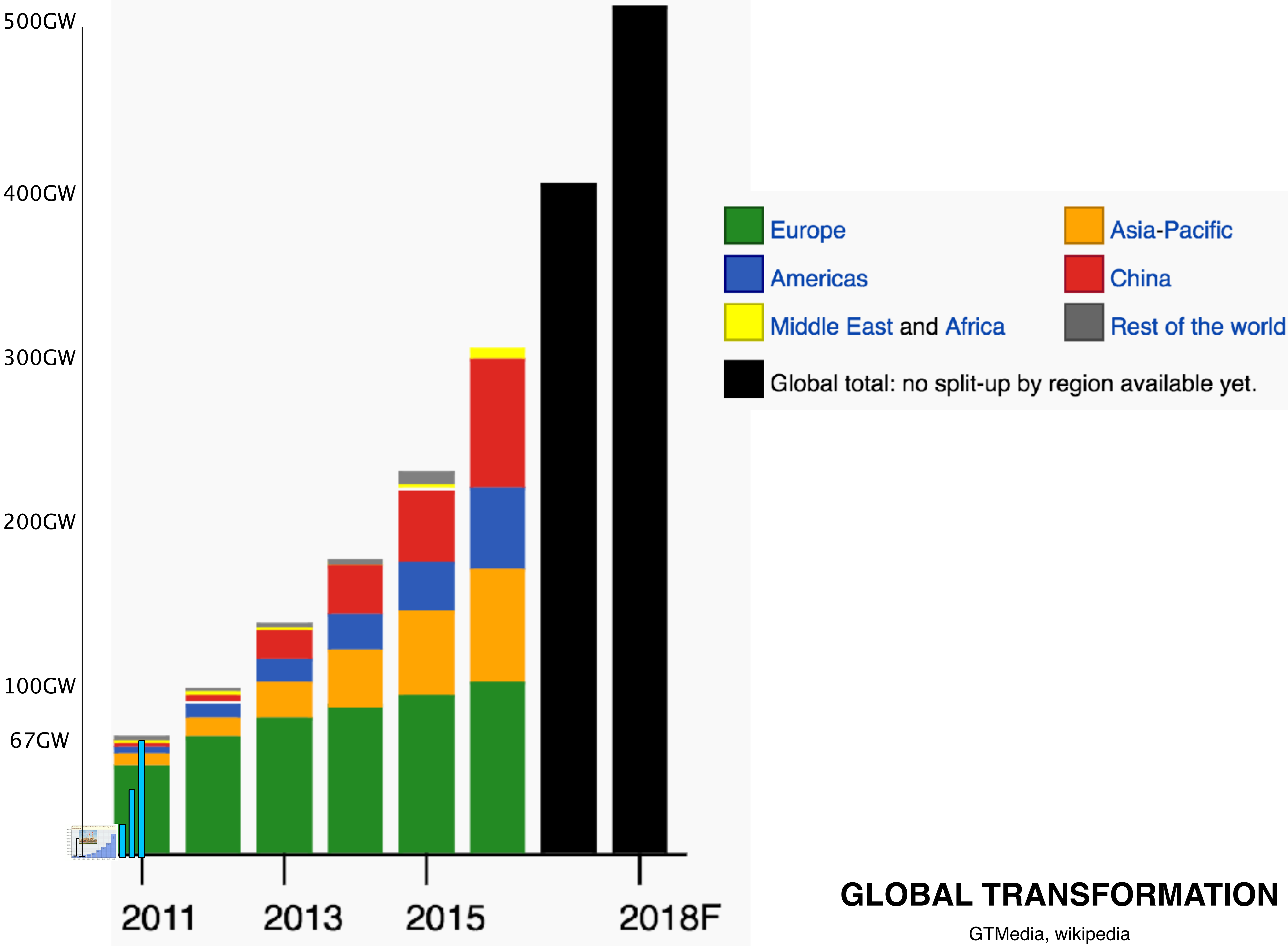
Source: http://www.energyandcapital.com/
Inset: Big Allis, first 1GW generator, in Queens.





GTMedia, wikipedia

GLOBAL TRANSFORMATION



GLOBAL TRANSFORMATION

GTMedia, wikipedia

~1GW TOTAL GLOBAL INSTALLED SOLAR IN 2000

~1GW OF NEW SOLAR INSTALLED EVERY 3 DAYS IN 2019

"Solar additions totaled 119 gigawatts globally in 2019" - Bloomberg Green

~1GW OF NEW SOLAR PROJECTED EVERY 1.8 DAYS IN 2022

Solar additions projected to exceed 200GW in 2022*

*Reports list 220 - 260GW for 2022

SHOULD EXCEED 1TW SOON

*1TW global capacity achieved in April 2022

https://www.bloomberg.com/news/articles/2020-09-01/the-world-added-more-solar-wind-than-anything-else-last-year

https://www.solarpowereurope.org/insights/market-outlooks/global-market-outlook-for-solar-power-2022

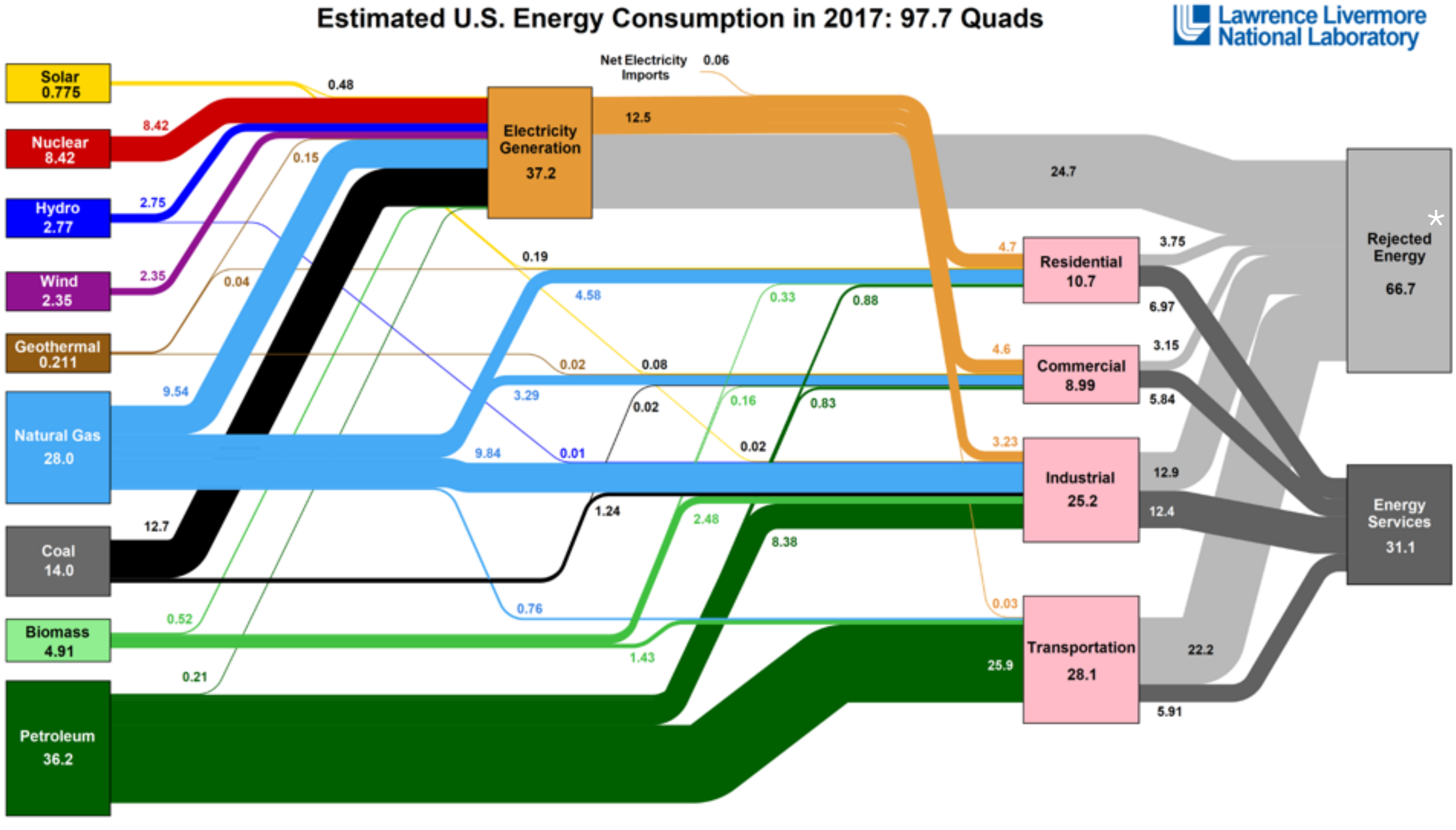
https://www.pv-magazine.com/2022/12/23/global-solar-capacity-additions-hit-268-gw-in-2022-says-bnef/

"THE FIRST TERAWATT OF SOLAR TOOK 70 YEARS. THE NEXT WILL TAKE 3."

- Pierre Verlinden, solar pioneer and former chief scientist at Trina Solar

https://www.pv-magazine.com/

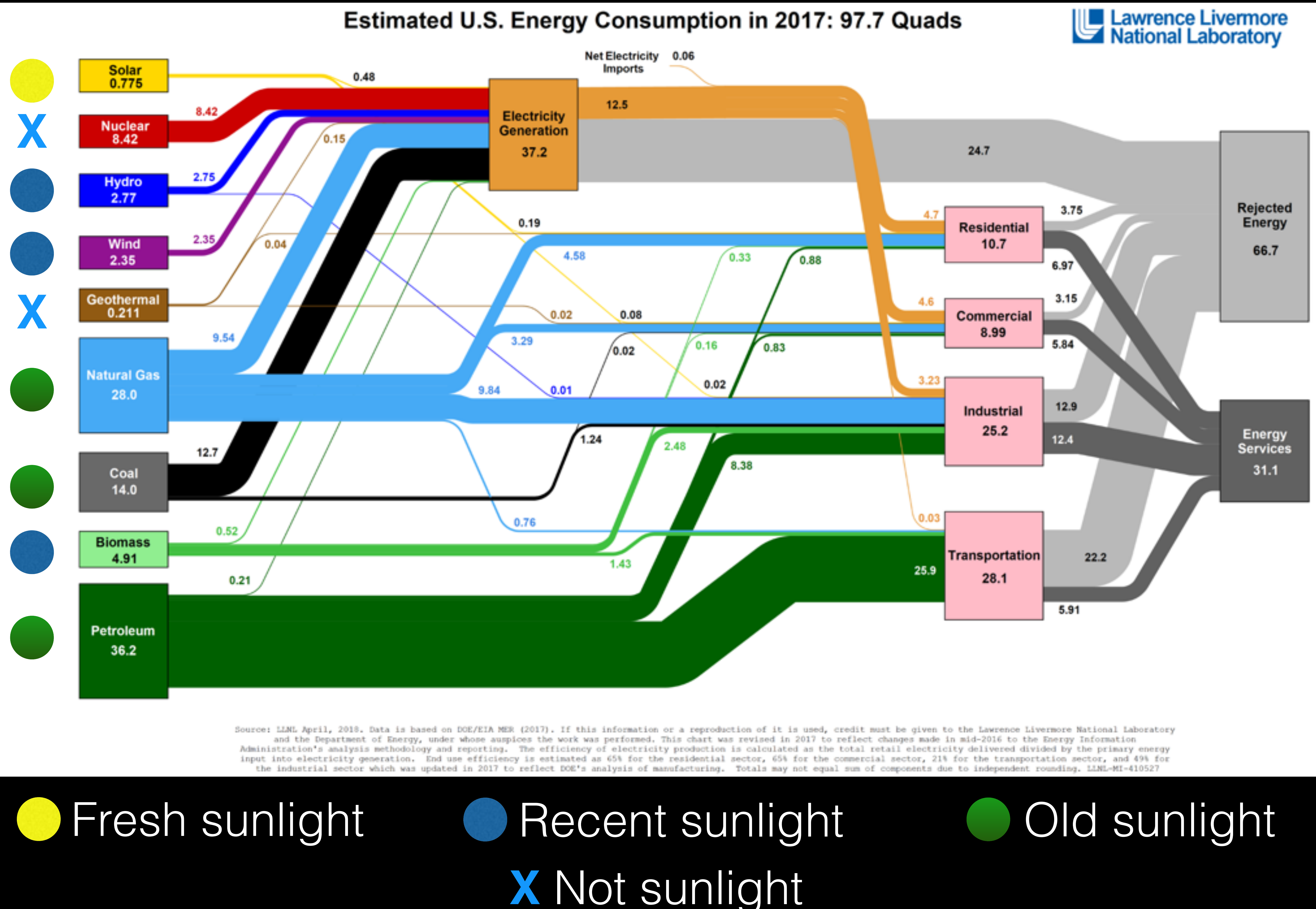
Energy directly from the sun

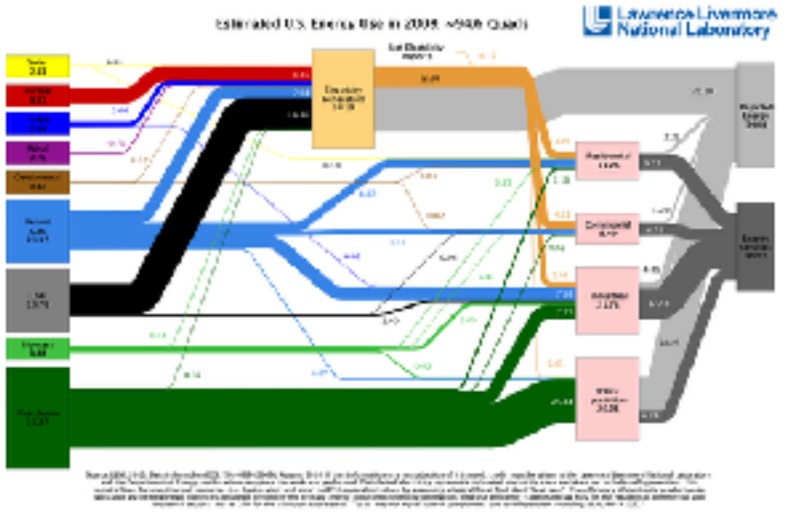


Source: LLNL April, 2018. Data is based on DOE/EIA MER (2017). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

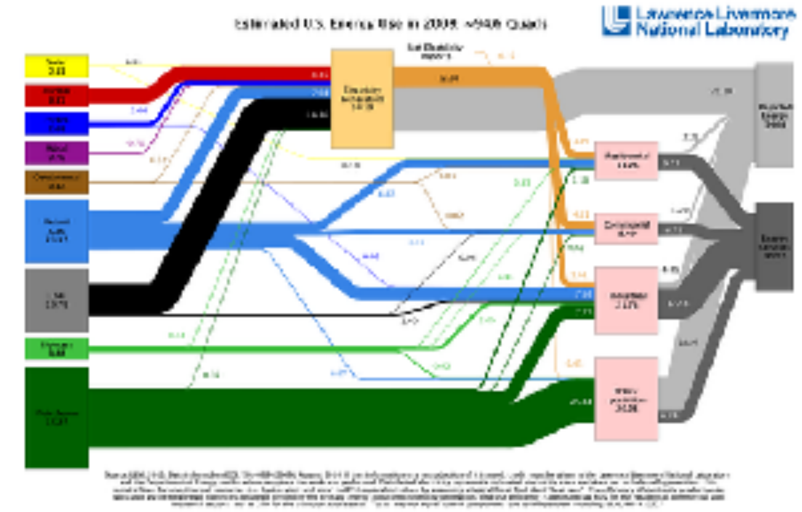
*for more on Rejected Energy, see http://aceee.org/sites/default/files/publications/researchreports/e13f.pdf

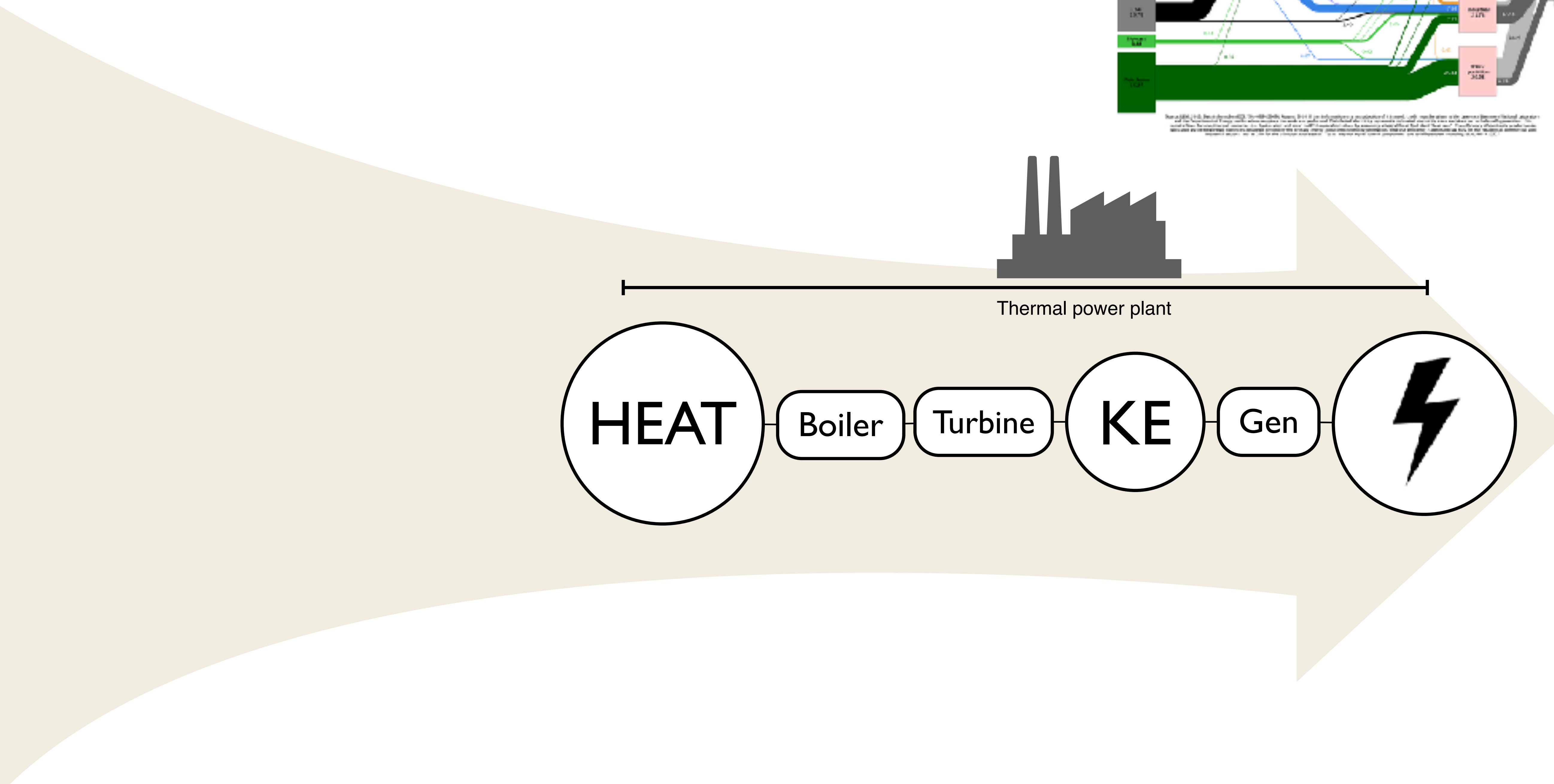
**for more on comparing energy quantities, see http://vaclavsmil.com/ and https://www.withouthotair.com/


Estimated U.S. Energy Consumption in 2017: 97.7 Quads
Lawrence Livermore National Laboratory
Solar 0.775
Nuclear 8.42
Hydro 2.77
Wind 2.35
Geothermal 0.211
Natural Gas 28.0
Coal 14.0
Biomass 4.91
Petroleum 36.2
Net Electricity Imports 0.06
Electricity Generation 37.2
12.5
24.7
Rejected Energy 66.7
Residential 10.7
Commercial 8.99
Industrial 25.2
Transportation 28.1
Energy Services 31.1
0.48
8.42
2.75
2.35
0.15
0.04
9.54
12.7
0.52
0.21
0.19
4.58
0.02
0.08
3.29
0.02
9.84
0.01
0.02
1.24
0.76
1.43
2.48
8.38
0.33
0.88
0.16
0.83
4.7
4.6
3.23
0.03
25.9
3.75
6.97
3.15
5.84
12.9
12.4
22.2
5.91
Source: LLNL April, 2018. Data is based on DOE/EIA MER (2017). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527
X
X
Fresh sunlight
Recent sunlight
Old sunlight
X Not sunlight

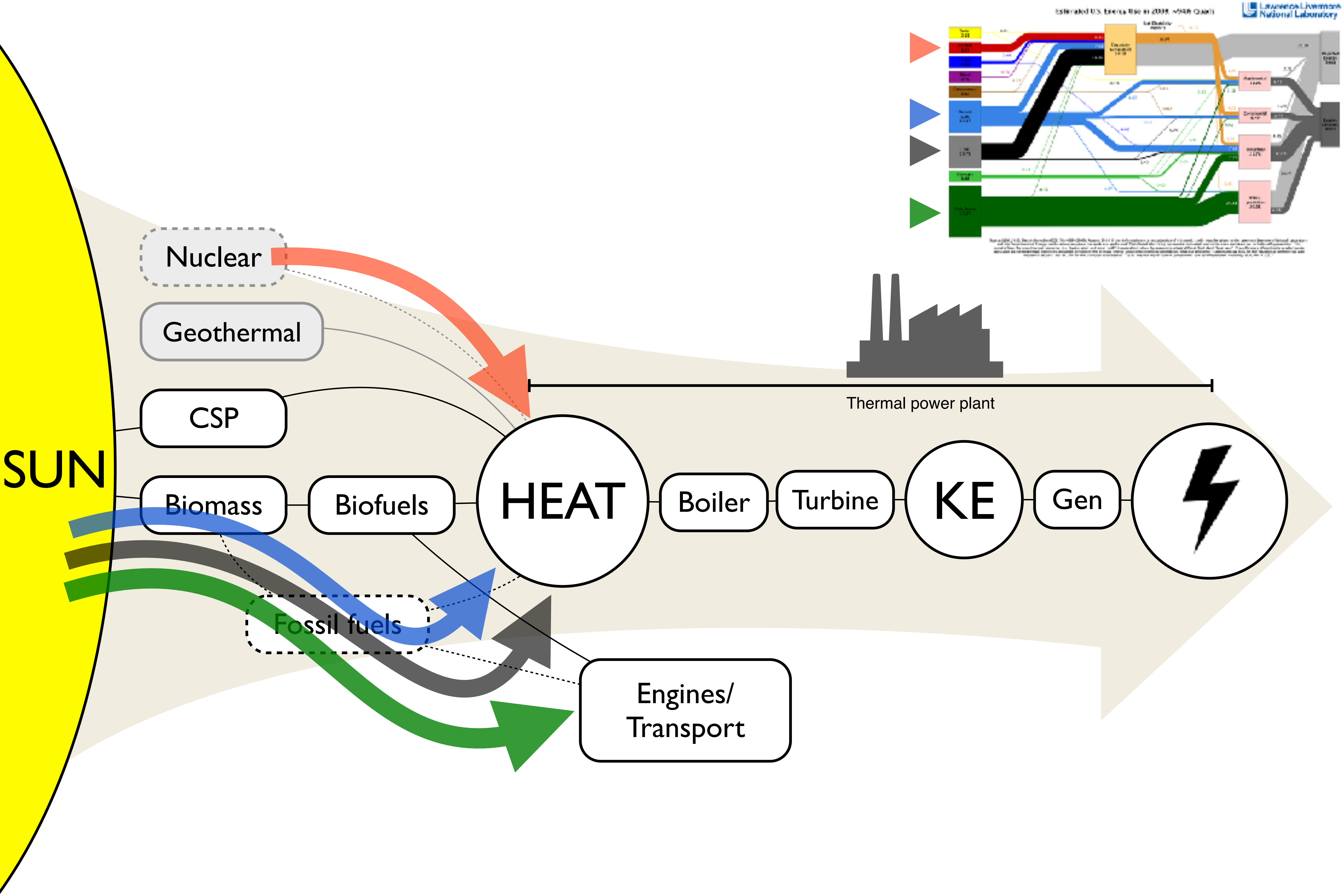


Review

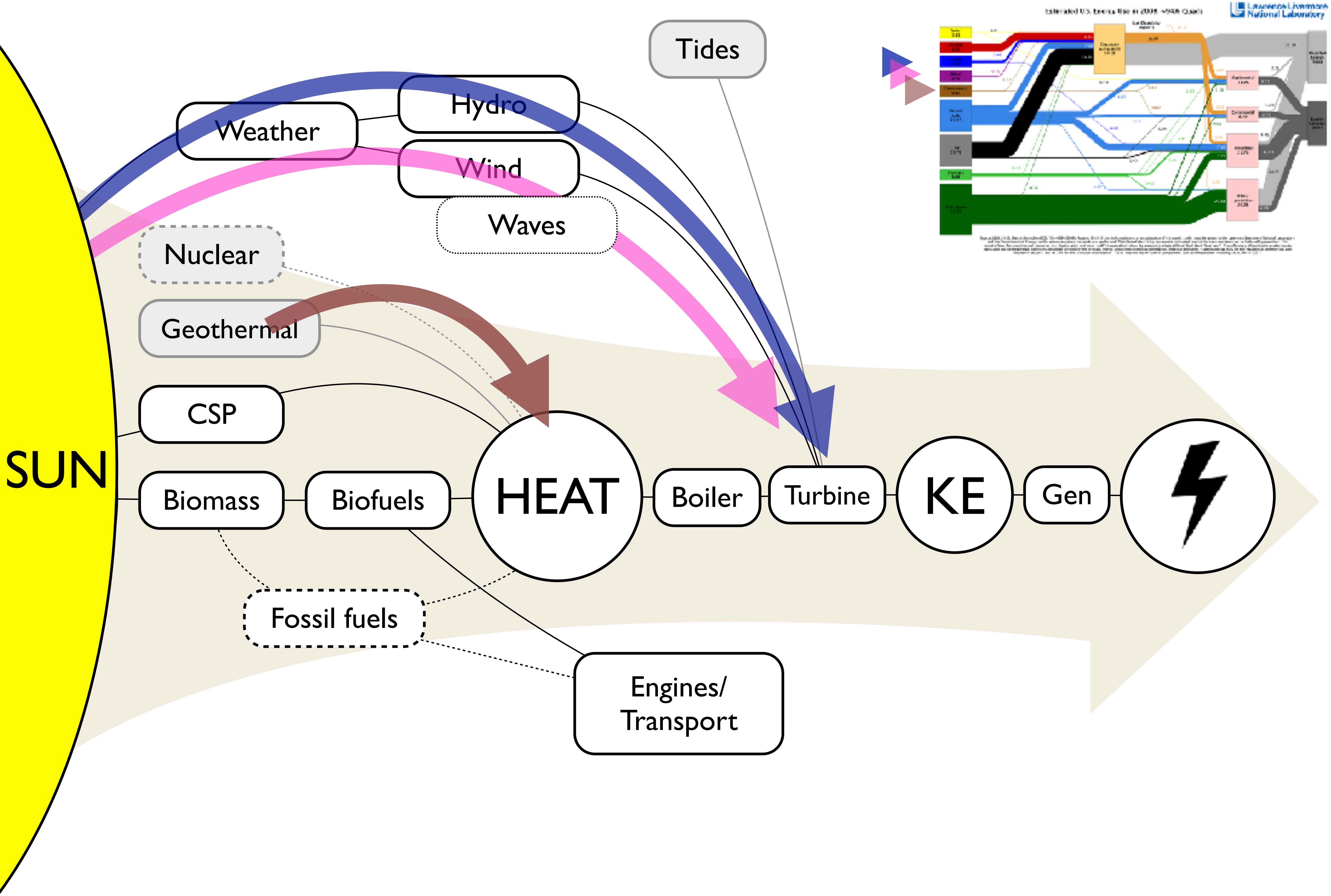




Review


Nuclear
Geothermal
CSP
SUN
Biomass
Biofuels
Fossil fuels
HEAT
Boiler
Turbine
KE
Gen
Thermal power plant
Engines/
Transport

Review


Tides
Weather
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Wind
Waves
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Fossil fuels
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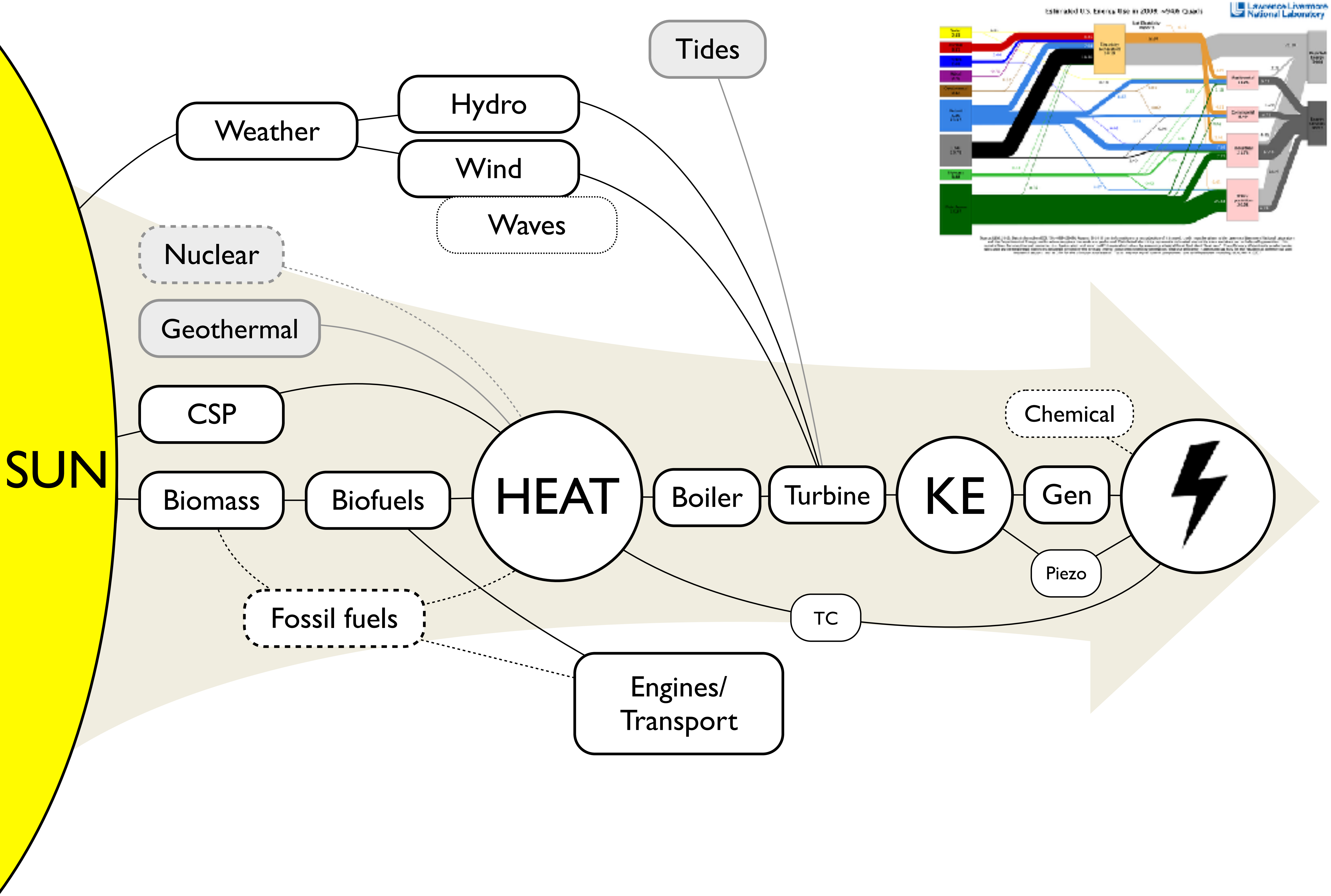
Review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HEAT
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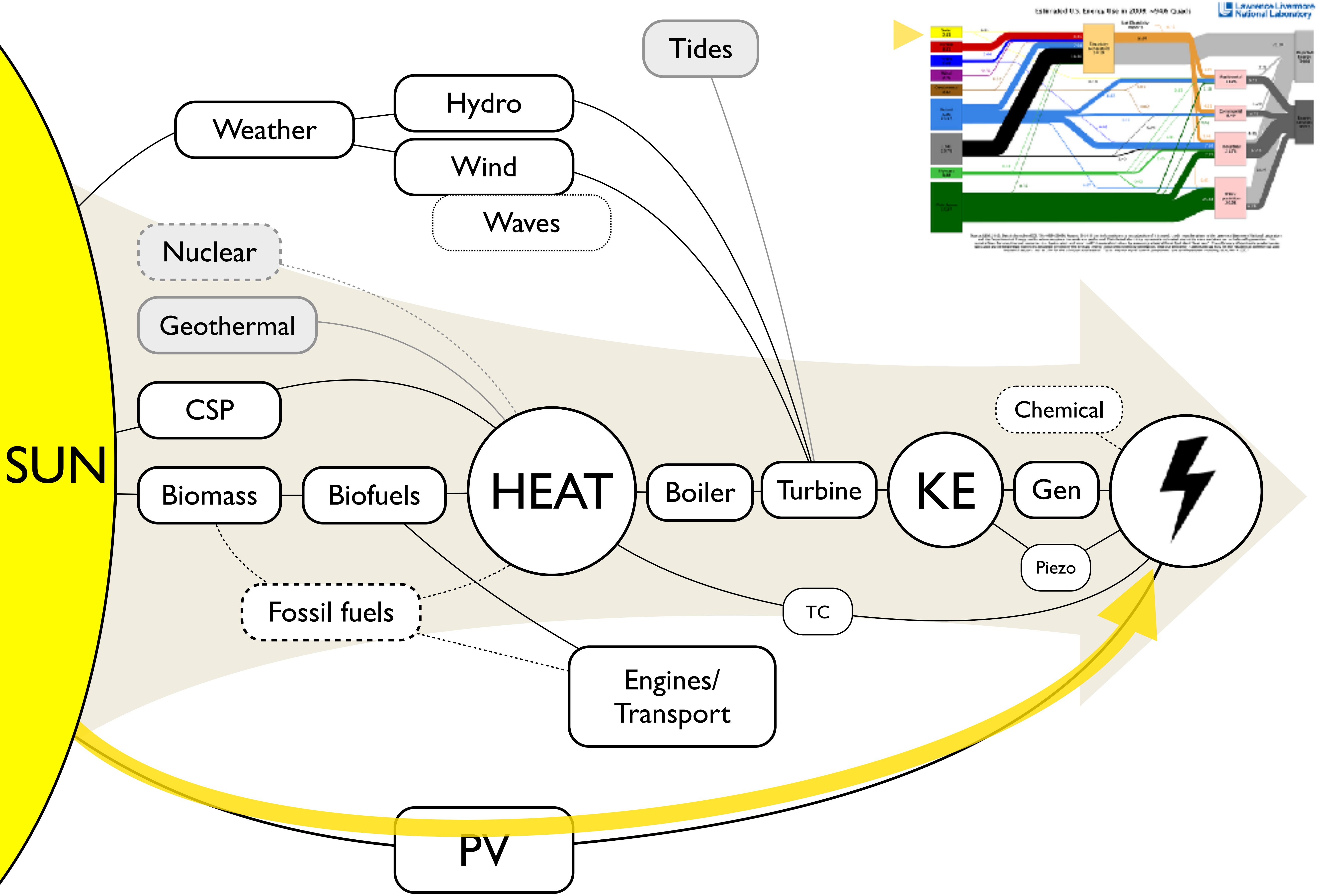
TC
Fossil fuels
Engines/
Transport

Review



SUN
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Geothermal
CSP
Biomass
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HEAT
Boiler
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Chemical
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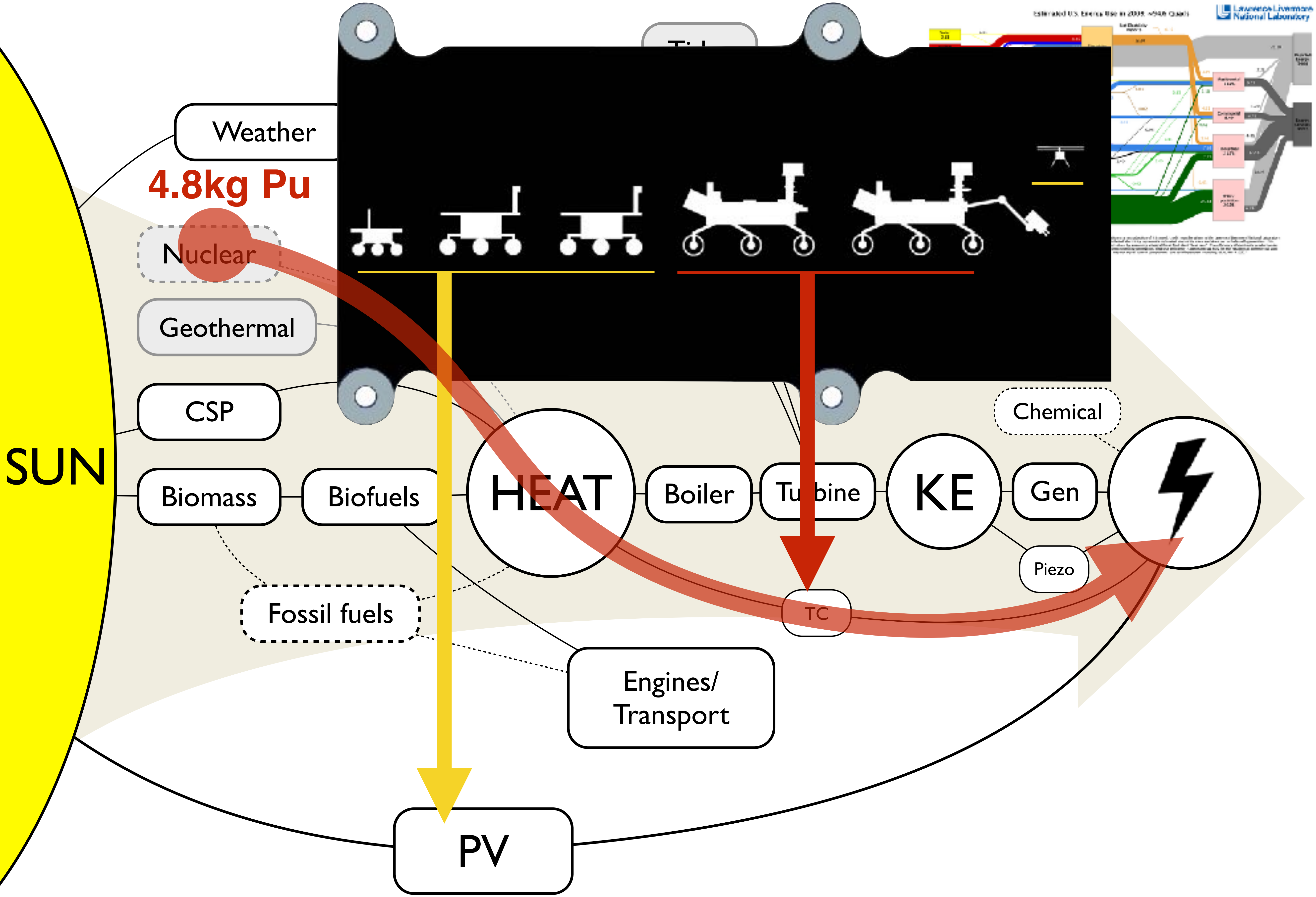
TC
Fossil fuels
Engines/
Transport
PV

Review


SUN
Weather
4.8kg Pu
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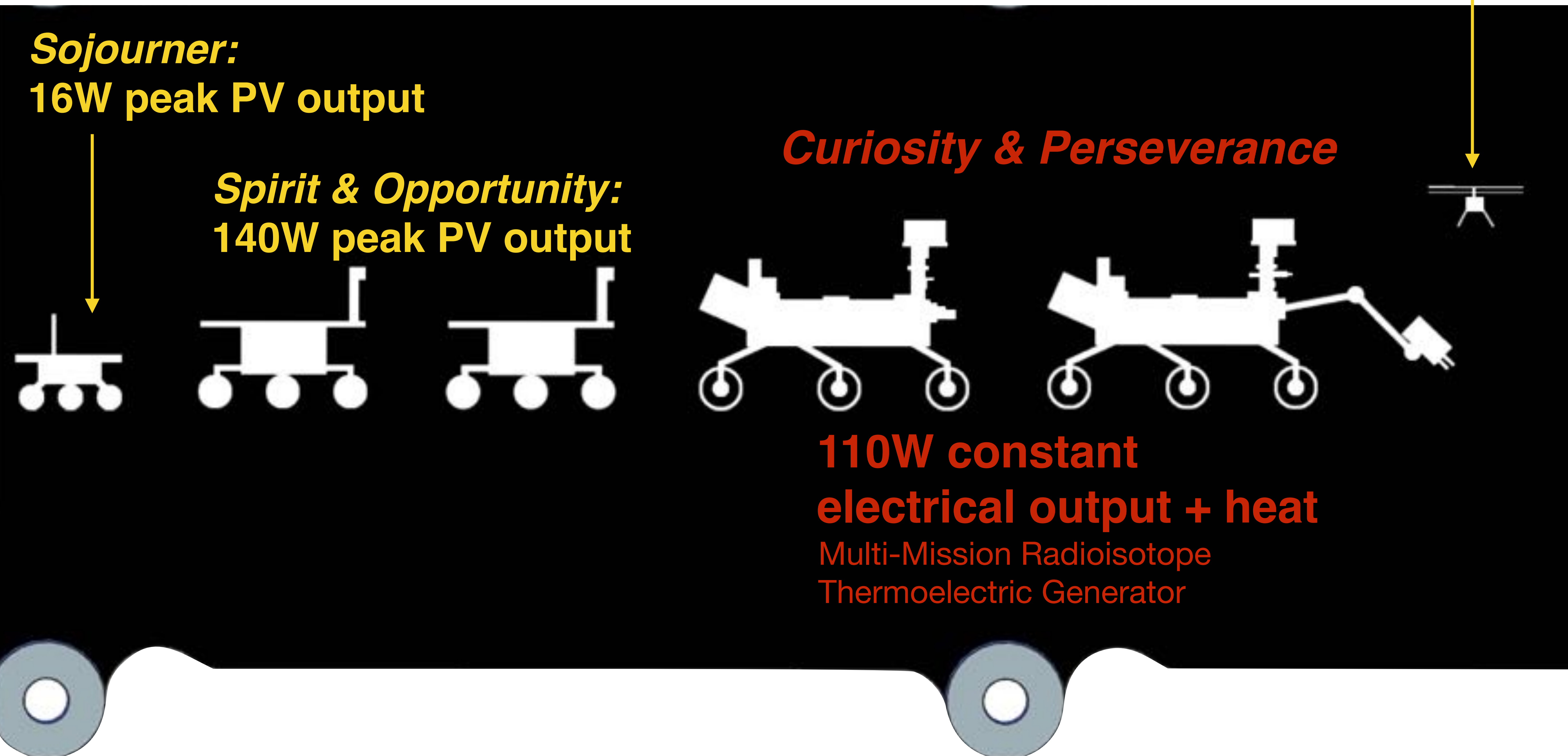
Geothermal
CSP
Biomass
Biofuels
HEAT
Boiler
Turbine
KE
Gen
Chemical
Piezo
TC
Fossil fuels
Engines/
Transport
PV

Review

Ingenuity copter: PV power never mentioned directly. Battery is **35Wh**, with **10Wh** for flight. Solar: 680cm2 of IMM-α Inverted Metamorphic Space Solar Cell from SolAero



Source: https://mars.nasa.gov/
https://rotorcraft.arc.nasa.gov/Publications/files/Balaram_AIAA2018_0023.pdf
https://solaerotech.com/space-solar-cells-cics/

Sun: 4.2 billion kg of H -> Energy / second
so 3.85×10^{26} Watts (385 yottawatts!)

Solar constant in space at Earth locale:

1368 W/m^2 ← Remember this number!

Global solar power:

87 PW (~7000x fossil fuel use)

IMMENSE POTENTIAL BUT…

source: Smil

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WHY NOT SOLAR?

source: Smil

Sun: 4.2 billion kg of H -> Energy / second
so 3.85 x 10^{26} Watts (385 yottawatts!)

Solar constant in space at Earth locale:
1368 W/m^2

Global solar power:
87 PW (~7000x fossil fuel use)

IMMENSE POTENTIAL BUT...

Distributed over Earth's sphere:
342 W/m^2

Average insolation (after reflection and absorption):
170 W/m^2

Intermittent, weather dependent

DIFFUSE AND INTERMITTENT

source: Smil

BUT REALLY . . . SOLAR

2015

THE BILLIONS IN CHANGE SOLUTION

Hans Free Electric™

The Hans Free Electric™ bike enables people to generate their own electricity. Here's how it works: A person pedals the hybrid bicycle, which drives a flywheel system, which turns a generator, which charges a batte… for … hour yields a day's worth of electricity for an av… It's electricity on demand. There's no utility bill, no n… wait for the sun to shine or the wind to blow, a…

https://web.archive.org/web/20161116093435/http://billionsinchange.com:80/solutions/free-electric

2018

BUT REALLY . . . SOLAR

HANS™ SOLAR BRIEFCASE

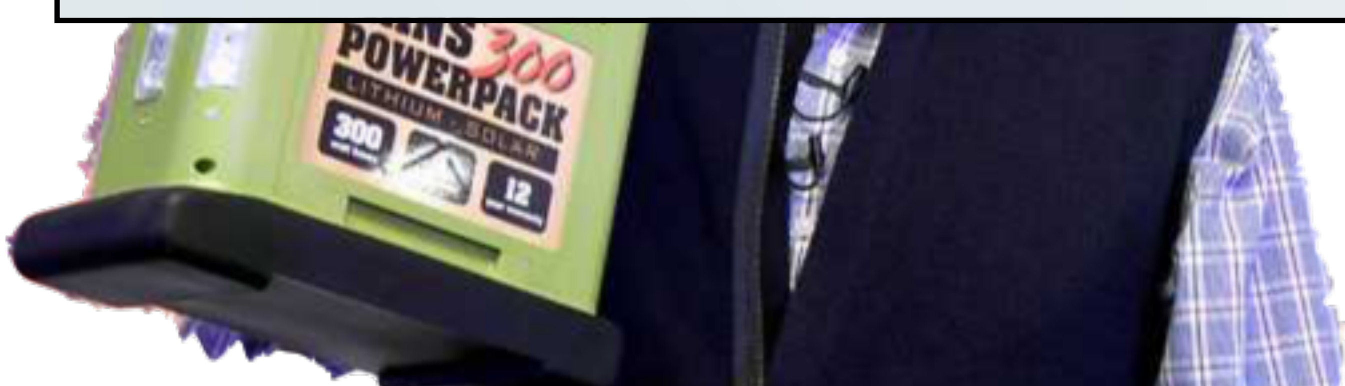
A Look Back At How We Arrived Here

It started with the goal to bring free electrical power to the billions of people worldwide who have little-to-no access to electricity. How? Provide a way for people to generate their own energy, store it, and use it for simple, yet life-changing, applications, such as light, communication, and education. The first solution created by Stage 2 was the HANS™ Free Electric bike.

However, after multiple field tests showed that the bike needed modifications, as did the battery, Stage 2 went back to the drawing board. Through the process of making these improvements, two completely new inventions emerged. The HANS™ PowerPack and HANS™ Solar BriefCase quickly leapfrogged the bike in terms of usability, affordability, and scalability.

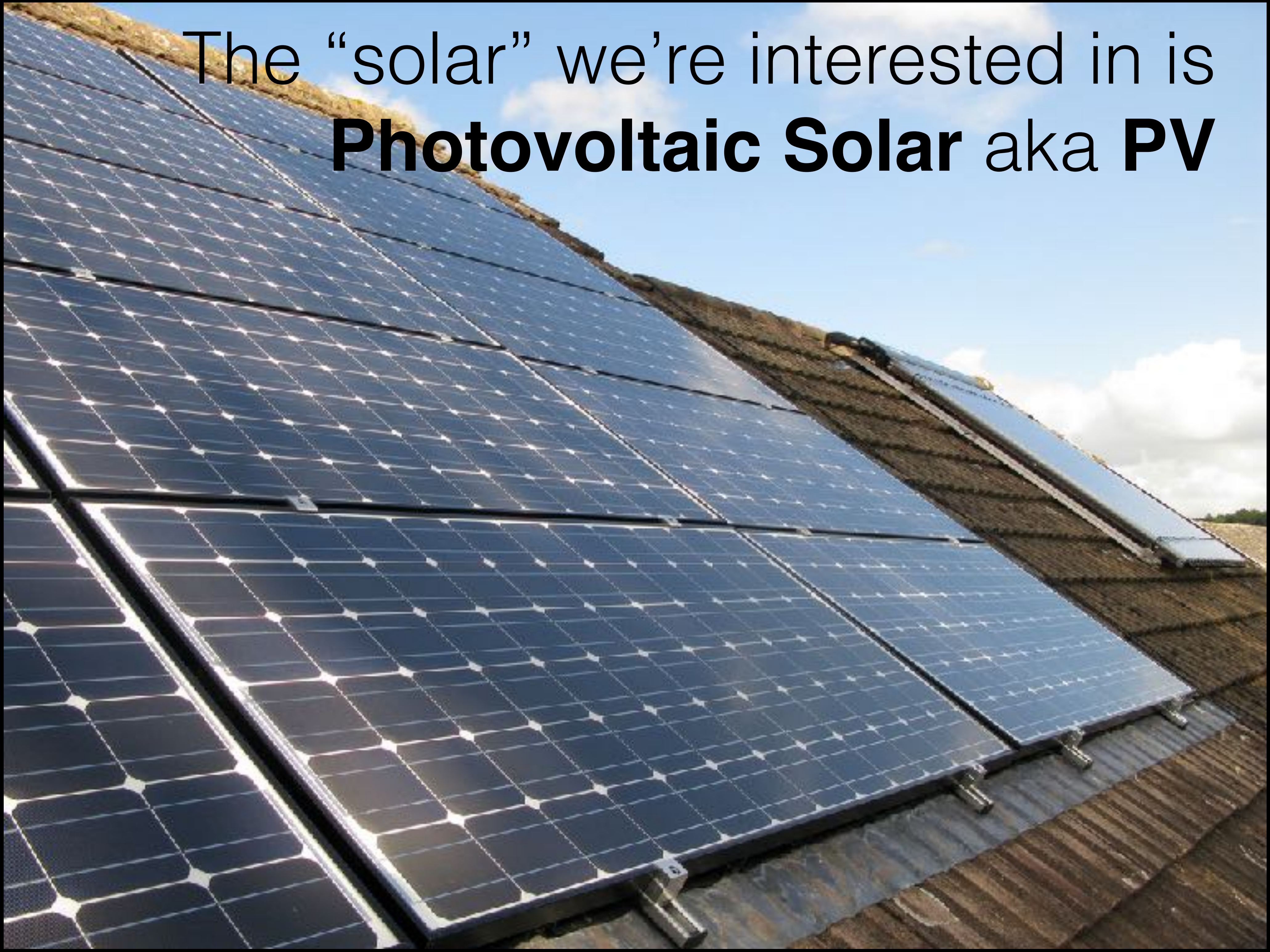
The current plan for the HANS™ Free Electric bike is to produce it on a limited basis for India only. There are no longer plans to make the bike available to the US market, and the existing US inventory of a few dozen bikes will be donated to the Billions in Change Foundation for charitable and fundraising purposes.

ergy/



GLOBAL TRANSFORMATION

WHAT IS SOLAR?


The “solar” we’re interested in is
Photovoltaic Solar aka **PV**

(Not “Concentrating Solar Power”, “Solar Thermal”, etc…)

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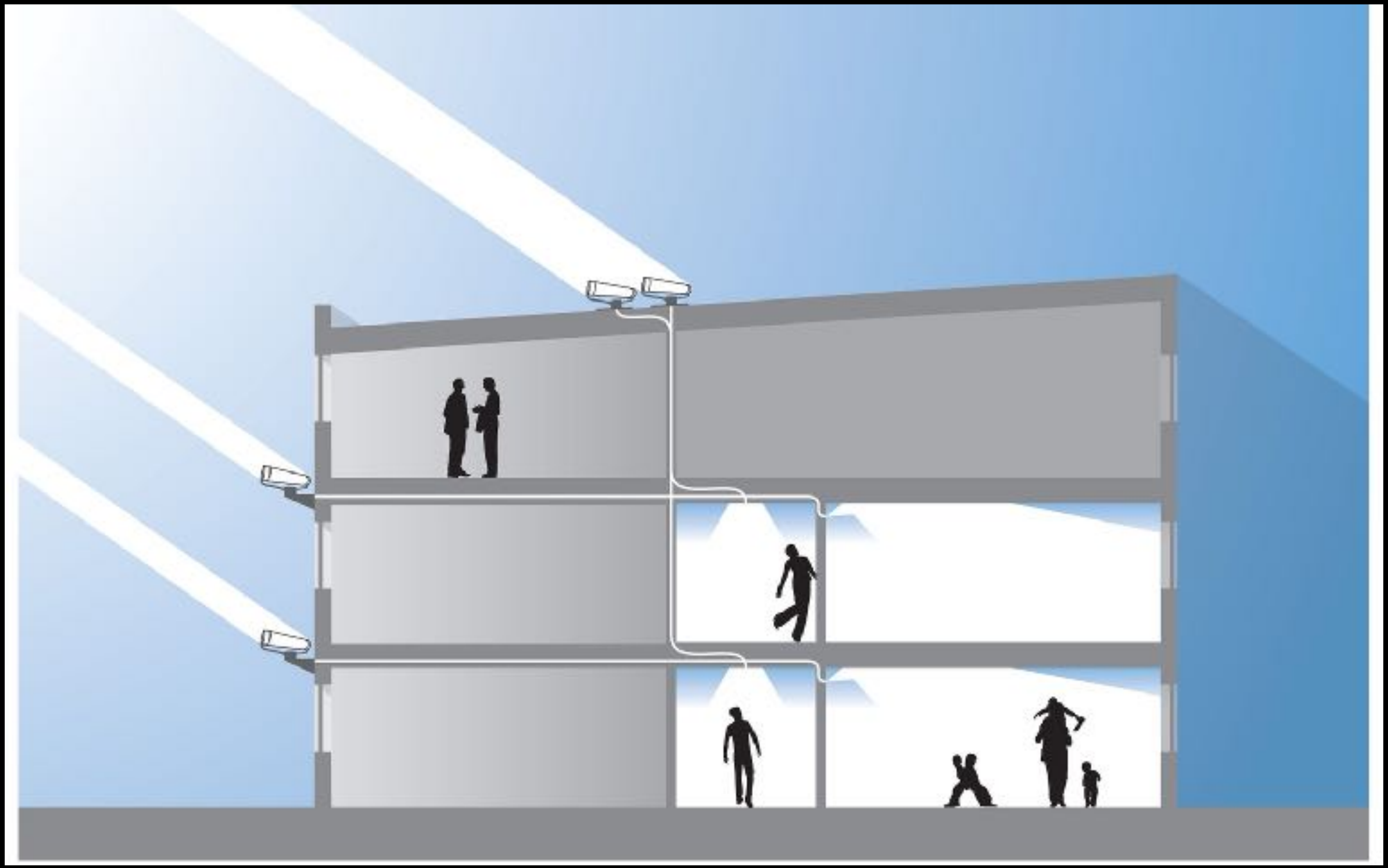


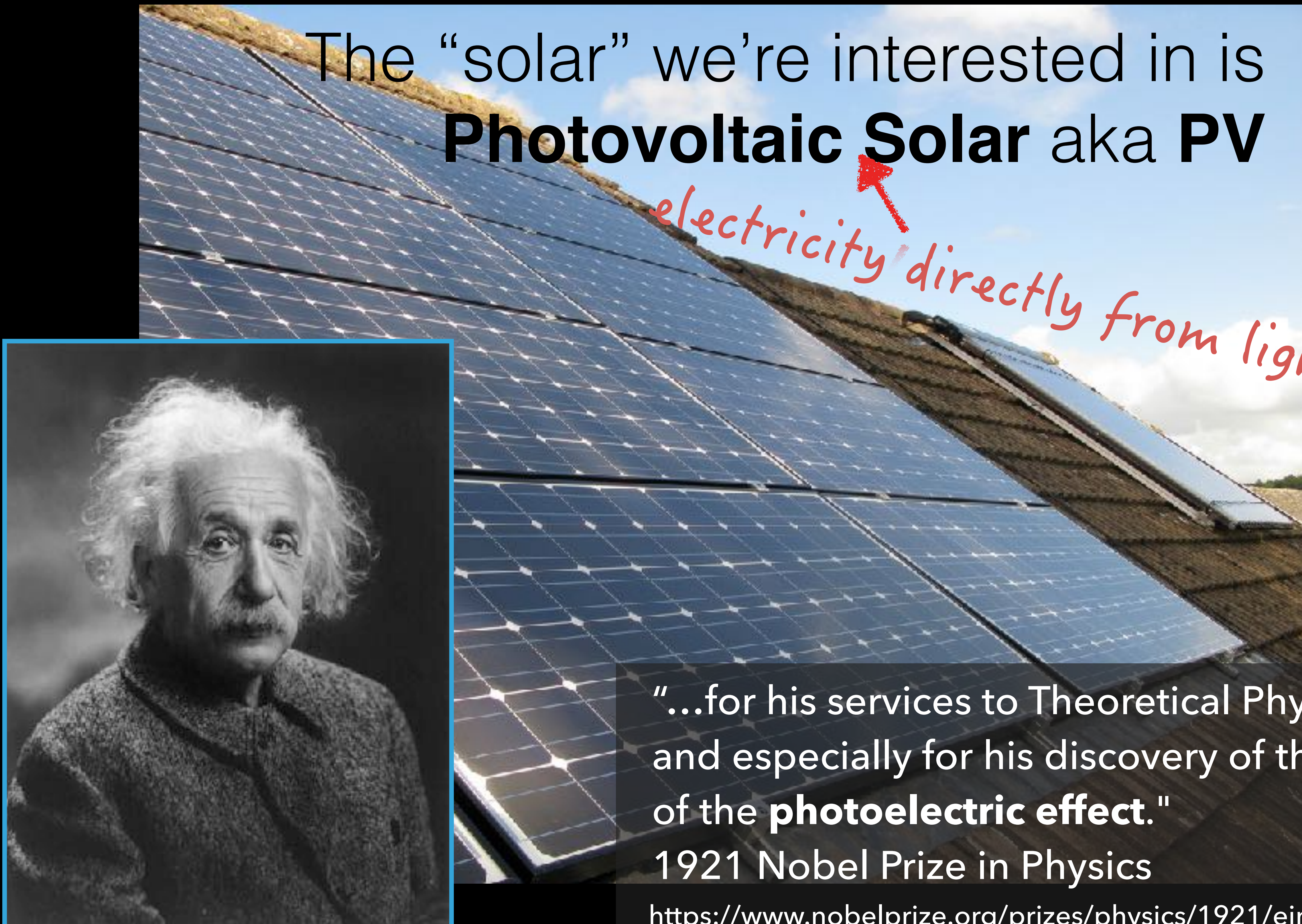
Parans

(Not indirect solar lighting, heliostats, etc…)

The “solar” we’re interested in is

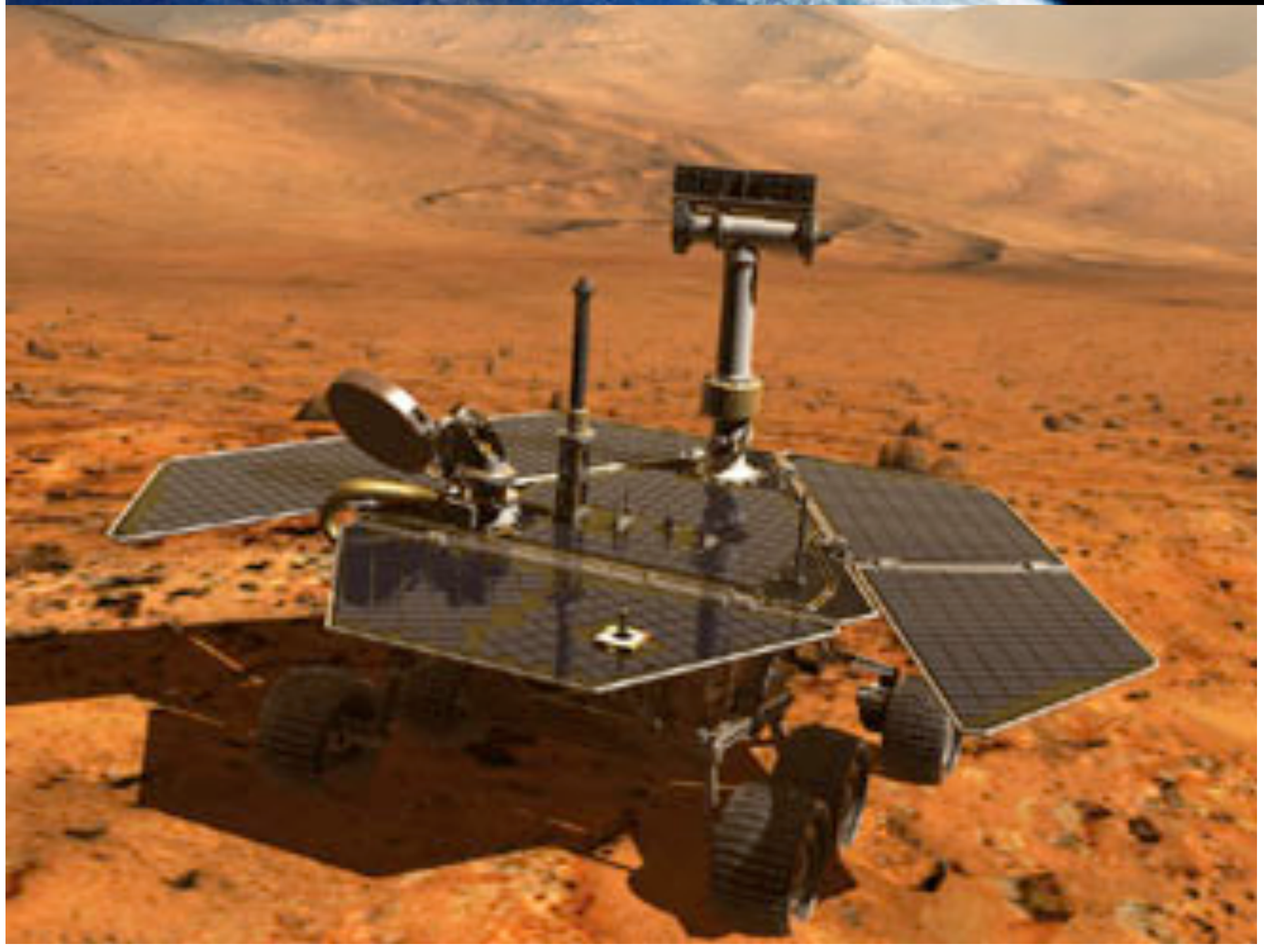
Photovoltaic Solar aka **PV**

electricity directly from light



“…for his services to Theoretical Physics, and especially for his discovery of the law of the **photoelectric effect**."
1921 Nobel Prize in Physics

https://www.nobelprize.org/prizes/physics/1921/einstein/facts/



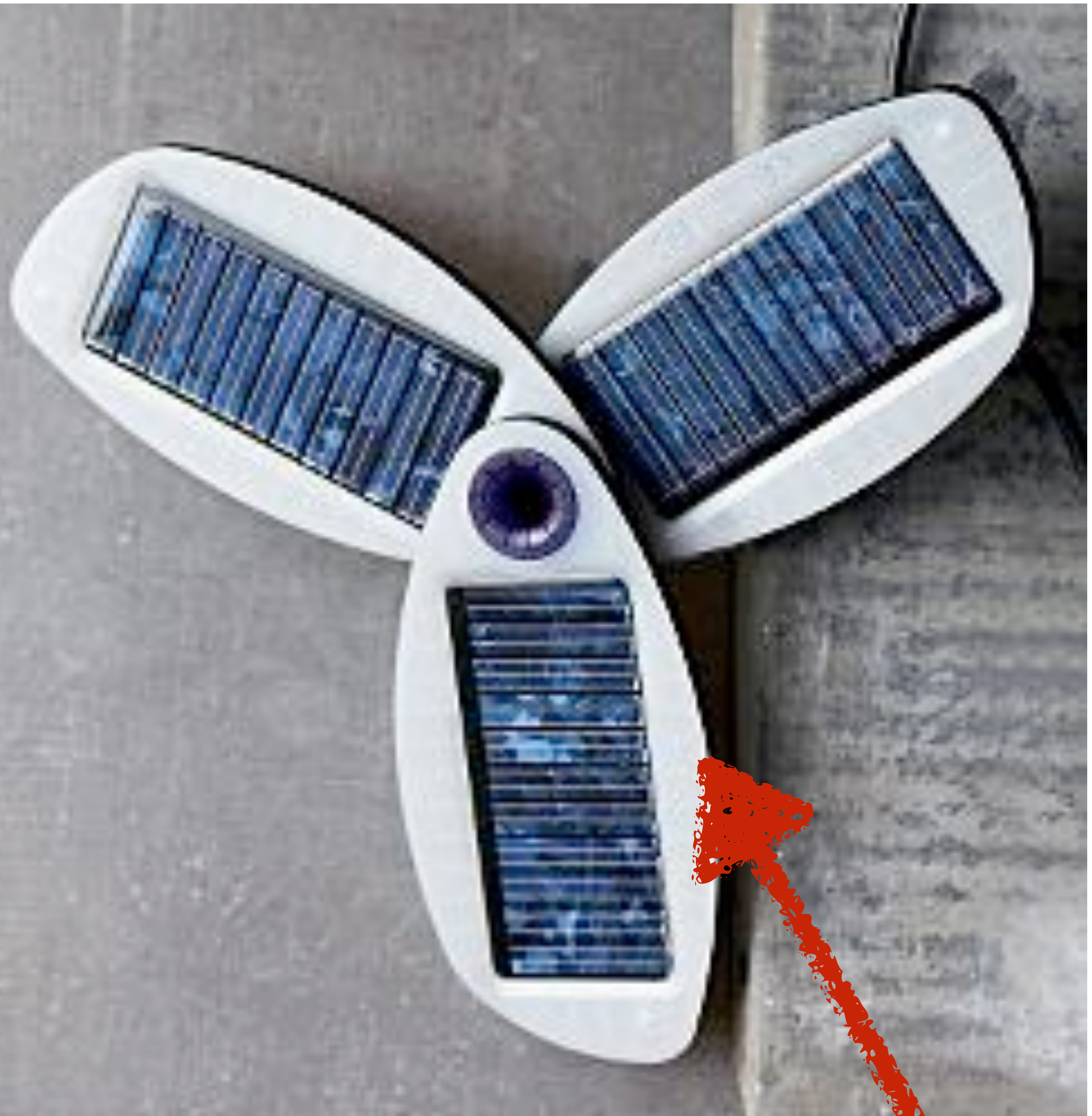
PV works everywhere!
Enabling technology for telecom and space exploration

MER originally planned for ~90 sols, have operated for over 2000.
140W GaAs/Ge cells

Terrestrial applications

Fishermen in Kenya attracting shrimp w/ solar-charged lights (photo:Siemens)

Overview



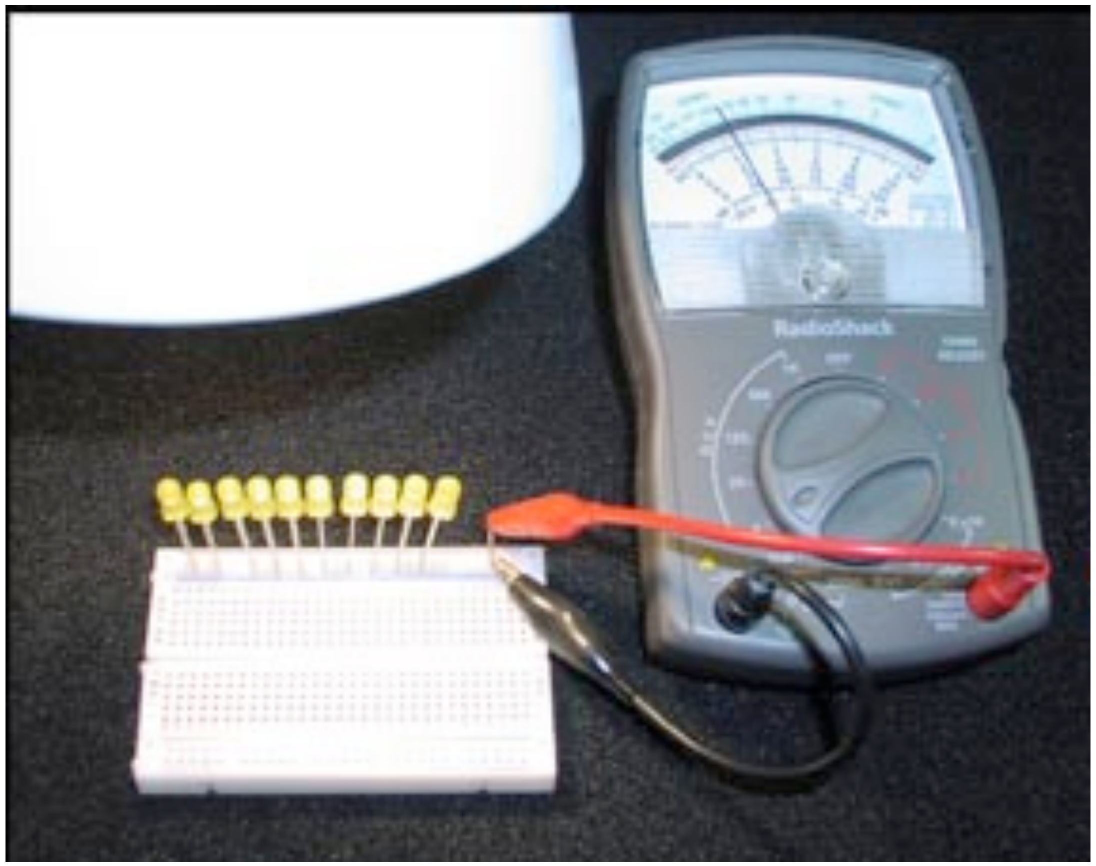
THE SAME STUFF!!!

Small and large commercial applications

Overview

HOW DOES SOLAR WORK?

All PV is similar in that:

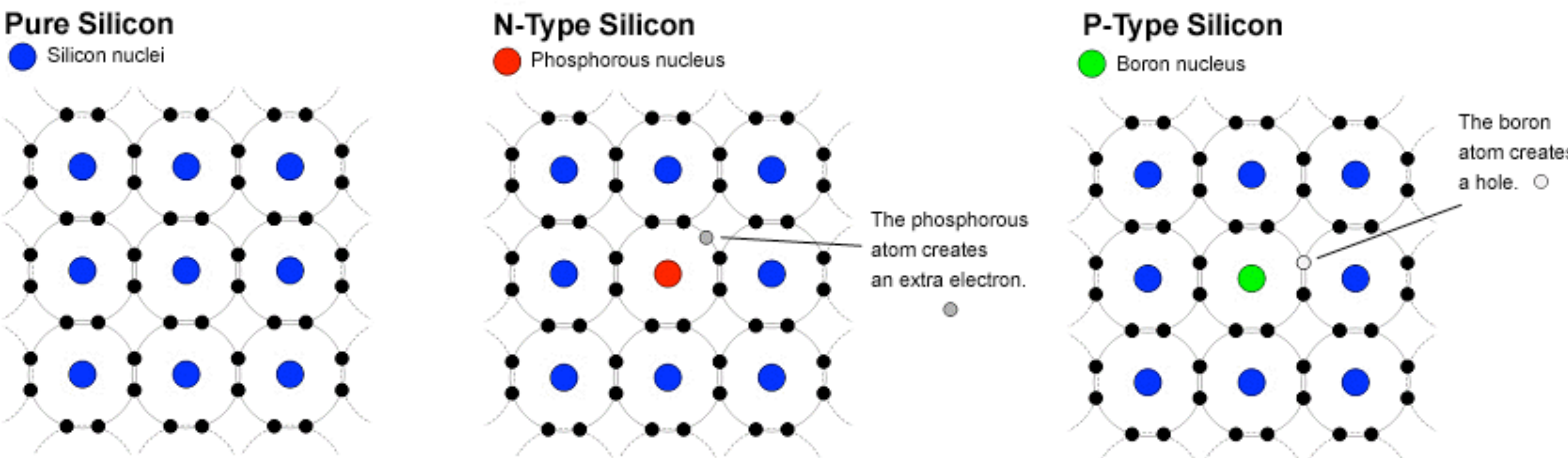


Photovoltaic materials directly convert light into electricity.

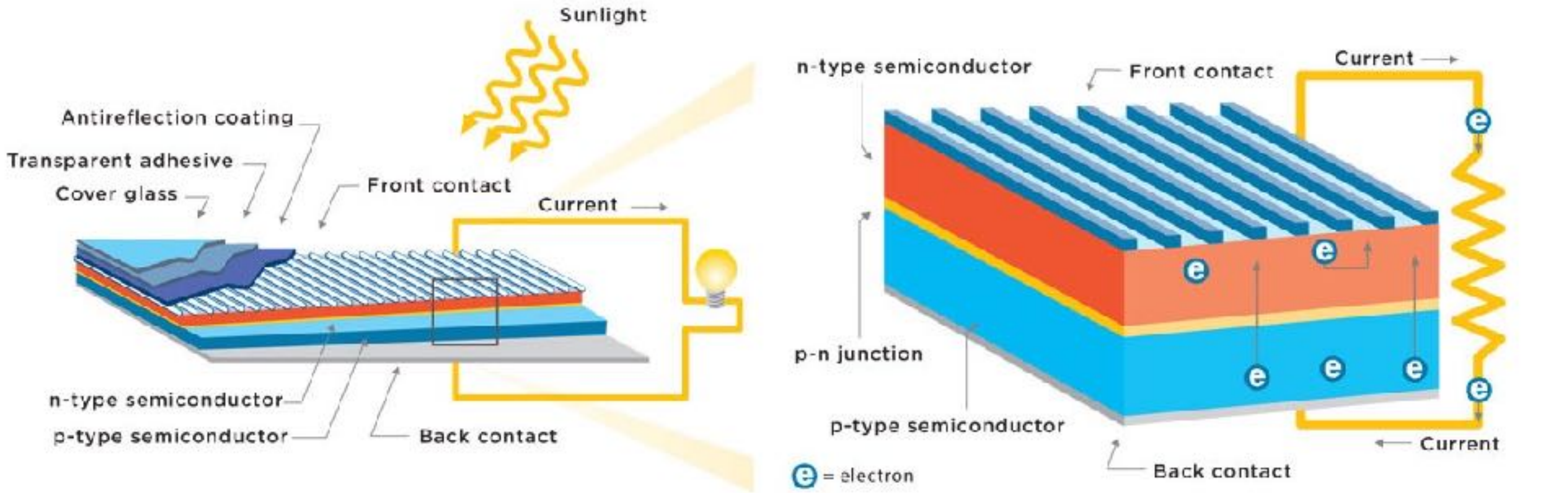
Most semiconductors (including LEDs) do this to some extent.

Source: http://www.imagesco.com/

A junction of P- and N-type materials forms a diode optimized to separate charge carriers when exposed to light



Source: http://www.techbites.com/



Solar cells are composed of two layers of semiconductor material with opposite charges. Sunlight hitting the surface of a cell knocks electrons loose, which then travel through a circuit from one layer to the other, providing a flow of electricity.

Source: Union of Concerned Scientists

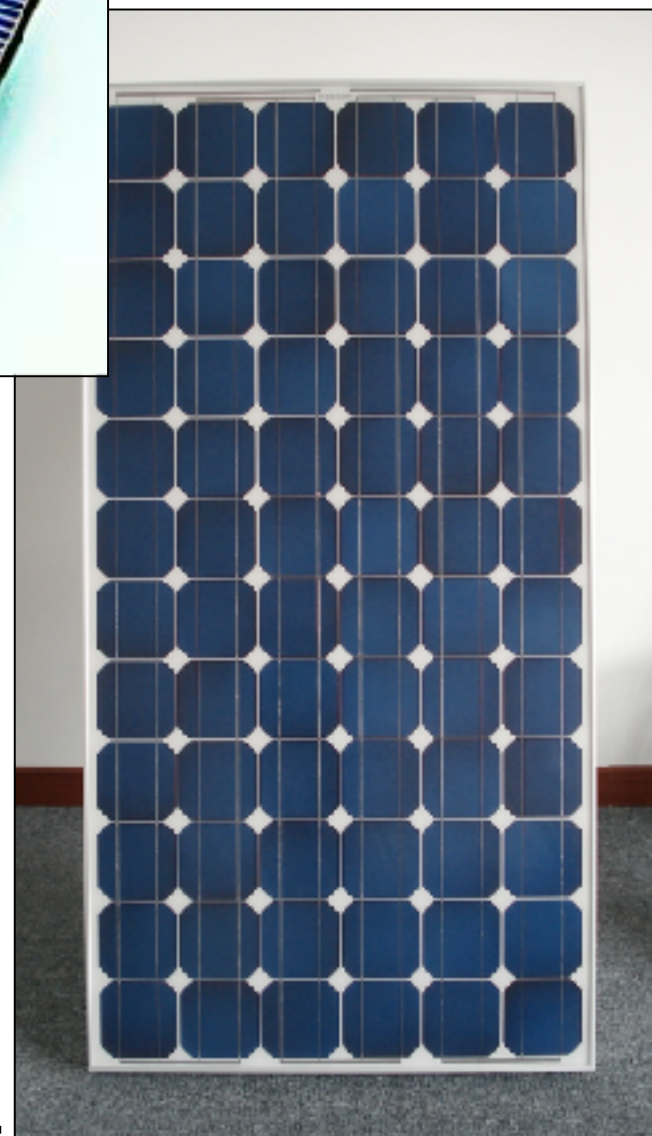
Basics

Cell

Cell:
Single piece of PV material.

Voltage dependent on semiconductor type

Current dependent on surface area.



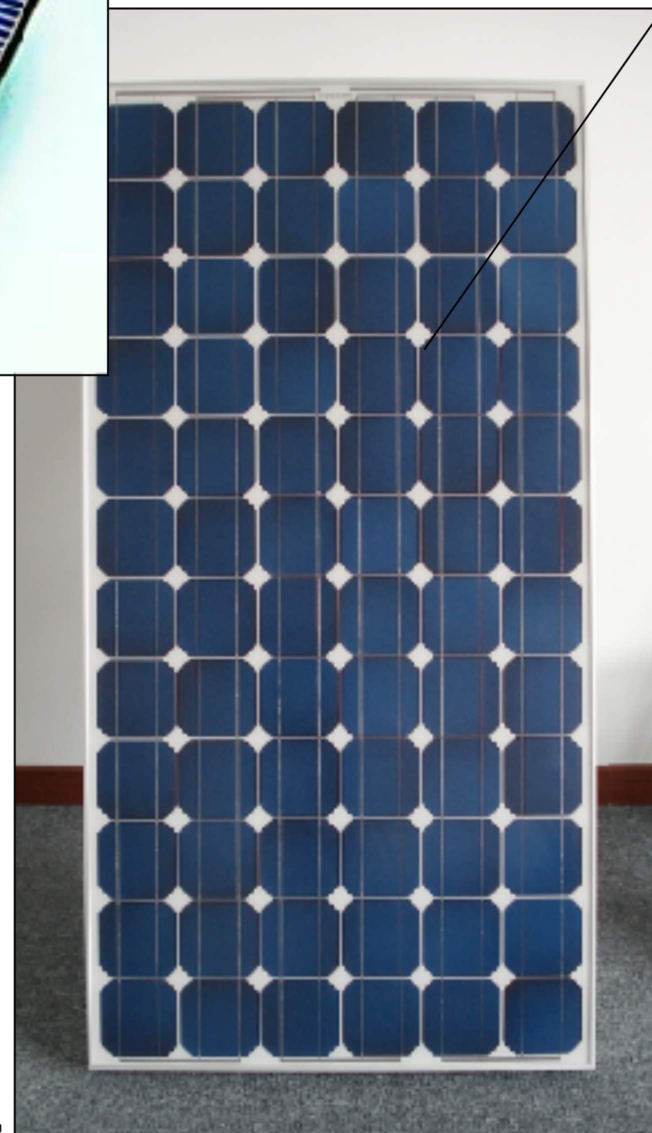
Module: group of cells

Array: group of modules

Basics

Cell

Module:
Multiple cells arranged in series and parallel groups to achieve desired voltage and current.

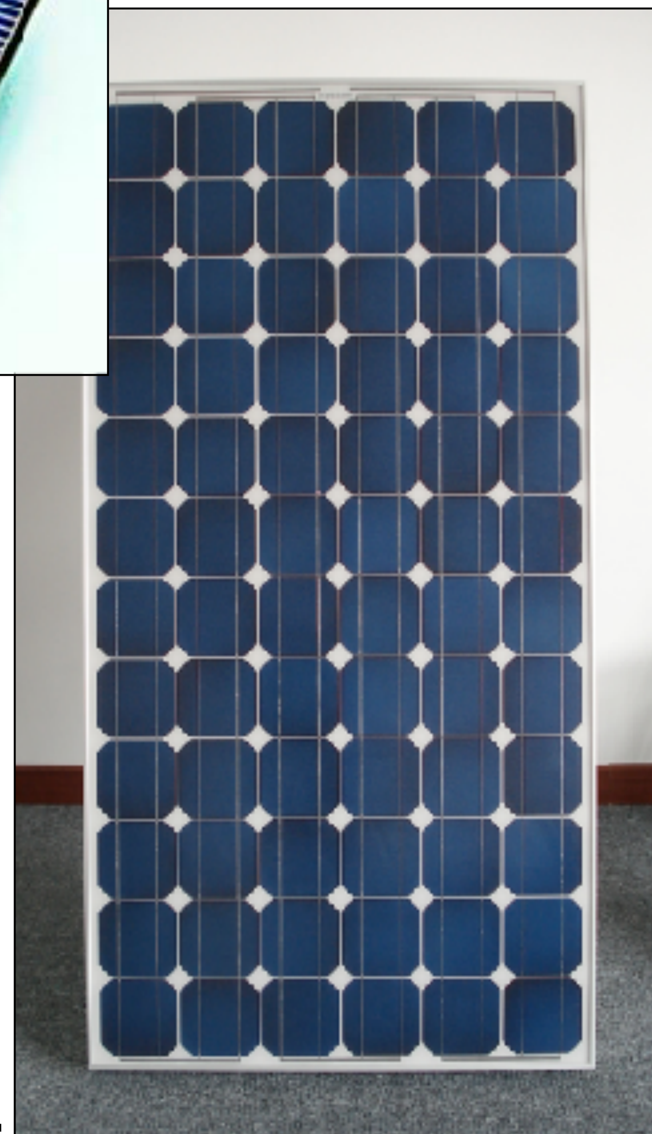


Module: group of cells

Array: group of modules

Basics

Cell



Module: group of cells

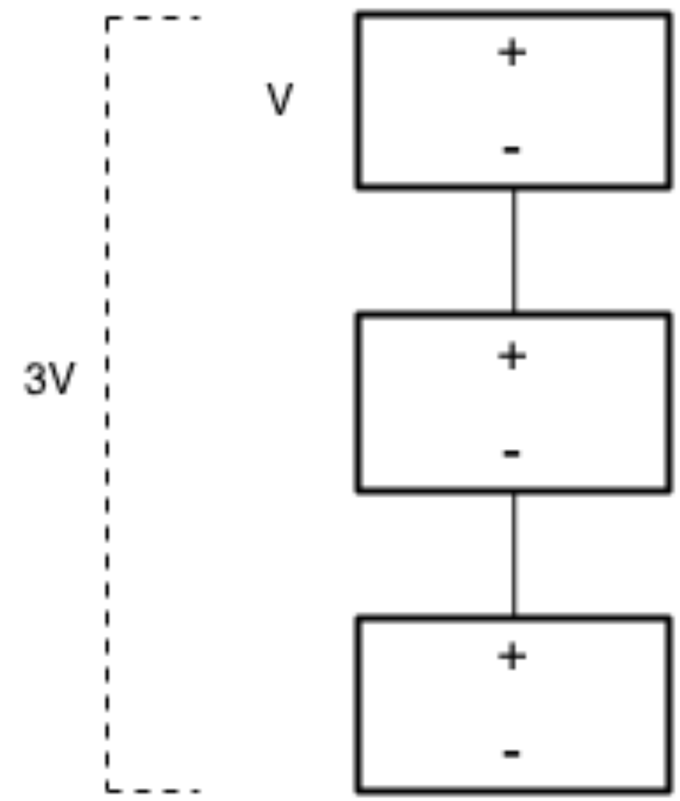
Array:
Multiple modules arranged in series and parallel groups to achieve desired voltage and current.

Array: group of modules

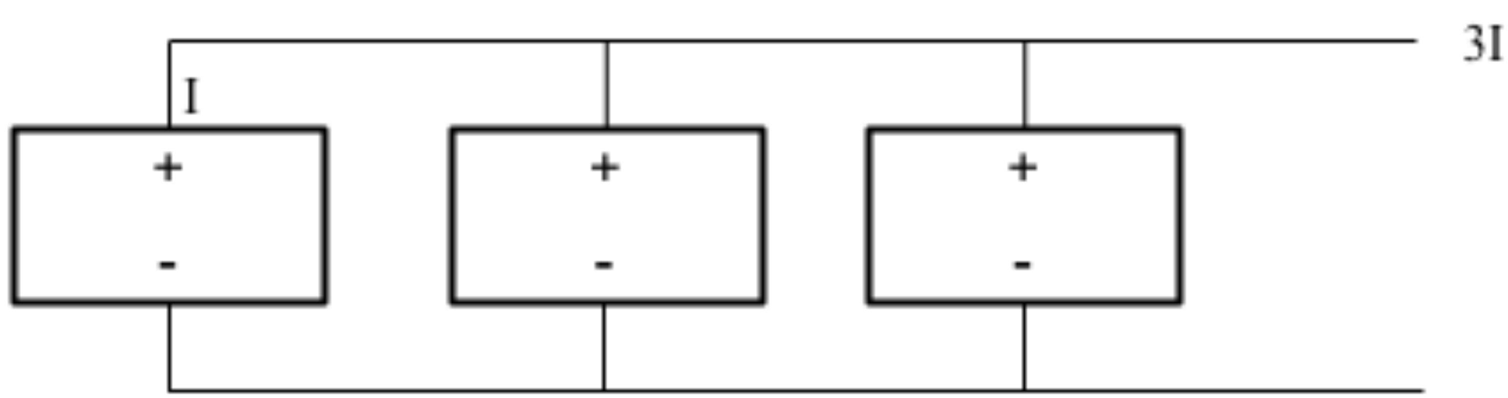
Basics

(Cell or module)

In ***series***: Voltage sums, current remains the same



In ***parallel***: Voltage stays the same, current sums



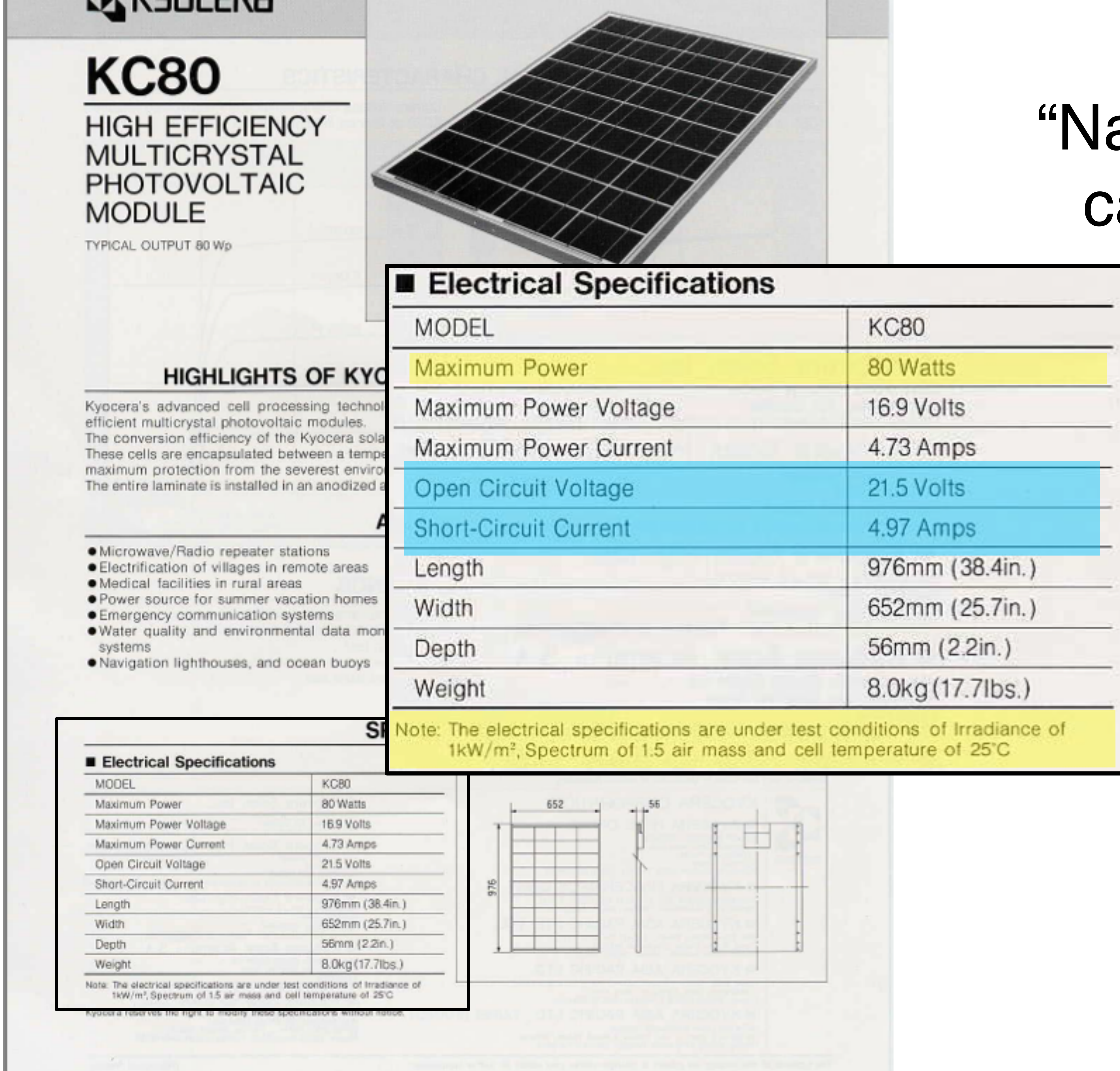
Metrics we care about are:

Rated performance
- "Watts-peak" under standardized conditions (AM1.5 1000W/m^2)

Open Circuit (OC) Voltage
- voltage measured with no load

Short Circuit (SC) Current
- current through short circuit

And of course, cost:
Cost / Watt



KC80

HIGH EFFICIENCY MULTICRYSTAL PHOTOVOLTAIC MODULE

TYPICAL OUTPUT 80 Wp

HIGHLIGHTS OF KYO

Kyocera's advanced cell processing technol
efficient multicrystal photovoltaic modules.
The conversion efficiency of the Kyocera sola
These cells are encapsulated between a tempe
maximum protection from the severest enviro
The entire laminate is installed in an anodized a

- Microwave/Radio repeater stations
- Electrification of villages in remote areas
- Medical facilities in rural areas
- Power source for summer vacation homes
- Emergency communication systems
- Water quality and environmental data mon systems
- Navigation lighthouses, and ocean buoys

■ Electrical Specifications

MODEL	KC80
Maximum Power	80 Watts
Maximum Power Voltage	16.9 Volts
Maximum Power Current	4.73 Amps
Open Circuit Voltage	21.5 Volts
Short-Circuit Current	4.97 Amps
Length	976mm (38.4in.)
Width	652mm (25.7in.)
Depth	56mm (2.2in.)
Weight	8.0kg (17.7lbs.)

Note: The electrical specifications are under test conditions of Irradiance of 1kW/m², Spectrum of 1.5 air mass and cell temperature of 25°C

“Nameplate capacity” = 80W

DIFFERENCES

Different types of PV are distinguished by:

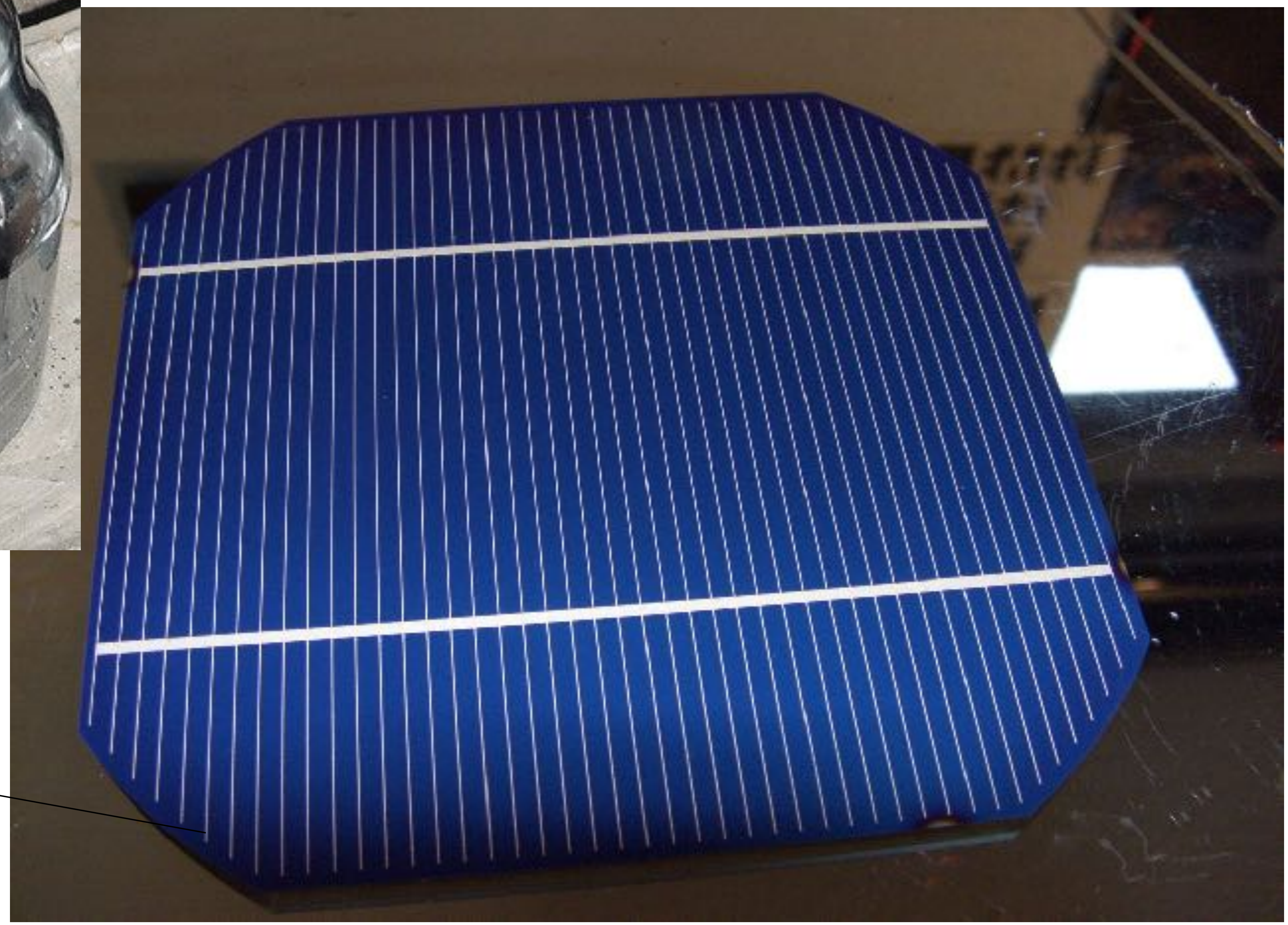
- Form of material (e.g. crystalline or thin film)

- Type of material (Si vs. CIGS vs...)

- Number of layers ("junctions")

Different types will have varying **efficiencies** under different **conditions**, and widely-ranging associated **costs**.

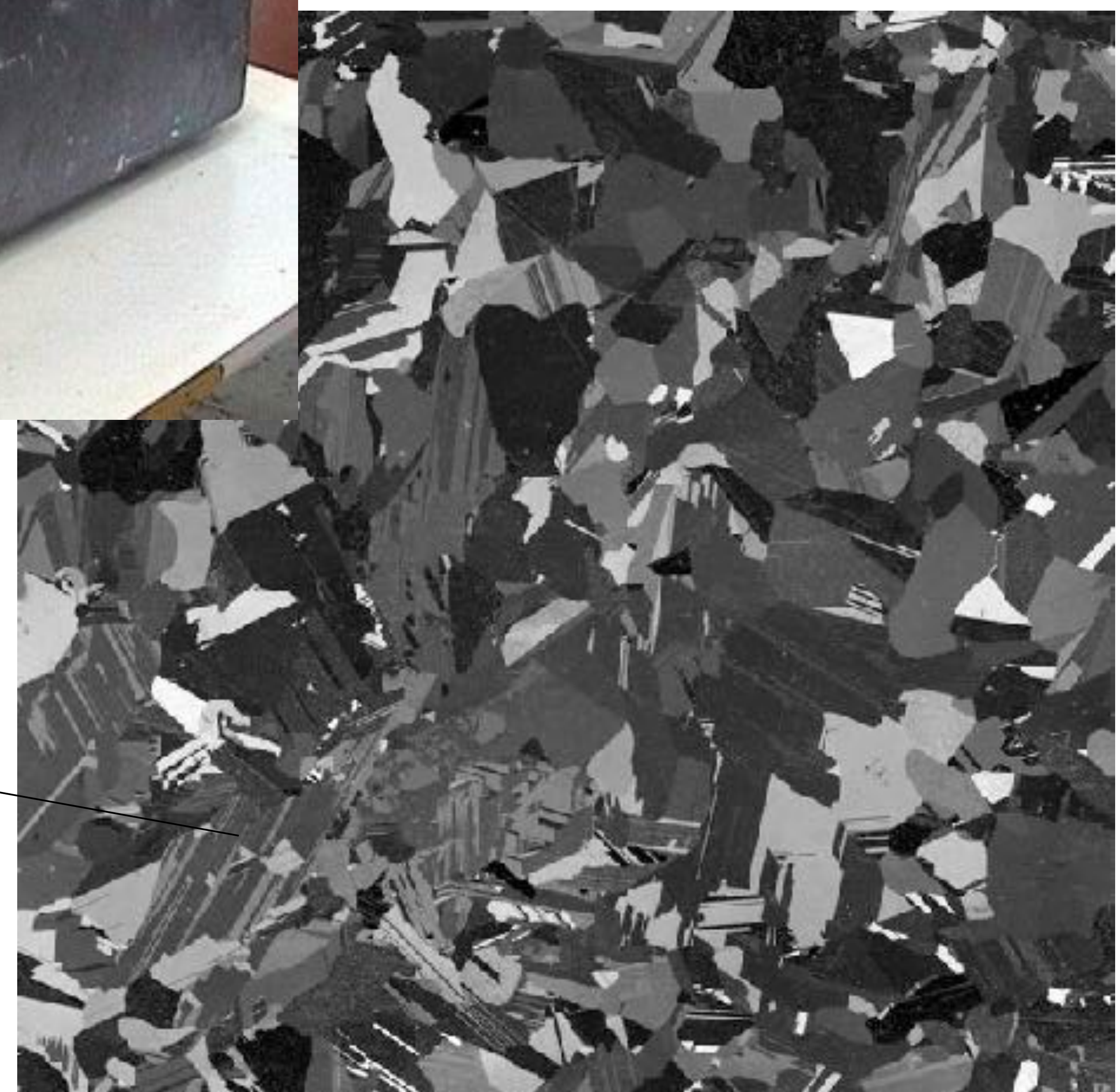
Mono-crystalline Si ingot and cell



Circa 300 um thick
Si layer

Differences

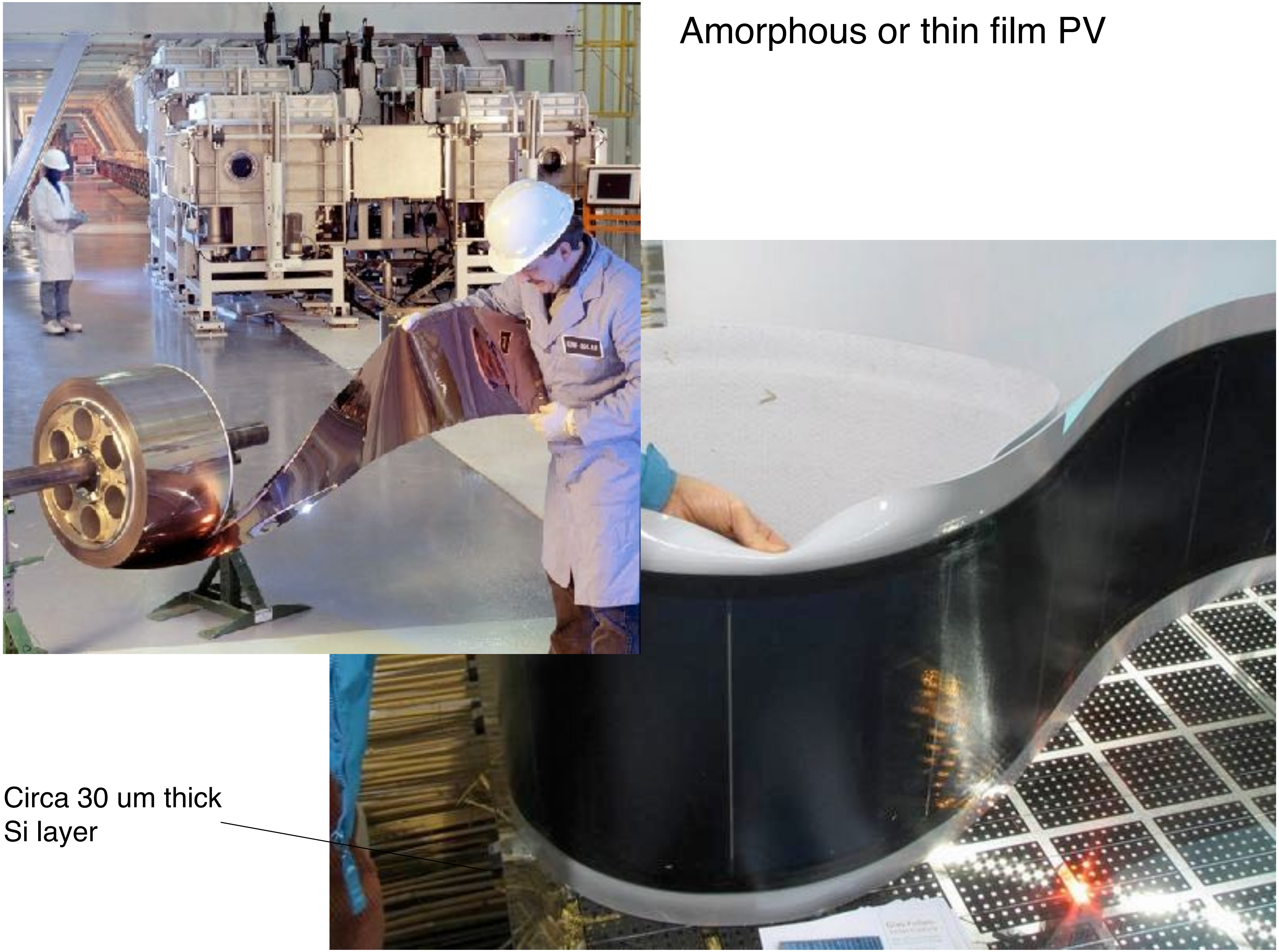
Polycrystalline Si
ingot and cell



Circa 300 um thick
Si layer

Differences

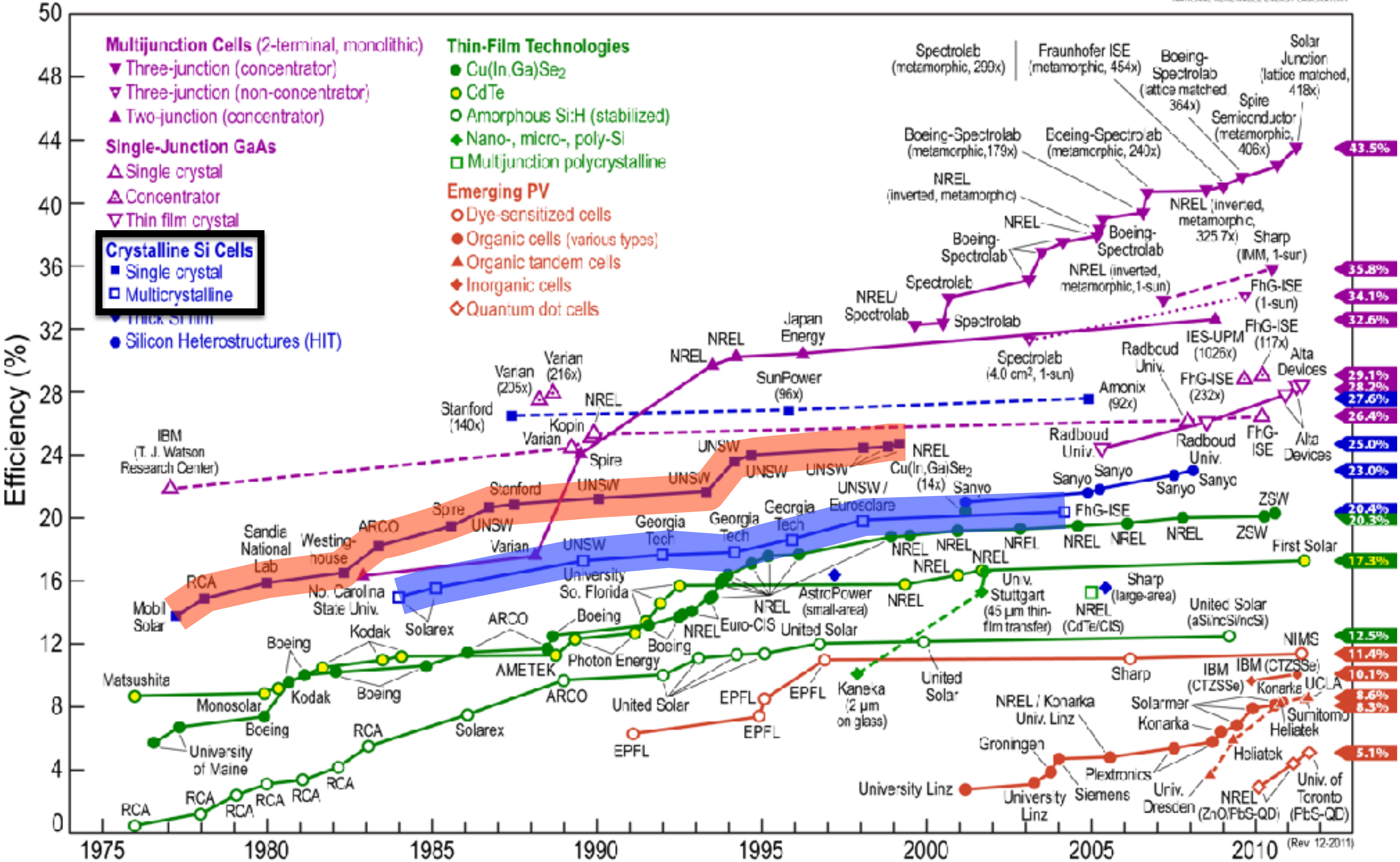
Amorphous or thin film PV



Circa 30 um thick
Si layer

Differences

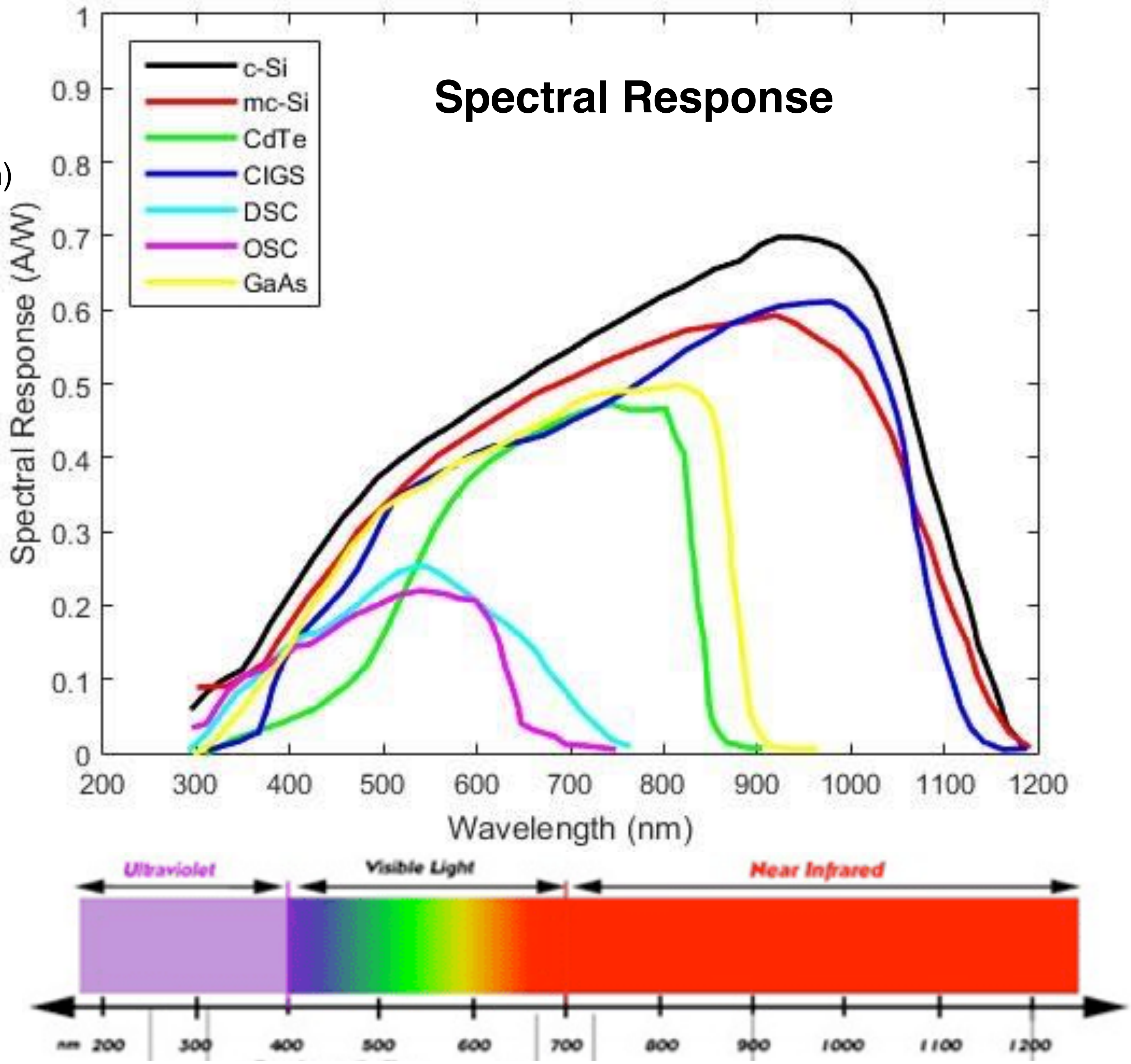
Best Research-Cell Efficiencies



Source: DOE NREL

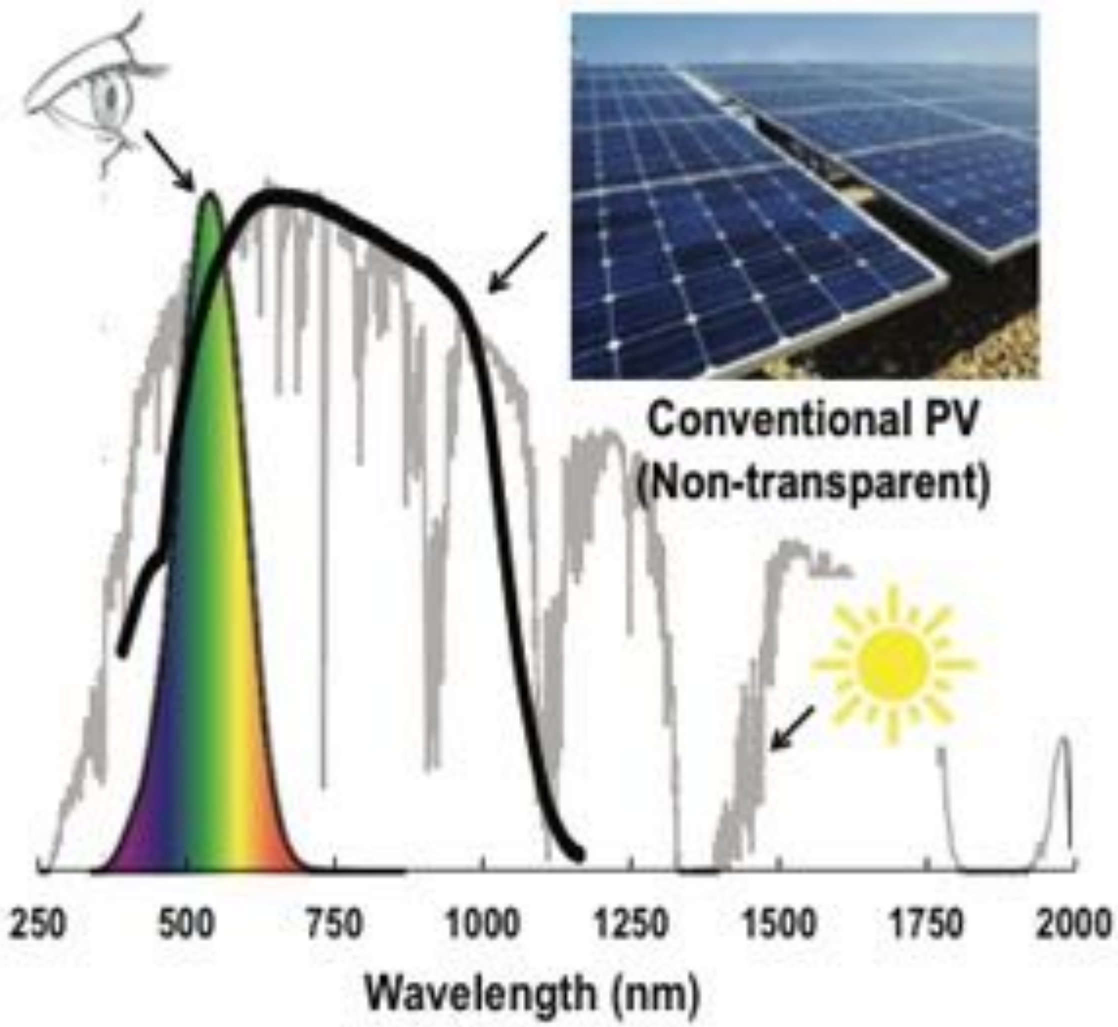
Differences

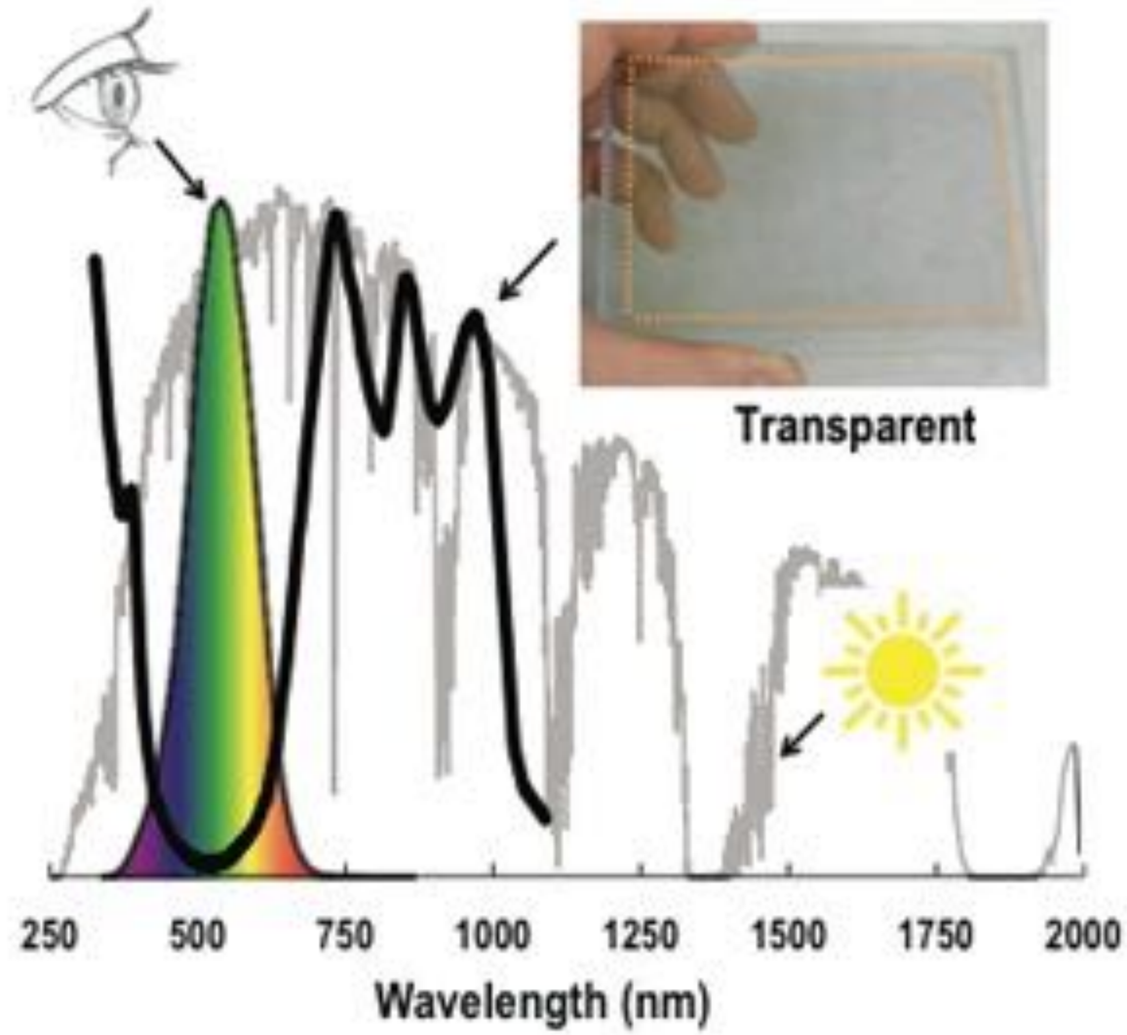
(Mono) Crystalline Si
Multi-crystalline Si
Cadmium Telluride (thin)
Copper-Indium-Gallium (thin)
Dye-Sensitized
Organic
Gallium Arsenide



Source: https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/effective-irradiance/spectral-response/

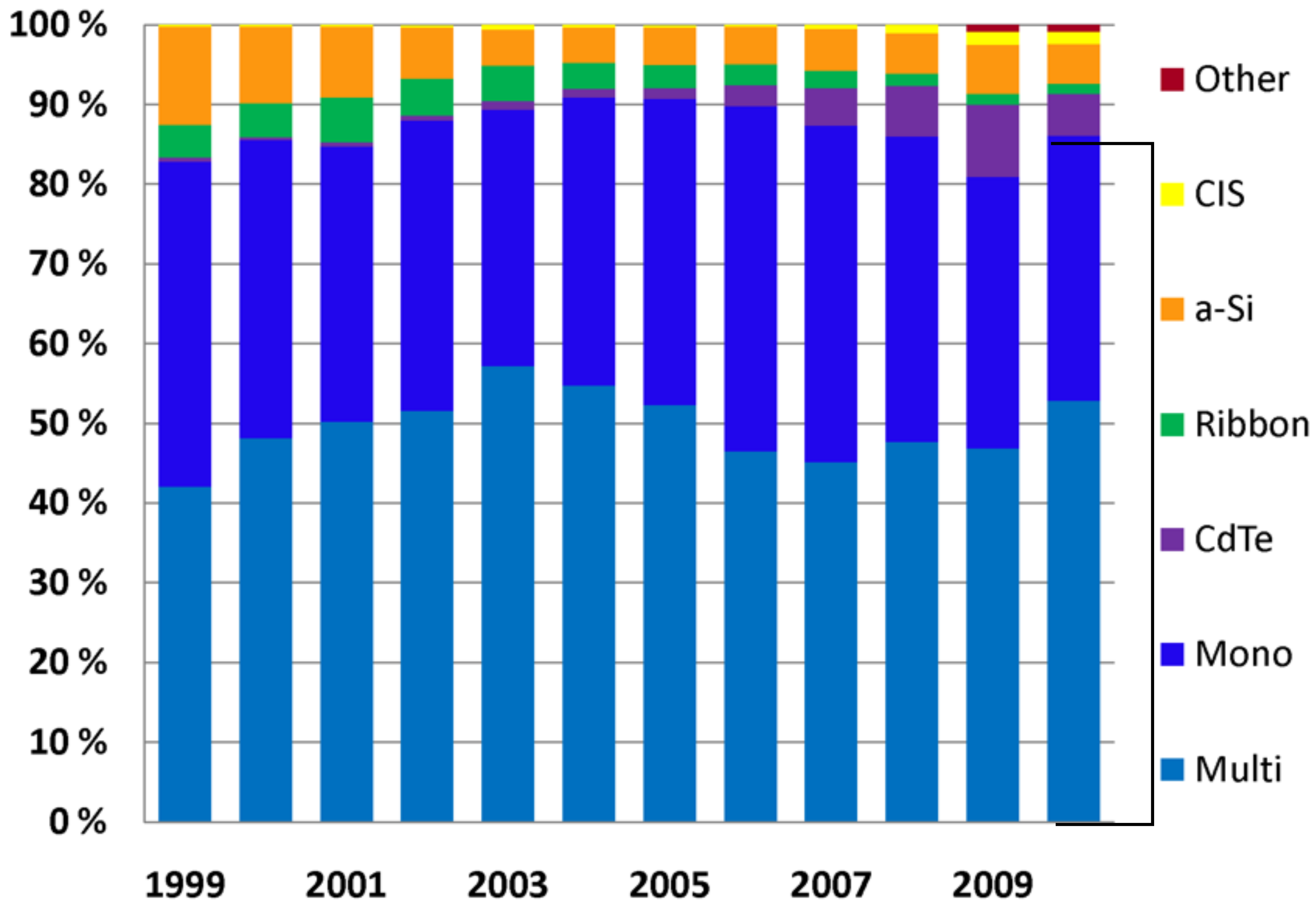
Differences





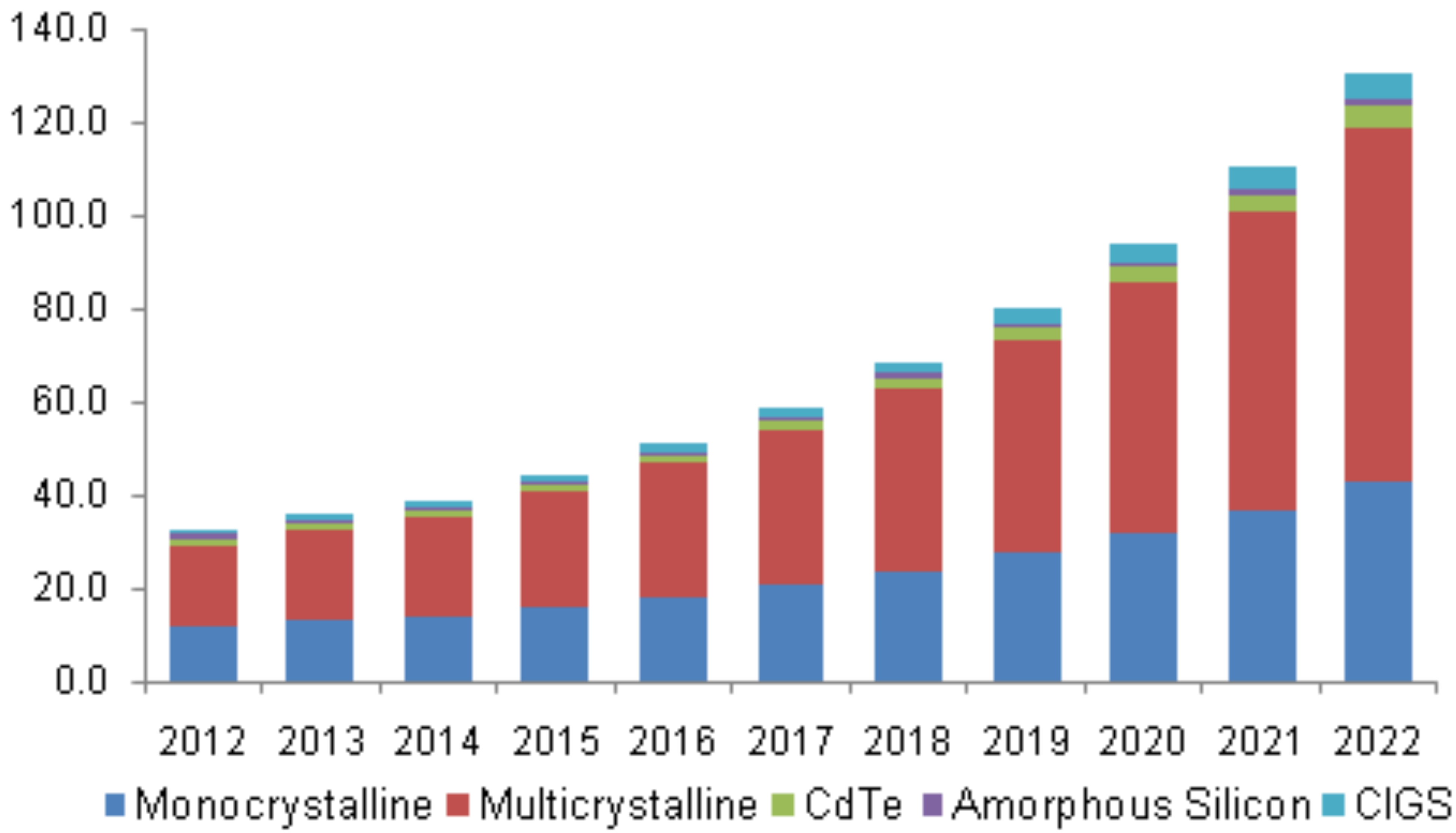
source: http://energy.mit.edu/news/transparent-solar-cells/

Differences



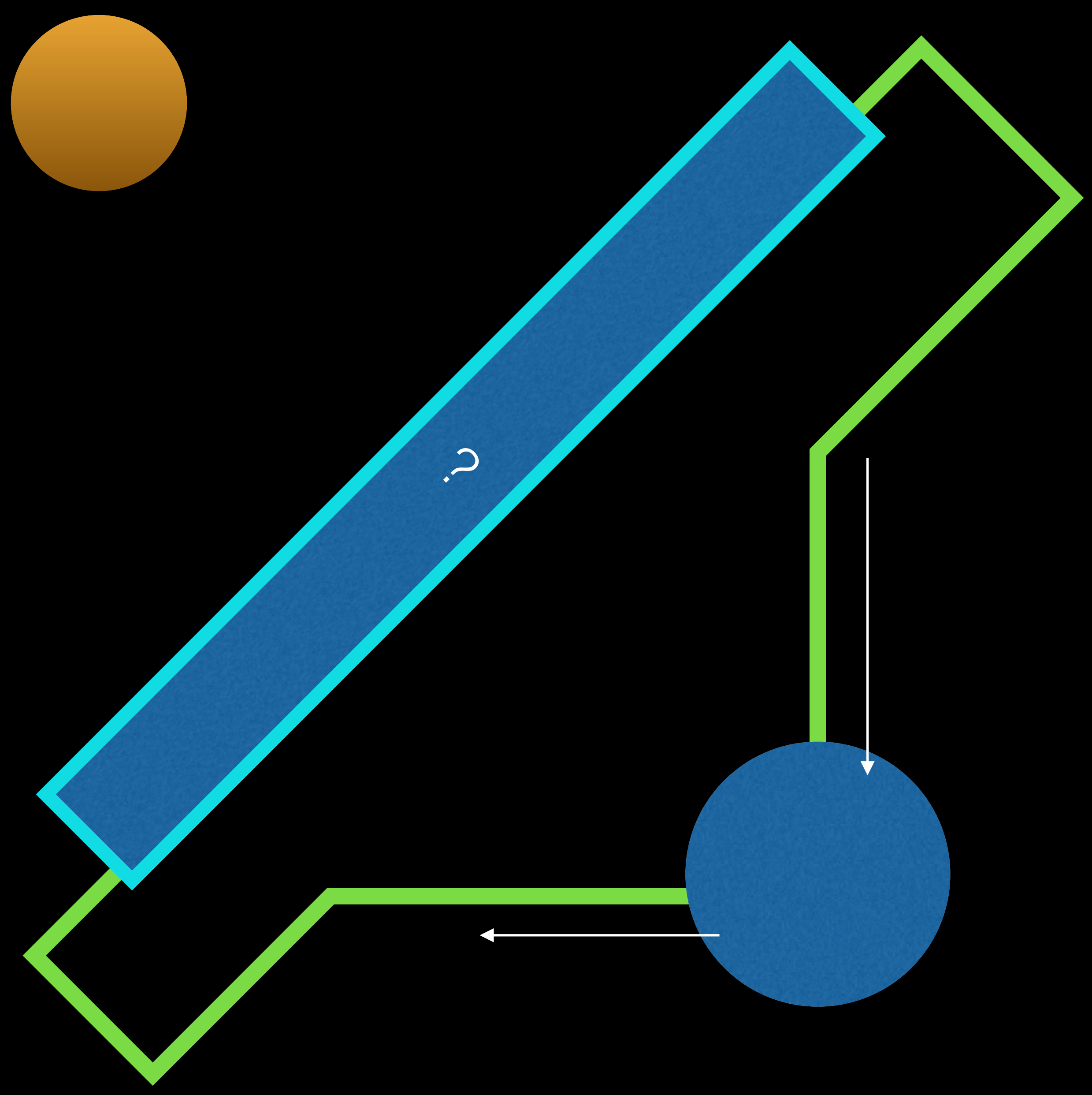
Source: Cleanenergy

Differences



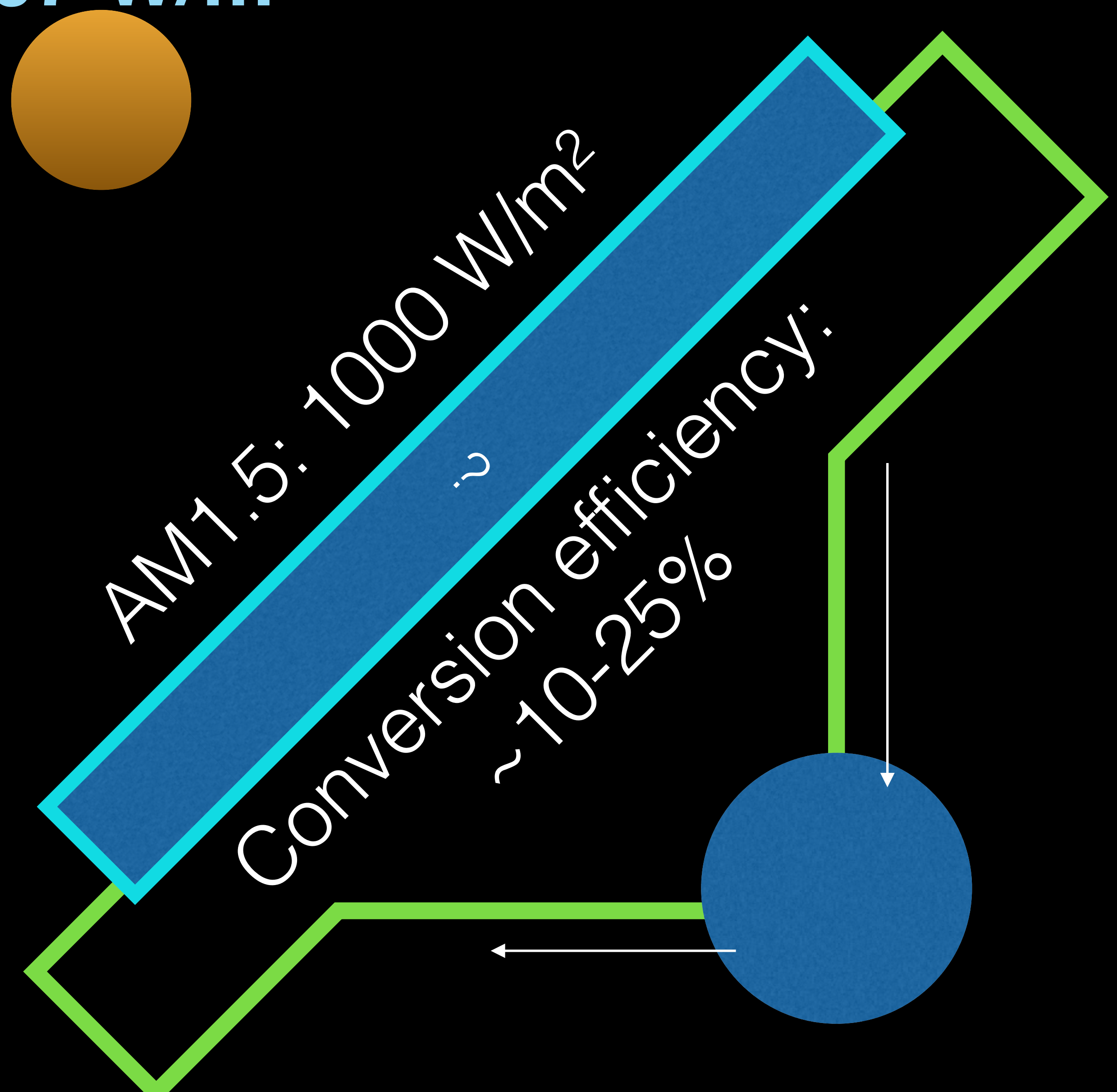
https://www.grandviewresearch.com/

Differences



Solar constant at Earth orbit:

1367 W/m²



DC electricity

Voltage depends on number of cells in series.

Current proportional to area and light intensity

Remember:
Watt is SI unit of power

1W = 1J/s

1W (electric) = 1V * 1A

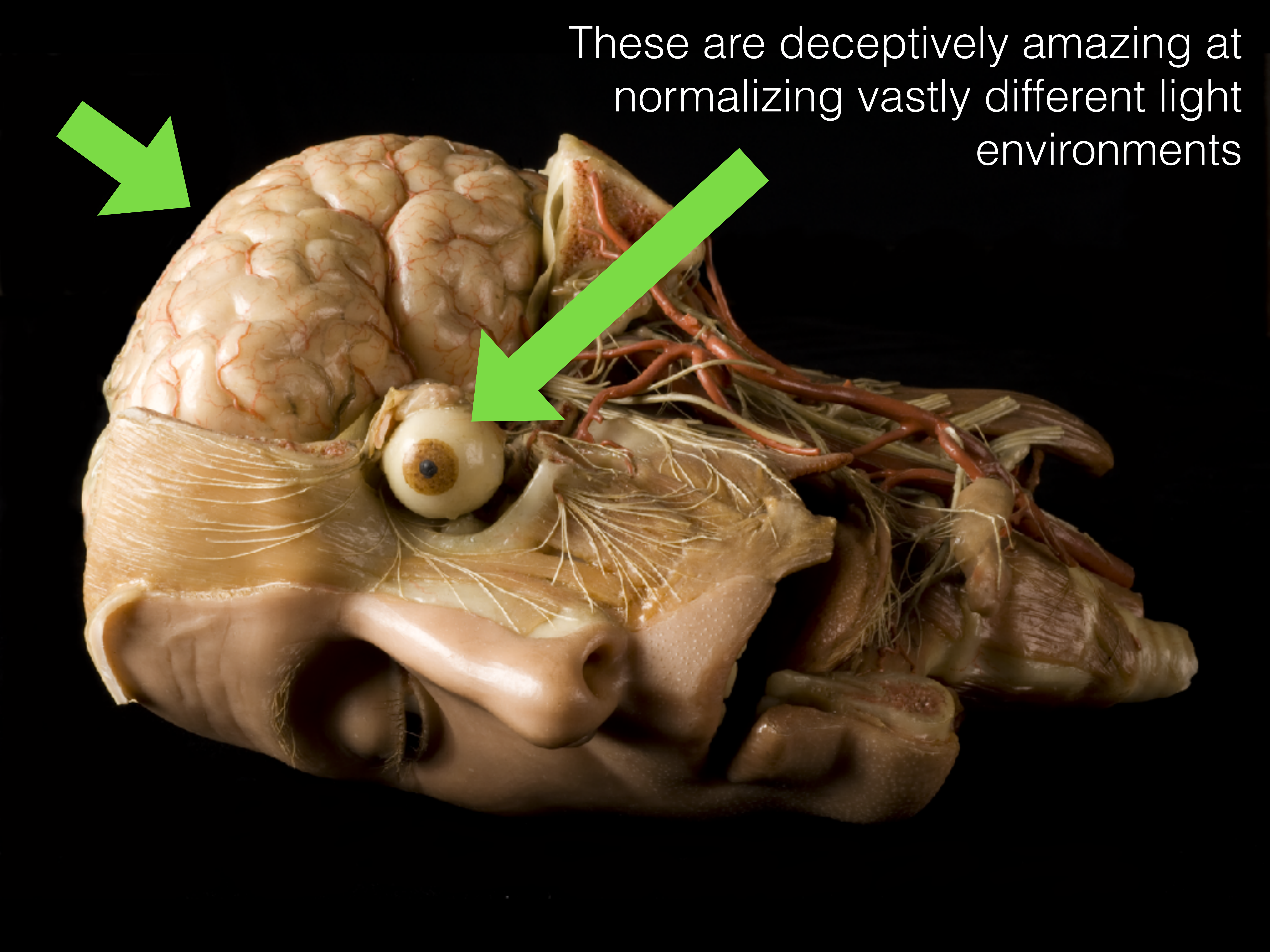
Reality check

Random solar panel from
www.solar-electric.com
AXITEC AC-290M/156-60S

290 Watts
17.83% efficiency
290/.178 = 1630W sunlight

So should be about
1.63m^2 for AM1.5

Dimensions:
64.57" x 39.06”
1.64m x .99m
1.62m^2


These are deceptively amazing at normalizing vastly different light environments

Solar constant at Earth orbit:

1367 W/m²

AM1.5: **1000 W/m²**

Average solar radiation for a location on the northern hemisphere with a latitude angle of 47° - 55°.

sunny, clear sky
summer: 600 - 1000 W/m²
winter: 300 - 500 W/m²

sunny, scattered clouds or partly cloudy
summer: 300 - 600 W/m²
winter: 150 - 300 W/m²

cloudy, fog
summer: 100 - 300 W/m²
winter: 50 - 150 W/m²

Typical indoor lighting:
1-2 W/m²

MOVA Globes are wild!

http://www.renewable-energy-concepts.com/solarenergy/solar-basics/insolation-weather.html

For later:

Local solar potential
Balance of system
Tracking methods
Concentrating systems
Solar lighting
Solar thermal

also:
Kardashev scale
Space based solar power
Dyson swarms

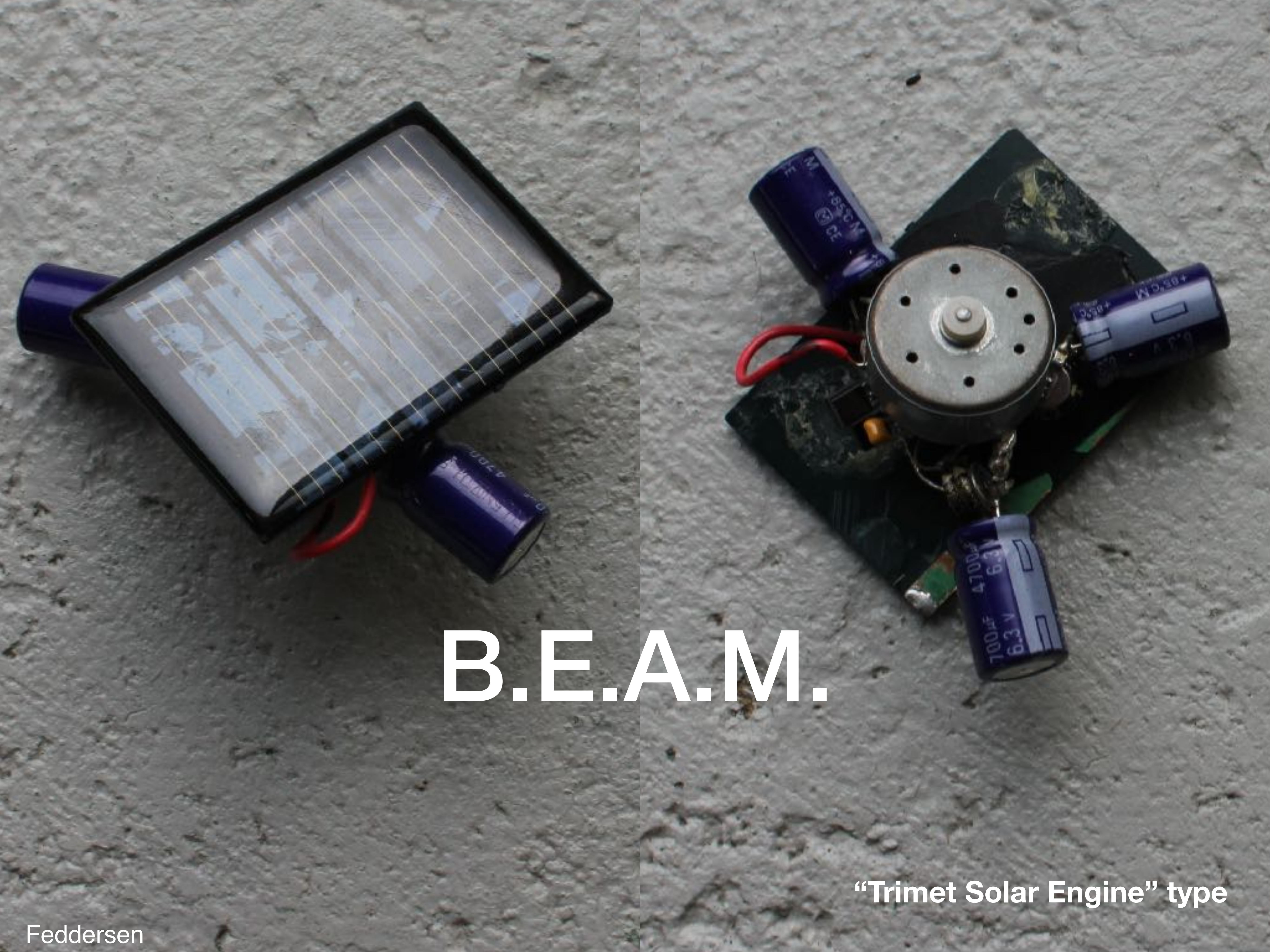
For now:

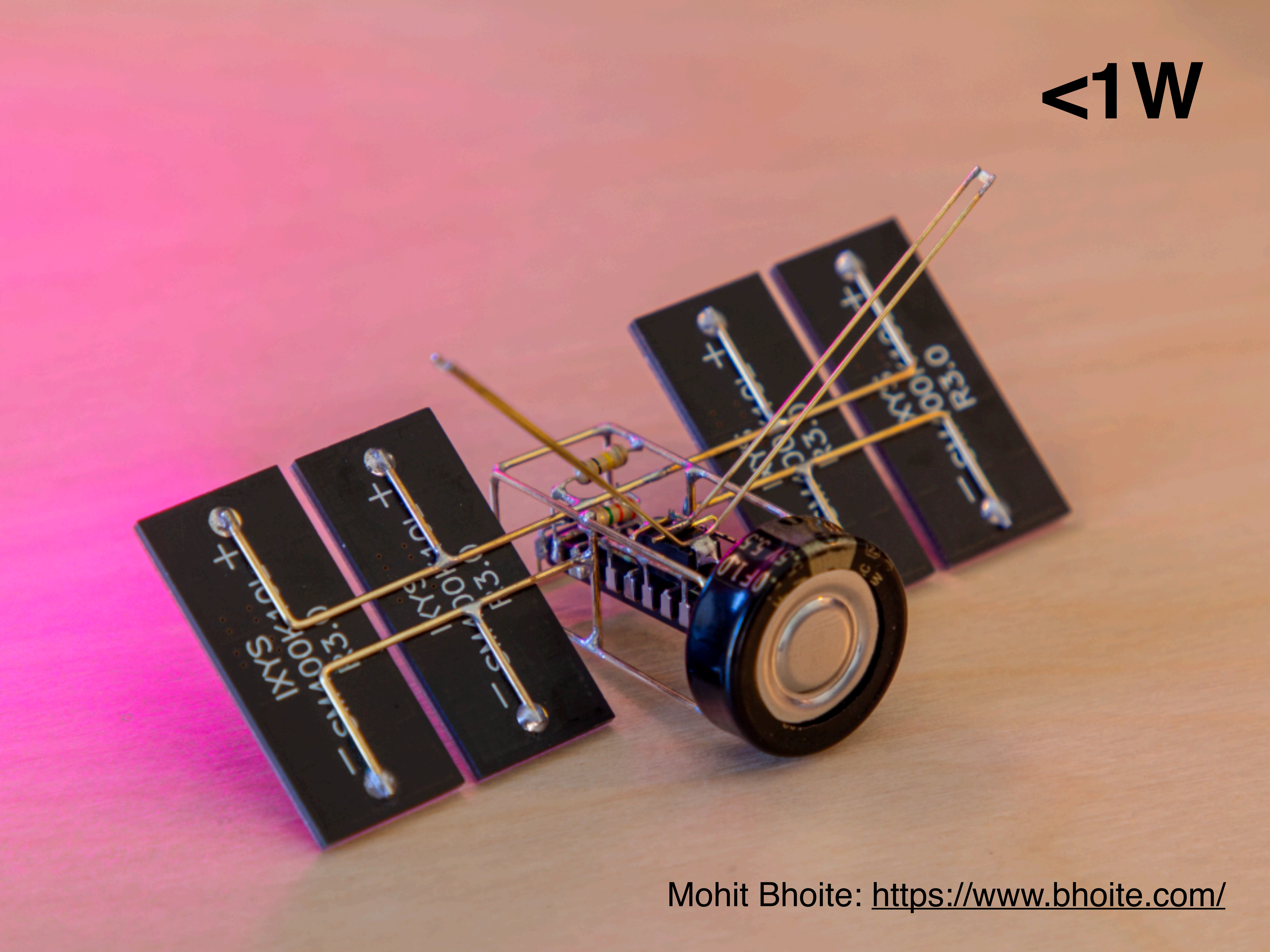
Preview: Planning a solar powered project
Different sizes of solar (1/10/100W)

Size: Very Small

BEAM circuits. <1W PVs charge capacitors, discharged through resistive loads by voltage monitor ICs. Can be extended to power microcontrollers and other circuits.

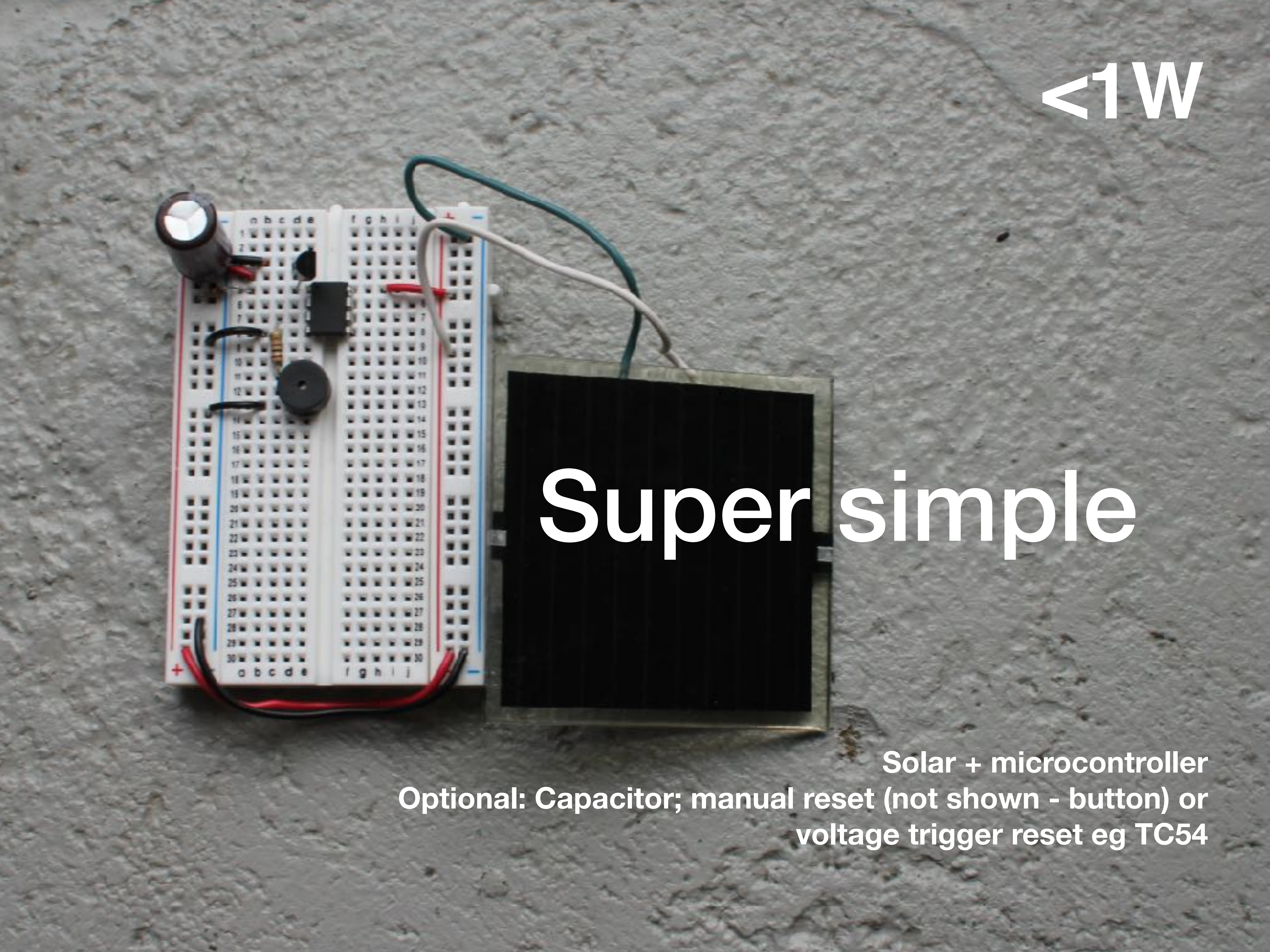
Solarbotics

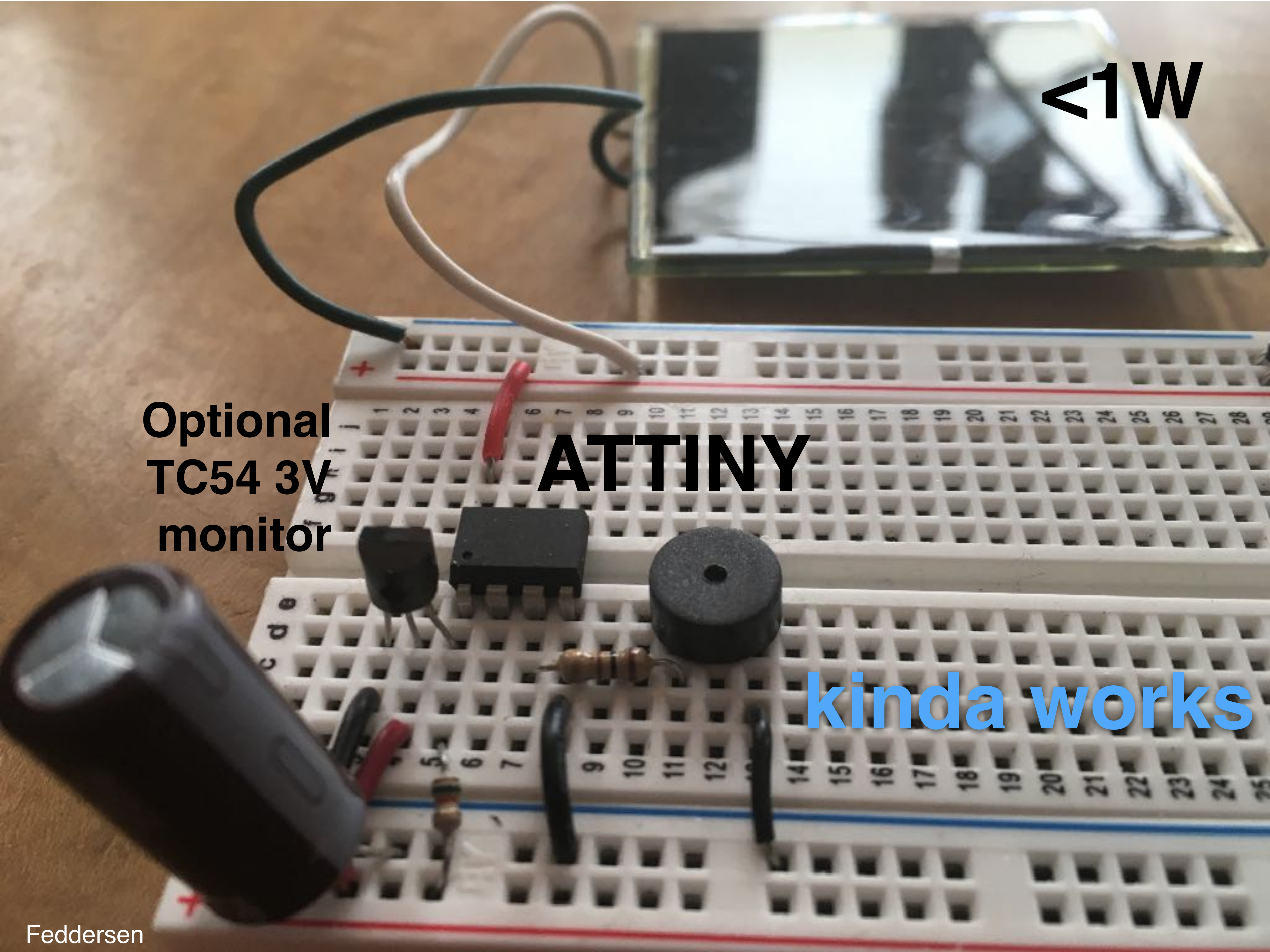

B.E.A.M.
"Trimet Solar Engine" type
Feddersen



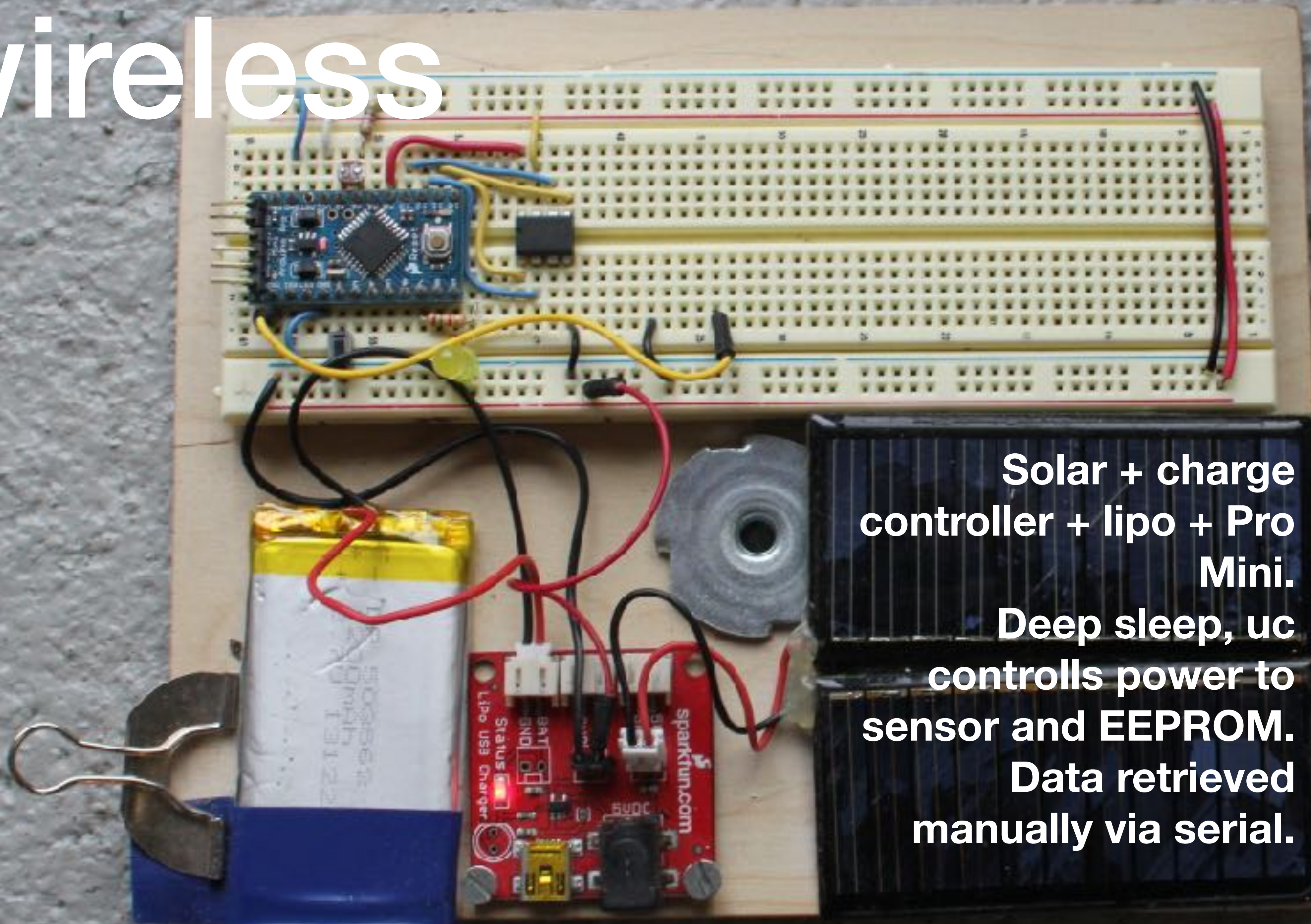
<1W

Mohit Bhoite: https://www.bhoite.com/

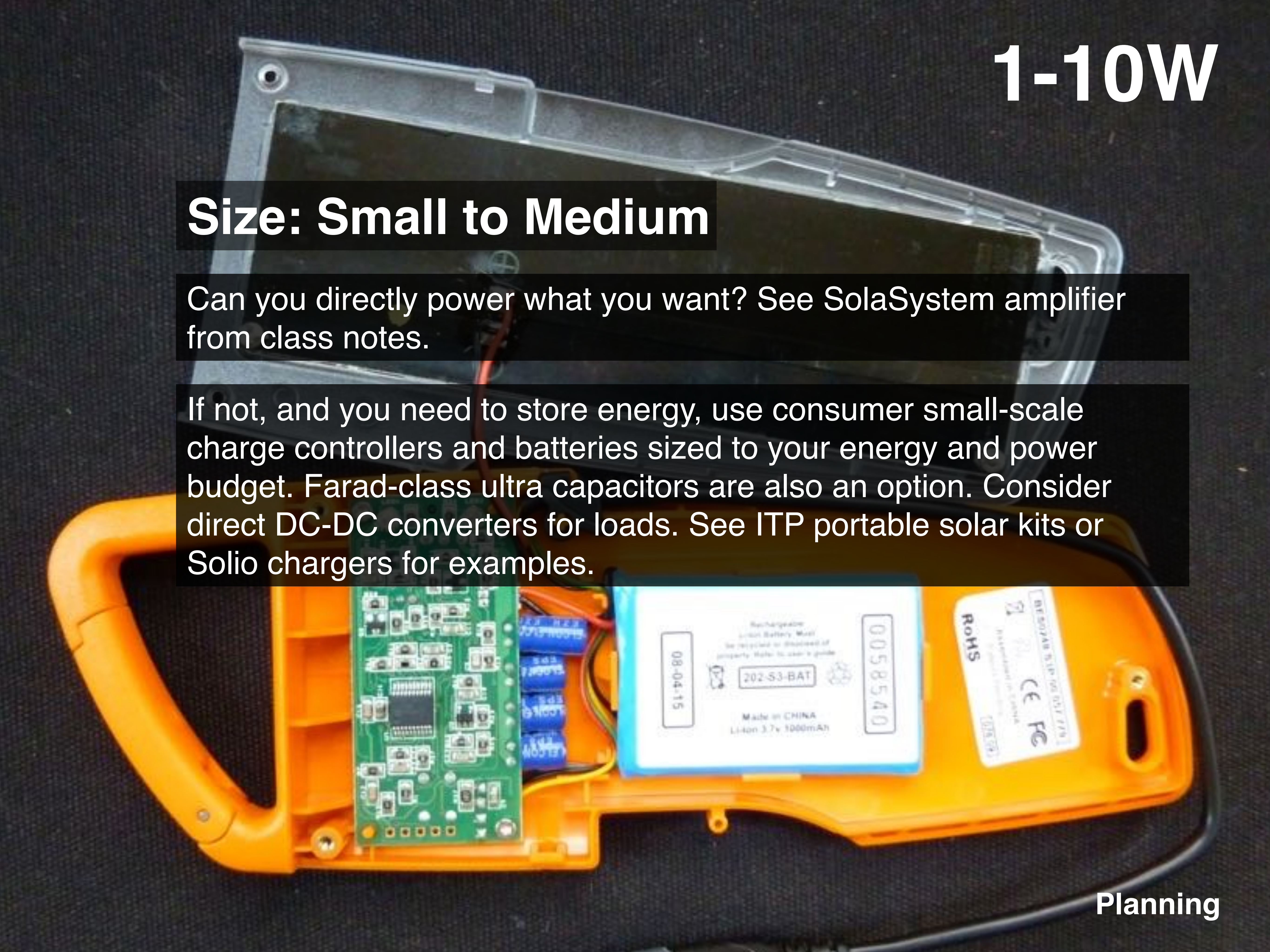

<1W
Super simple
Solar + microcontroller
Optional: Capacitor; manual reset (not shown - button) or
voltage trigger reset eg TC54


<1W
Optional
TC54 3V
monitor
ATTINY
kinda works
Feddersen

Very low power, no wireless <1W



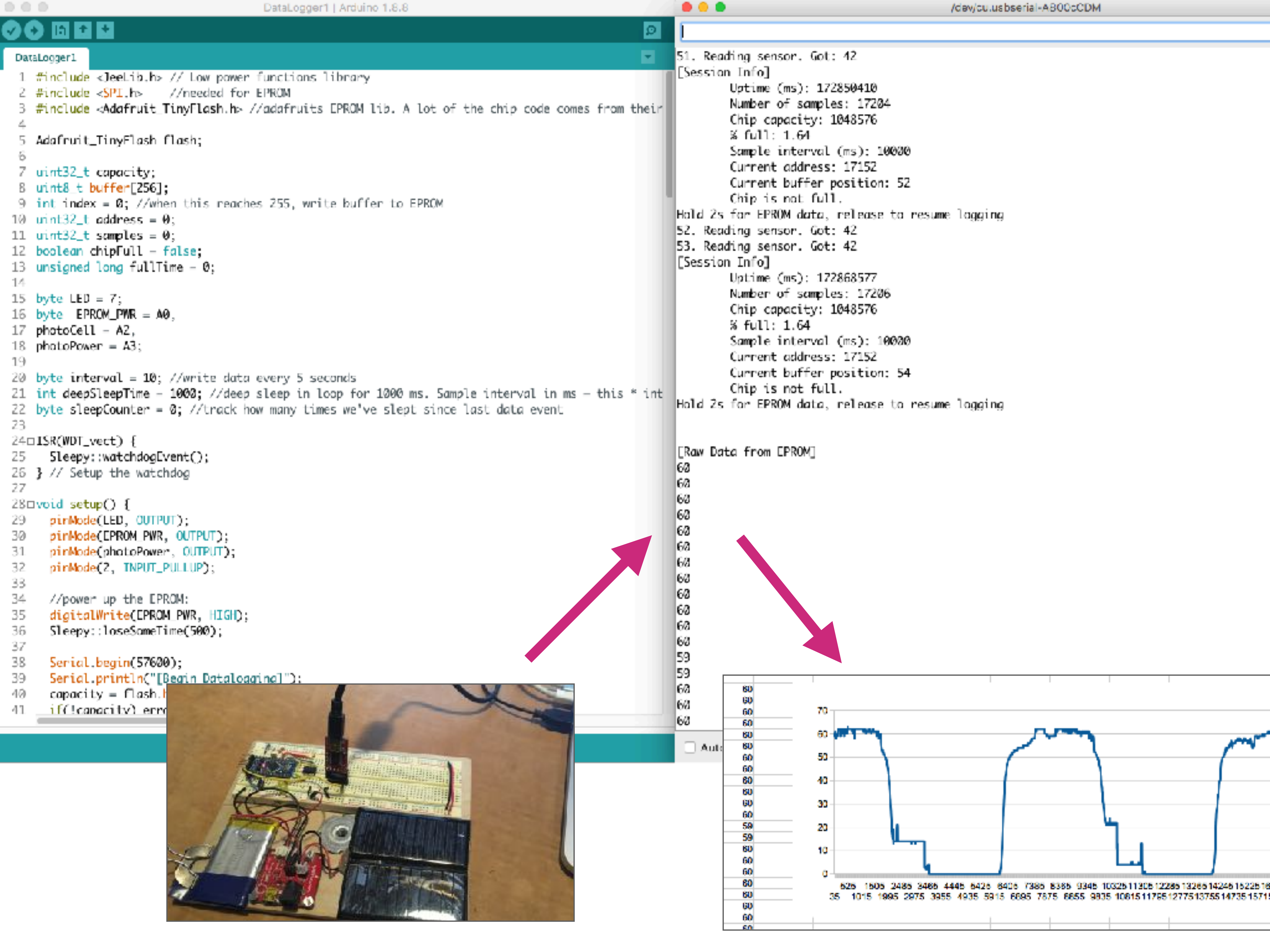
Solar + charge controller + lipo + Pro Mini.
Deep sleep, uc controlls power to sensor and EEPROM.
Data retrieved manually via serial.



Size: Small to Medium

Can you directly power what you want? See SolaSystem amplifier from class notes.

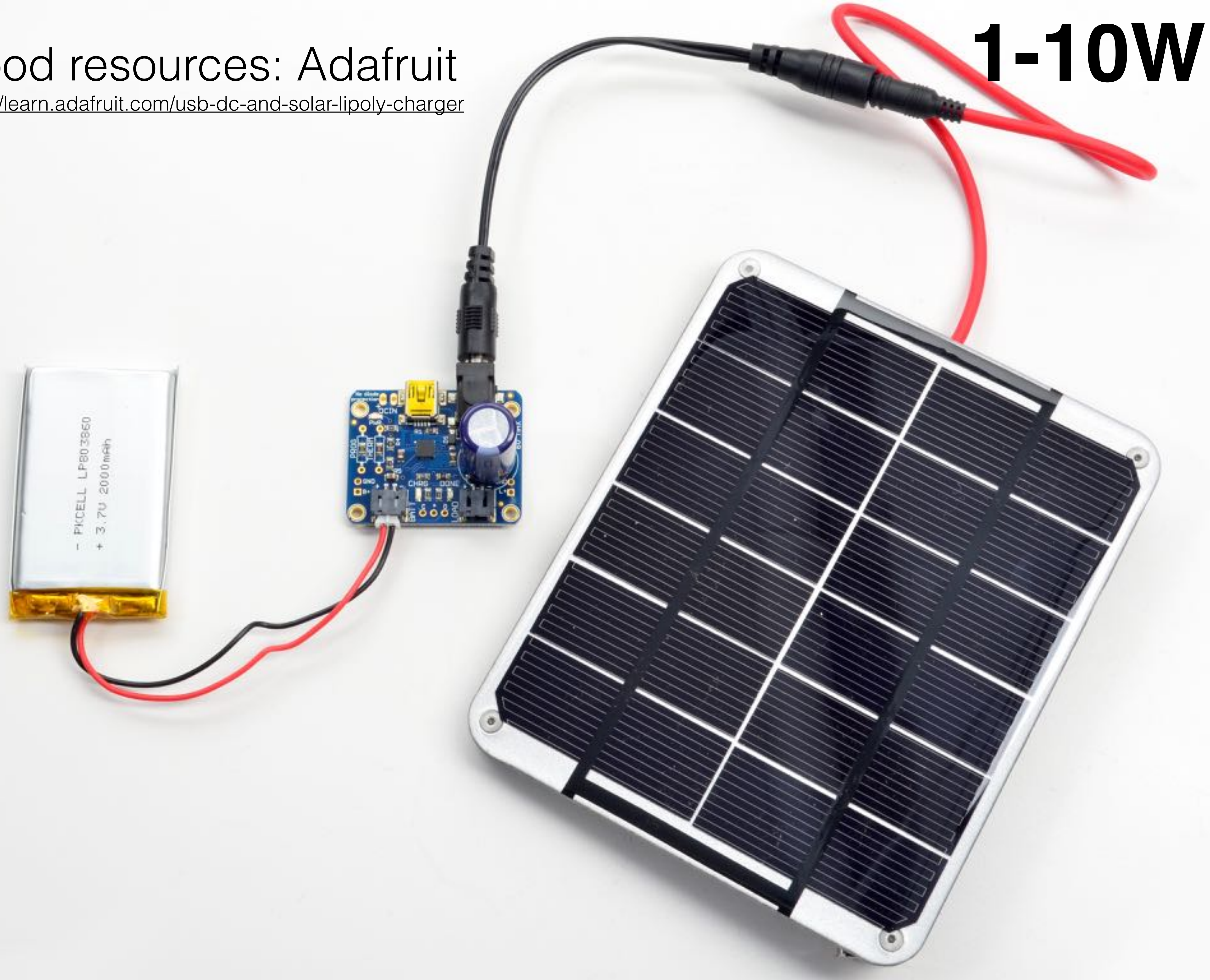
If not, and you need to store energy, use consumer small-scale charge controllers and batteries sized to your energy and power budget. Farad-class ultra capacitors are also an option. Consider direct DC-DC converters for loads. See ITP portable solar kits or Solio chargers for examples.

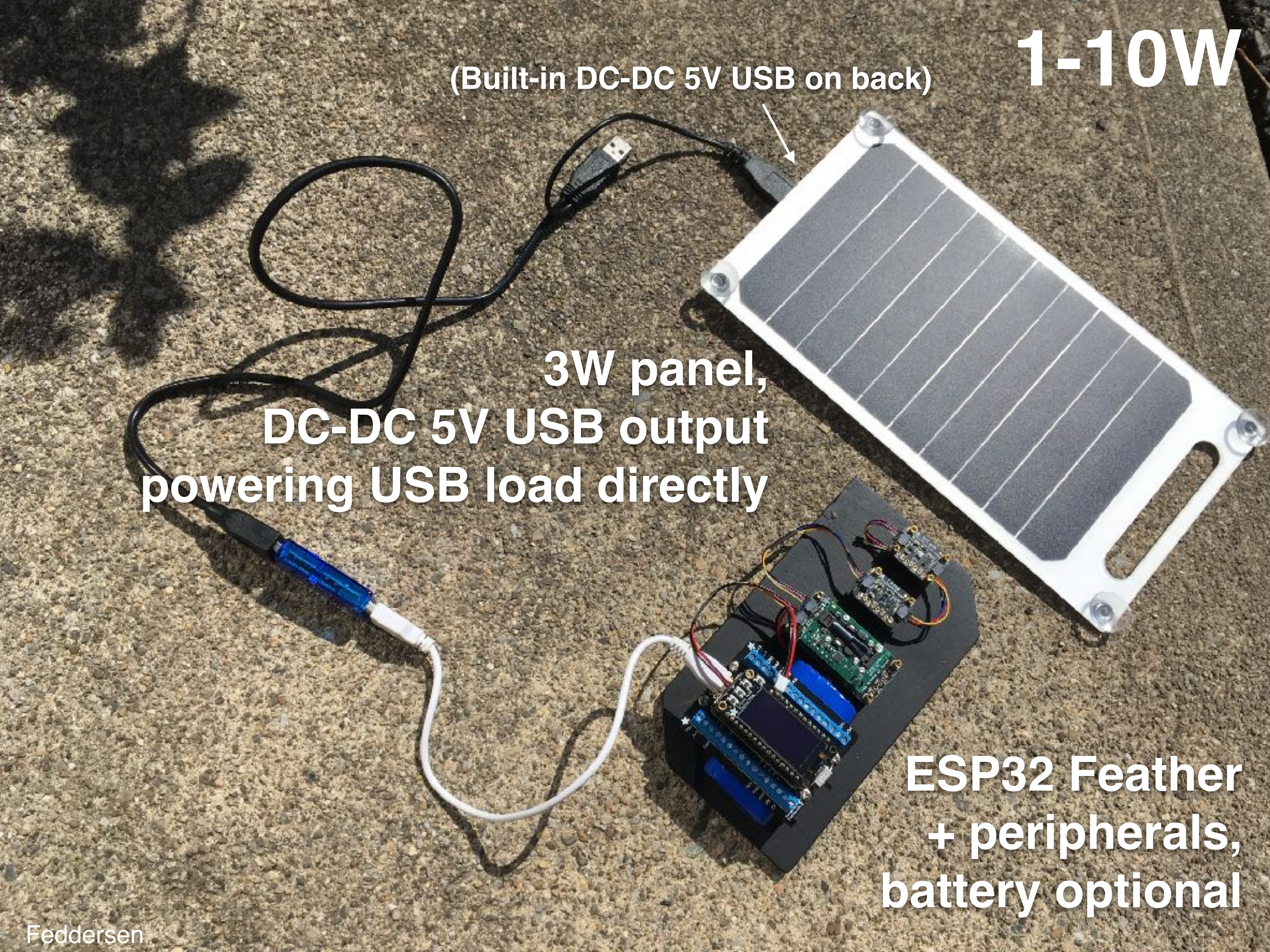

DataLogger1 | Arduino 1.8.8
DataLogger1
#include <JeeLib.h> // Low power functions library
#include <SPI.h> //needed for EPROM
#include <Adafruit_TinyFlash.h> //adafruits EPROM lib. A lot of the chip code comes from their
Adafruit_TinyFlash flash;
uint32_t capacity;
uint8_t buffer[256];
int index = 0; //when this reaches 255, write buffer to EPROM
uint32_t address = 0;
uint32_t samples = 0;
boolean chipFull = false;
unsigned long fullTime = 0;
byte LED = 7;
byte EPROM_PWR = A0,
photoCell = A2,
photoPower = A3;
byte interval = 10; //write data every 5 seconds
int deepSleepTime = 1000; //deep sleep in loop for 1000 ms. Sample interval in ms = this * int
byte sleepCounter = 0; //track how many times we've slept since last data event
ISR(WDT_vect) {
Sleepy::watchdogEvent();
} // Setup the watchdog
void setup() {
pinMode(LED, OUTPUT);
pinMode(EPROM_PWR, OUTPUT);
pinMode(photoPower, OUTPUT);
pinMode(2, INPUT_PULLUP);
//power up the EPROM:
digitalWrite(EPROM_PWR, HIGH);
Sleepy::loseSomeTime(500);
Serial.begin(57600);
Serial.println("[Begin Datalogging]");
/dev/cu.usbserial-A900cCDM
51. Reading sensor. Got: 42
[Session Info]
Uptime (ms): 172850410
Number of samples: 17204
Chip capacity: 1048576
% full: 1.64
Sample interval (ms): 10000
Current address: 17152
Current buffer position: 52
Chip is not full.
Hold 2s for EPROM data, release to resume logging
52. Reading sensor. Got: 42
53. Reading sensor. Got: 42
[Session Info]
Uptime (ms): 172868577
Number of samples: 17206
Chip capacity: 1048576
% full: 1.64
Sample interval (ms): 10000
Current address: 17152
Current buffer position: 54
Chip is not full.
Hold 2s for EPROM data, release to resume logging
[Raw Data from EPROM]
60
60
60
60
60
60
60
60
60
60
60
60
59
59
60
60
60
70
60
50
40
30
20
10
0

Good resources: Adafruit

https://learn.adafruit.com/usb-dc-and-solar-lipoly-charger

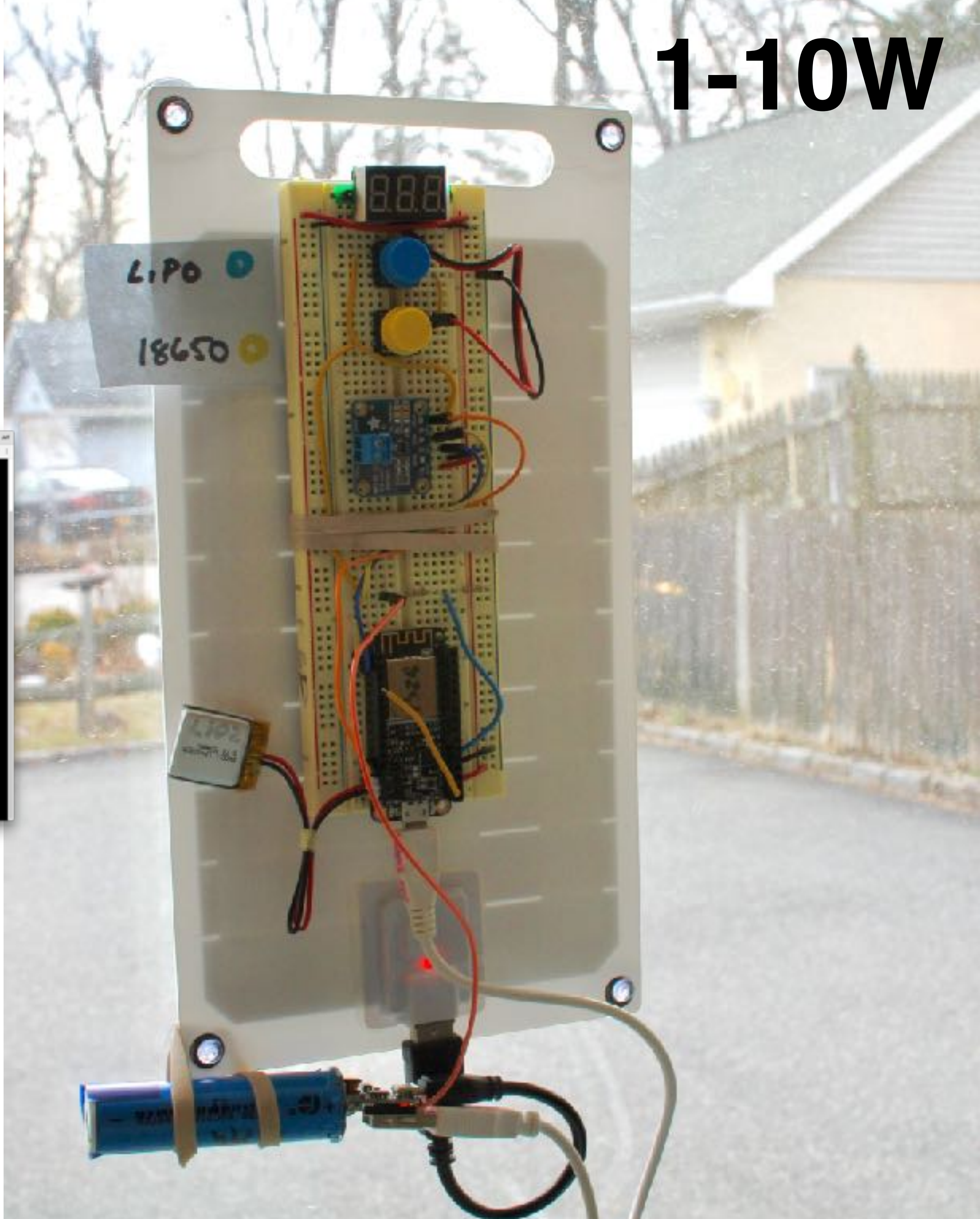
1-10W



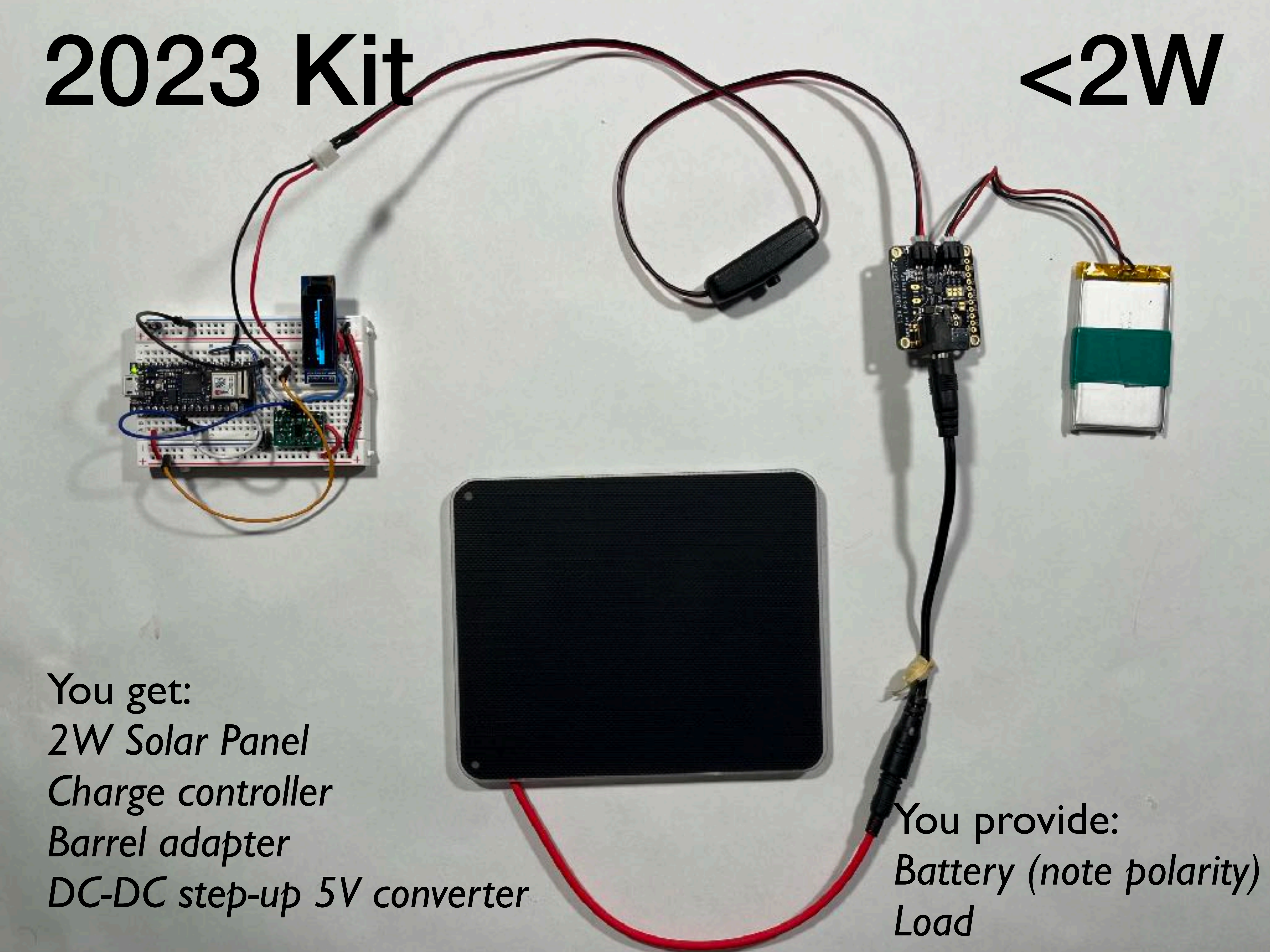

1-10W
(Built-in DC-DC 5V USB on back)
3W panel,
DC-DC 5V USB output
powering USB load directly
ESP32 Feather
+ peripherals,
battery optional
Feddersen

Off-the-shelf

1-10W

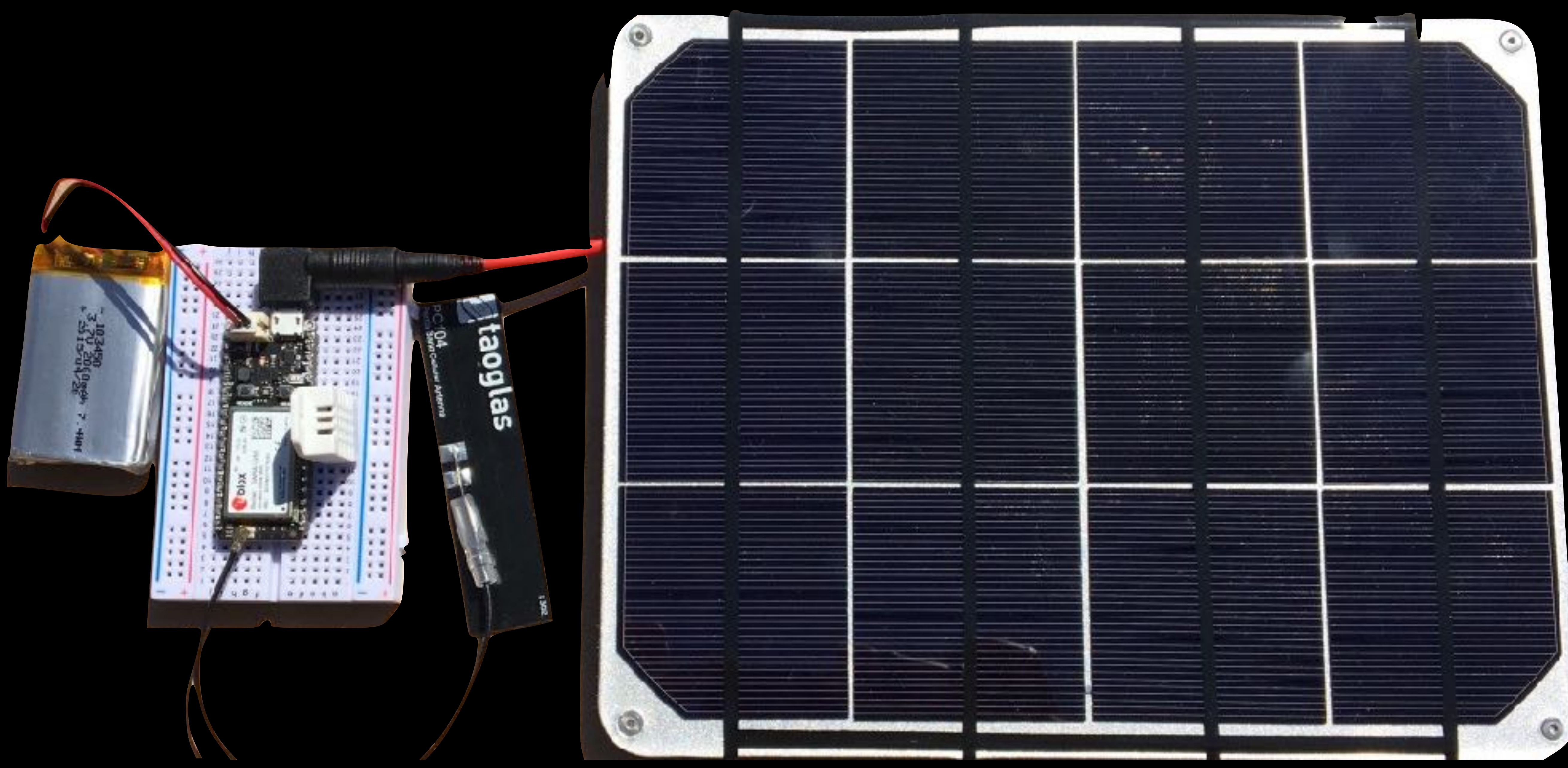


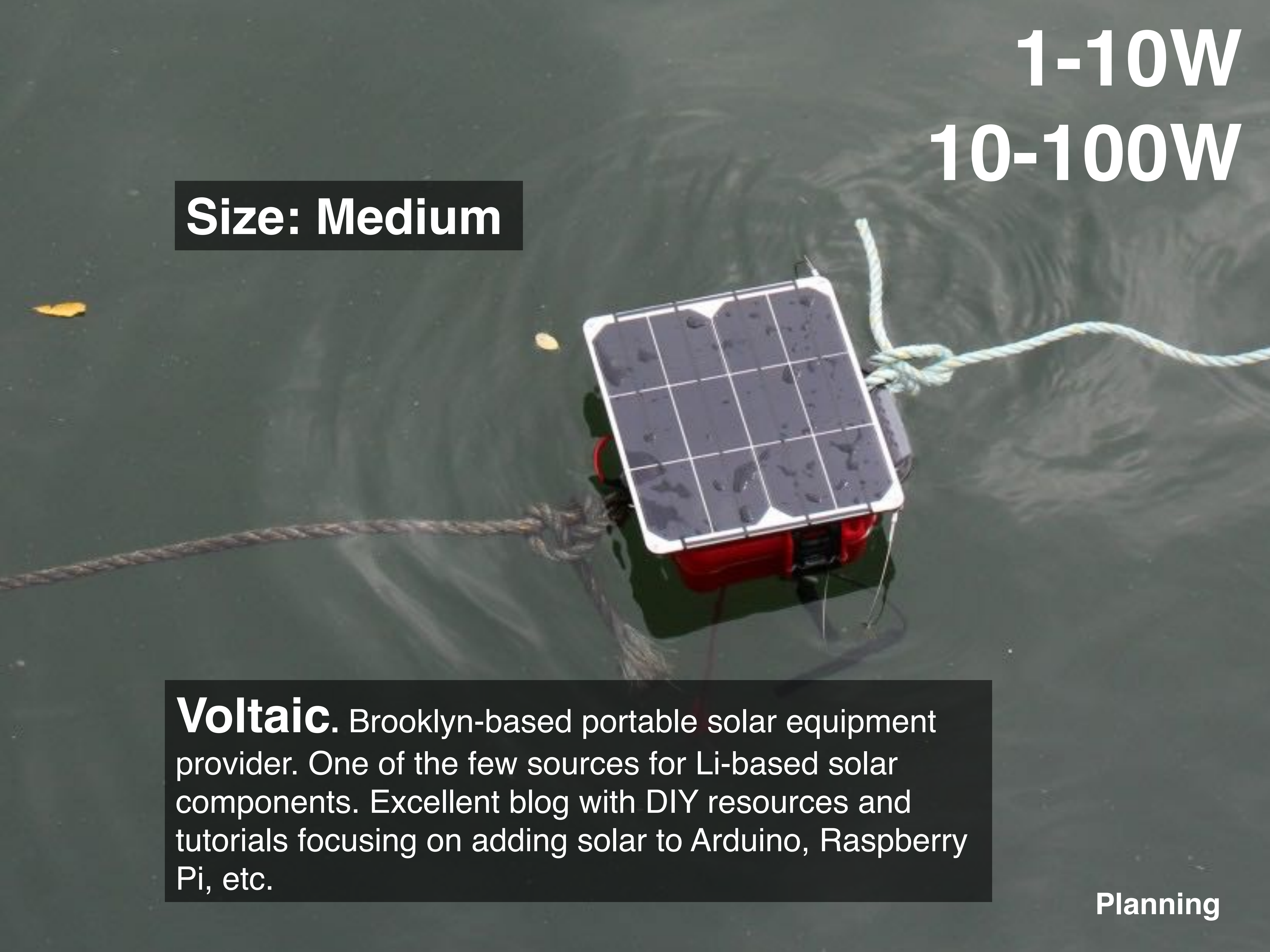
USB Solar panel + USB battery
ESP8266, deep sleep
I2C sensor
Data via MQTT to io.adafruit.com
Manual voltage monitoring with push buttons


2023 Kit
<2W
You get:
2W Solar Panel
Charge controller
Barrel adapter
DC-DC step-up 5V converter
You provide:
Battery (note polarity)
Load

Good resources: Voltaic
http://www.voltaicsystems.com/blog/

1-10W
10-100W





1-10W
10-100W

Size: Medium

Voltaic. Brooklyn-based portable solar equipment provider. One of the few sources for Li-based solar components. Excellent blog with DIY resources and tutorials focusing on adding solar to Arduino, Raspberry Pi, etc.

>50W

Size: Medium to large

Use commercial grade modules, battery chargers and batteries. Mature products exist for **off-grid** markets. Use inverter as de facto common interface for AC loads.

Feddersen

>50W

Alternate pathway: no-logic system, activity follows available light

Patrick Marold, "Solar Drones", 2016

https://patrickmarold.com/solar-drones-national-music-centre