Photovoltaics

Conversion of light to electricity

Energy
ITP / NYU / Feddersen

TODAY:

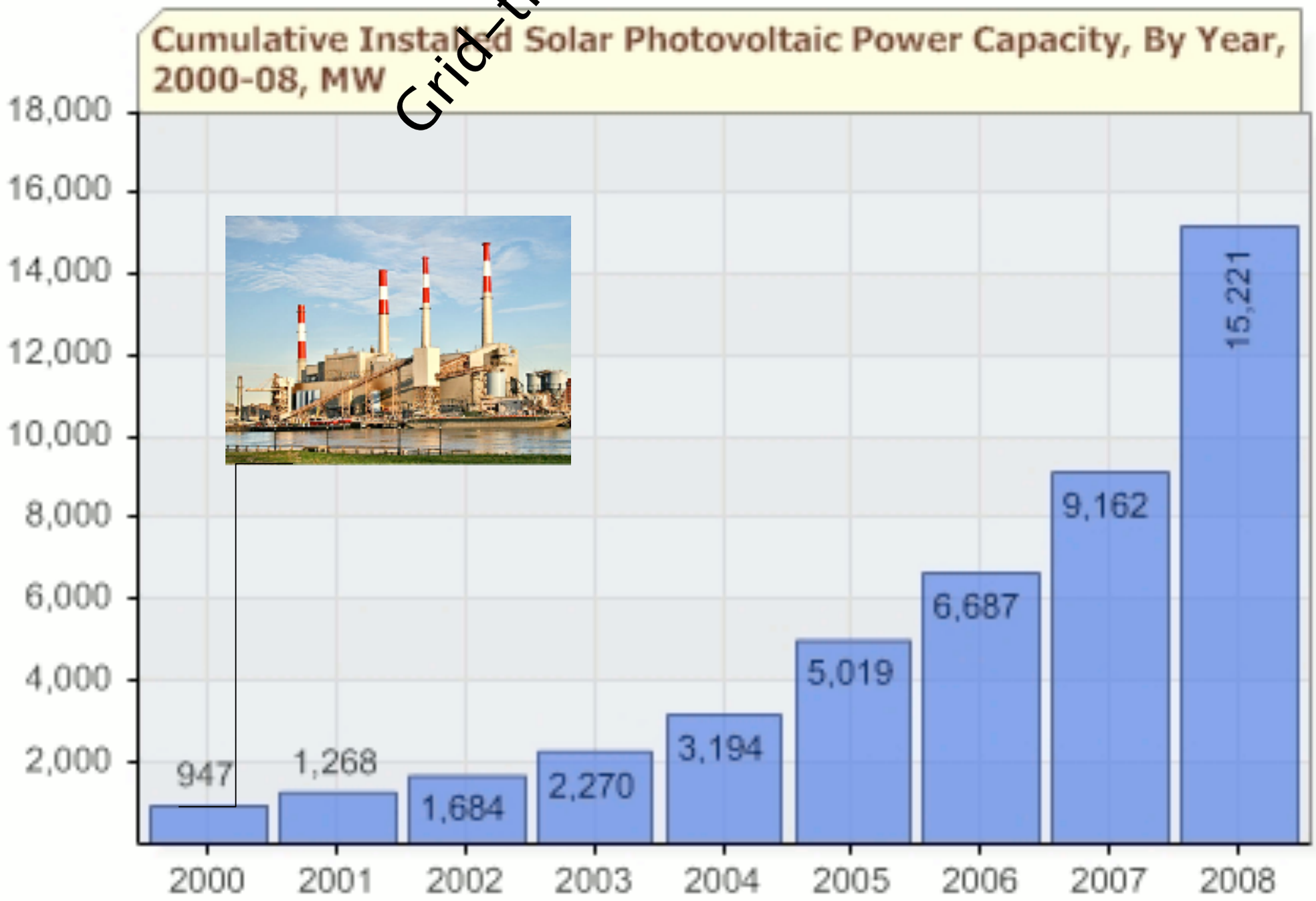
- Why is solar important?
- What exactly is photovoltaic (PV) solar?
- How does PV work?
- Preview: How can I plan a small/medium/large solar project?

WHY SOLAR?

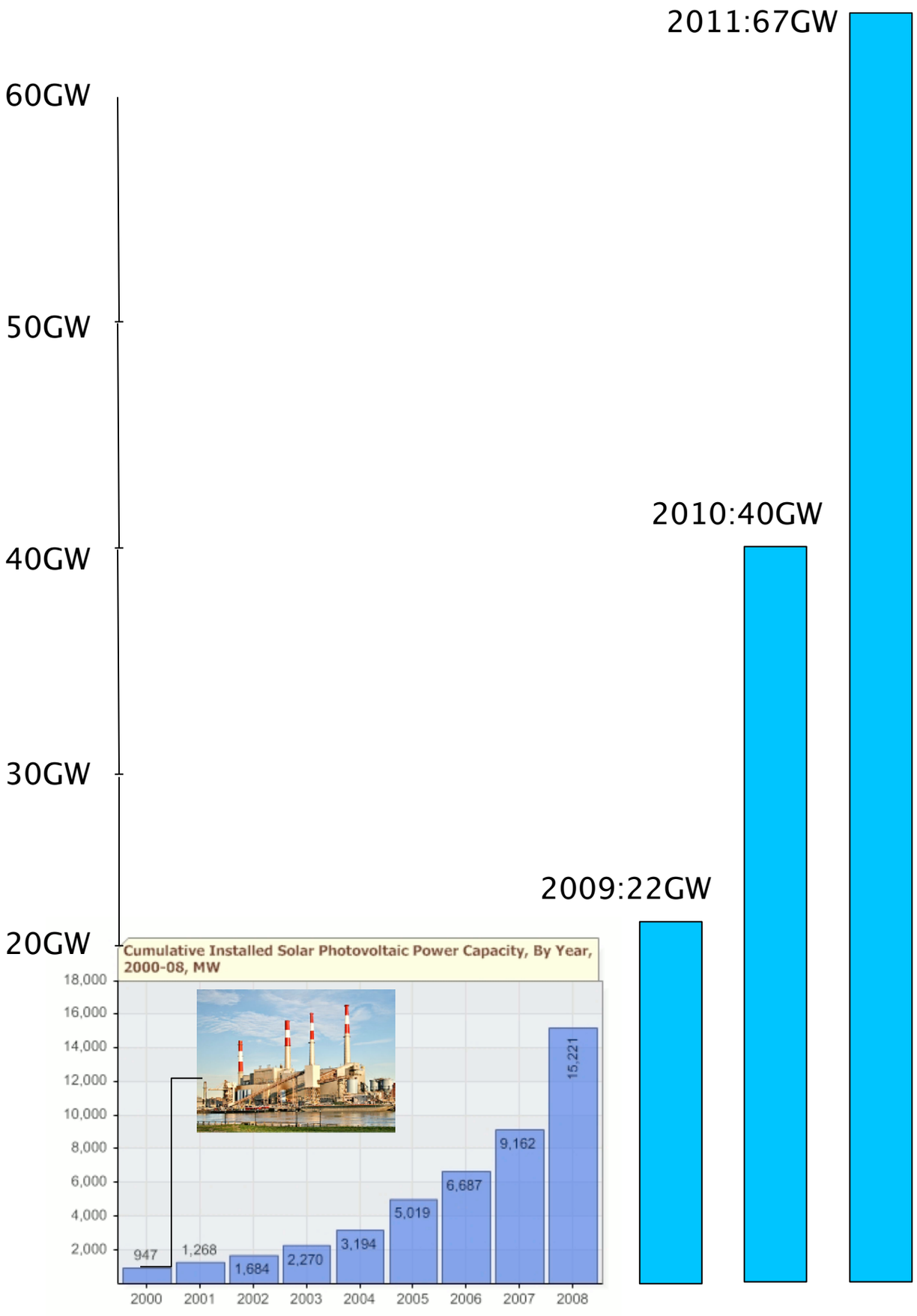
Energy directly from the sun, powering a

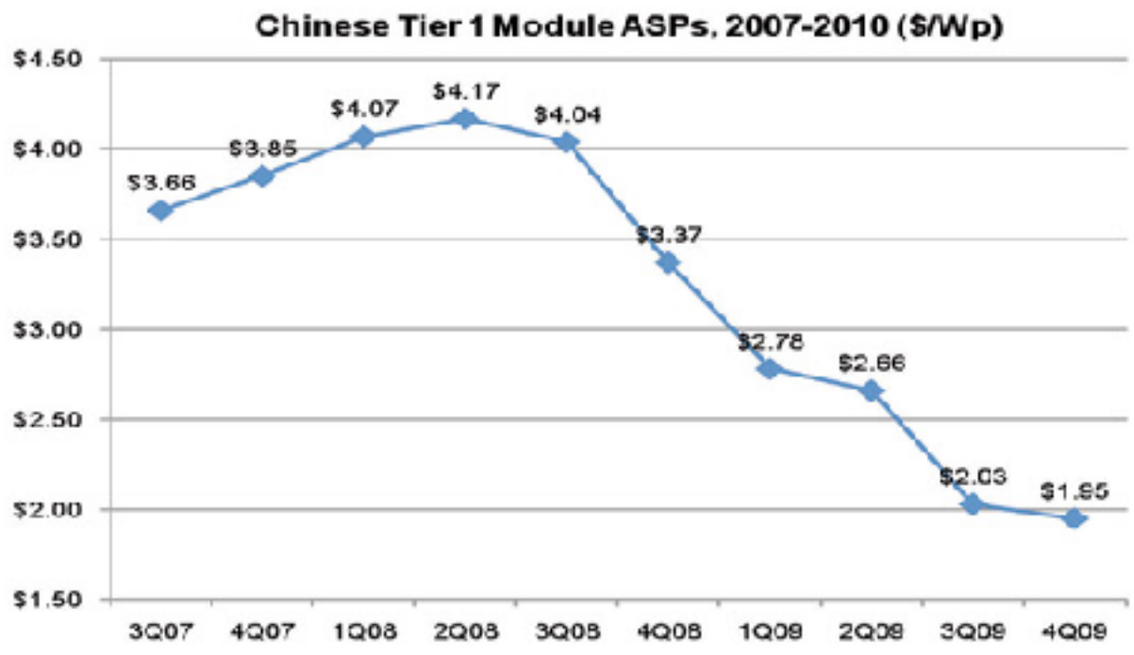
GLOBAL TRANSFORMATION

happening right now



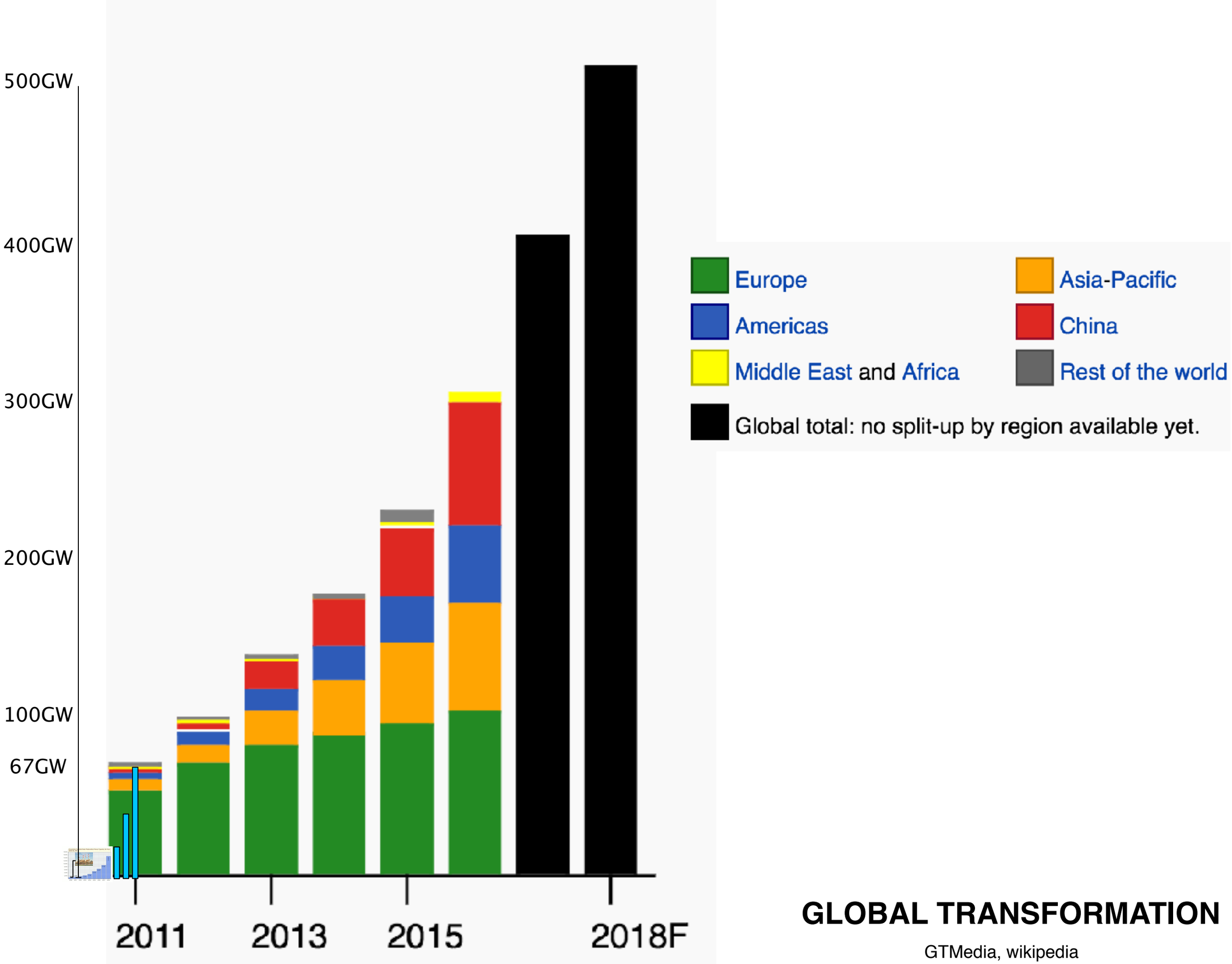
Source: http://www.energyandcapital.com/
Inset: Big Allis, first 1GW generator, in Queens.





GTMedia, wikipedia

GLOBAL TRANSFORMATION



GLOBAL TRANSFORMATION

GTMedia, wikipedia

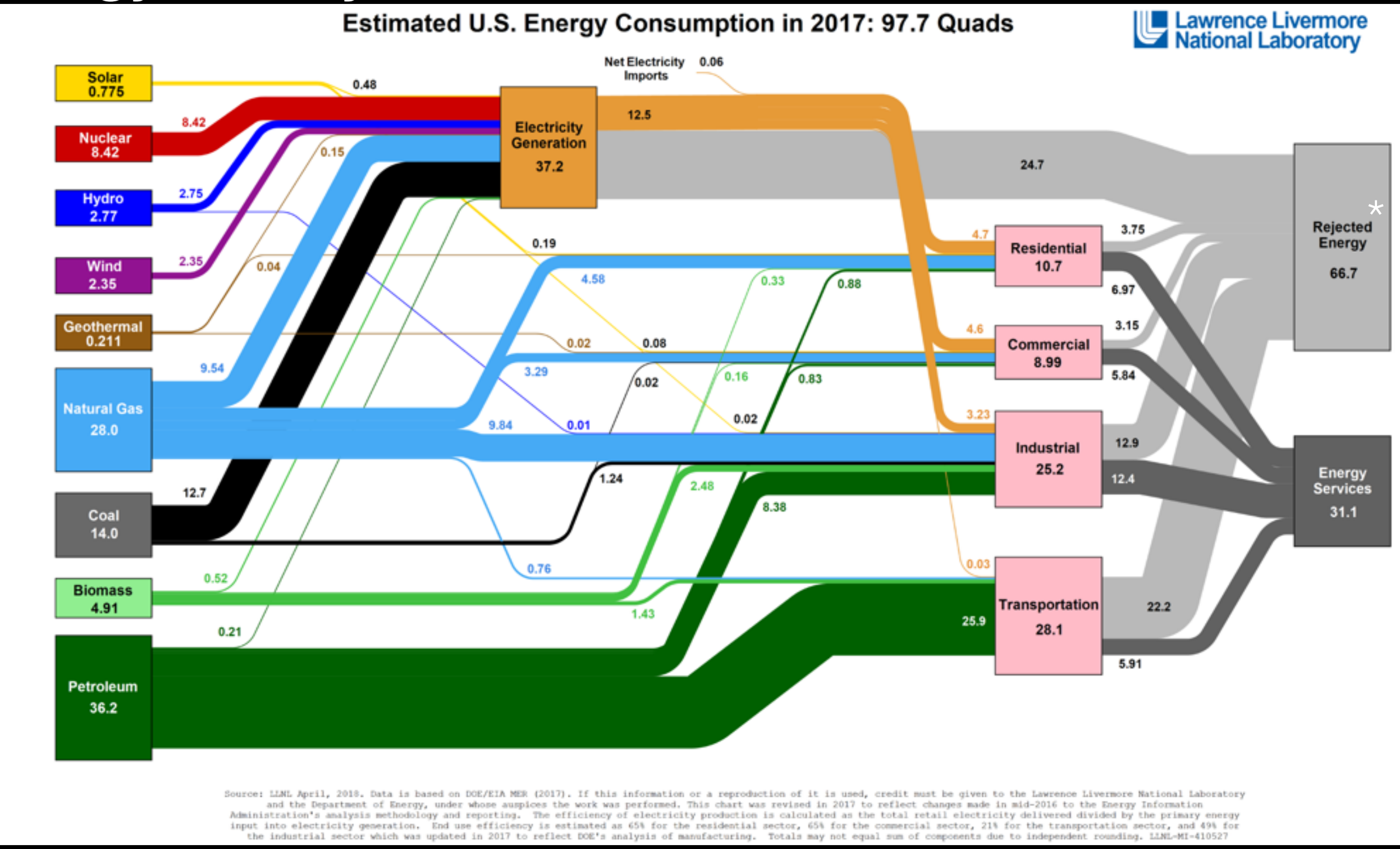
~1GW TOTAL GLOBAL INSTALLED SOLAR IN 2000

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

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

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

Energy directly from the sun

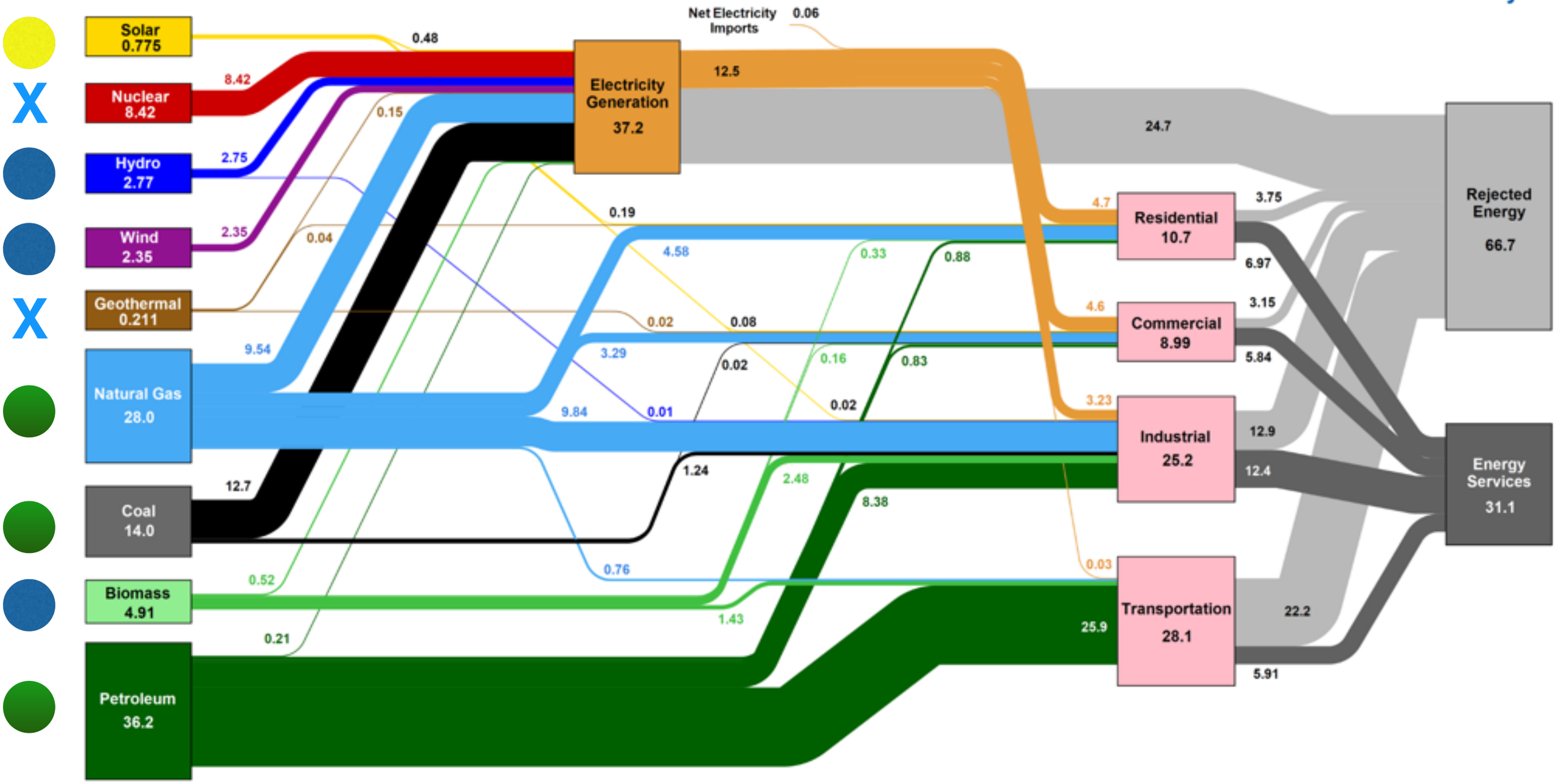


*for more on Rejected Energy, see http://aceee.org/sites/default/files/publications/researchreports/e13f.pdf

**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

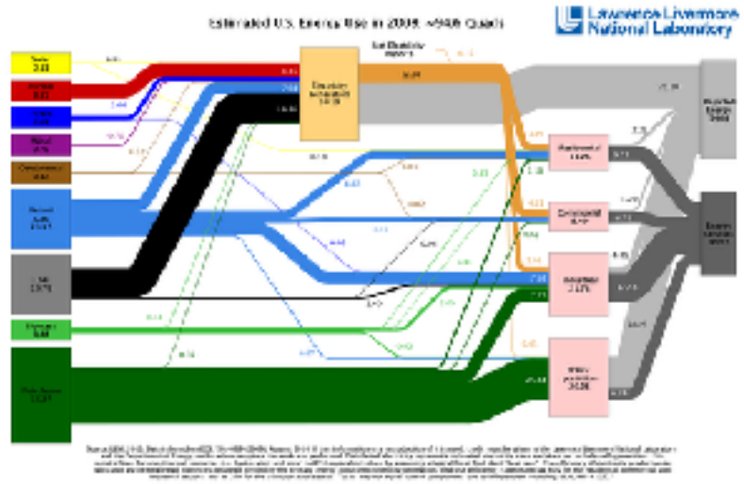
Lawrence Livermore National Laboratory



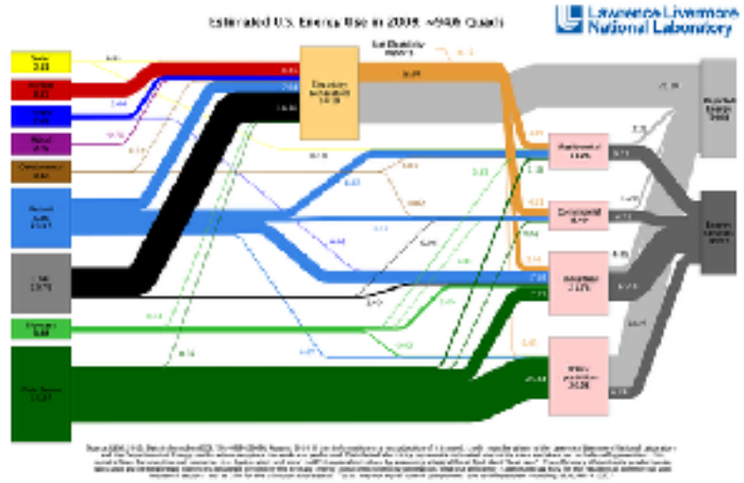
Source: LLNL April, 2018. Data is based on DOE/EIA MER (2017). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes 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

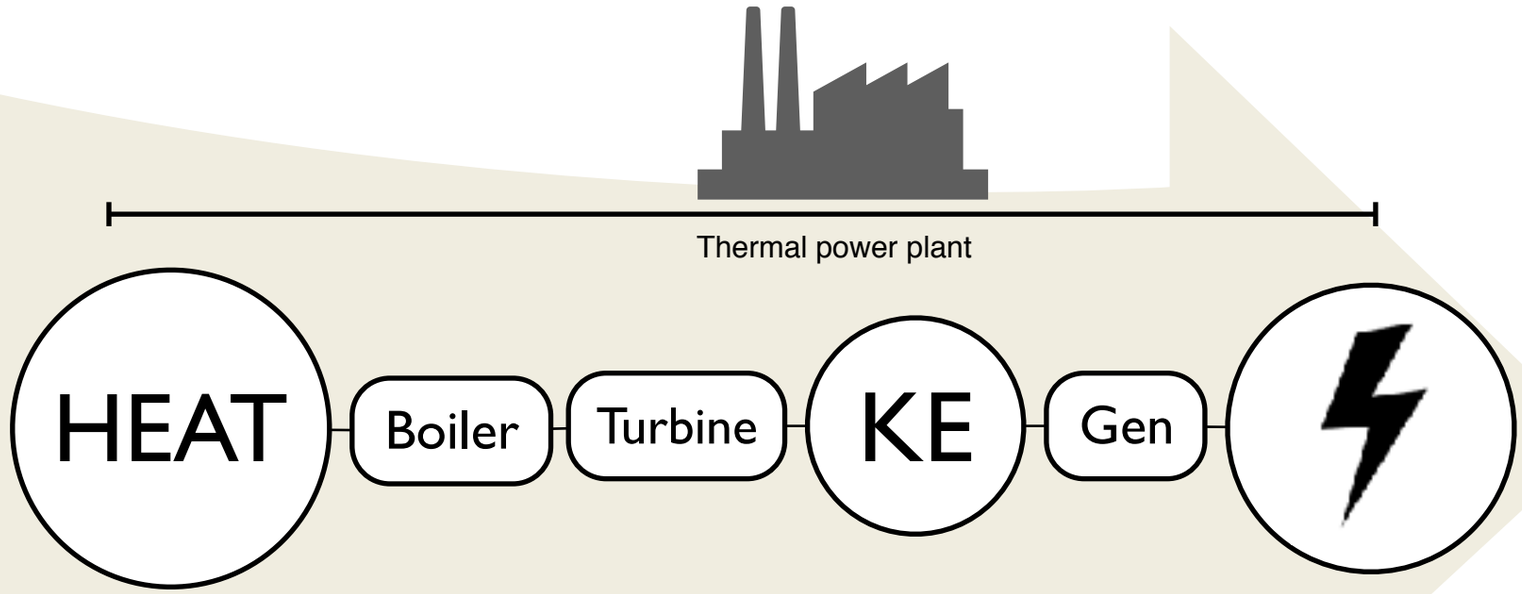
● Fresh sunlight ● Recent sunlight ● Old sunlight

X Not sunlight

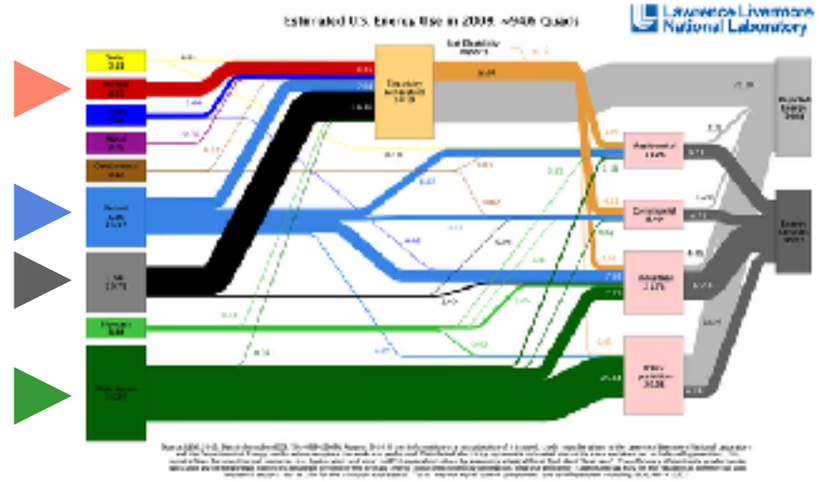


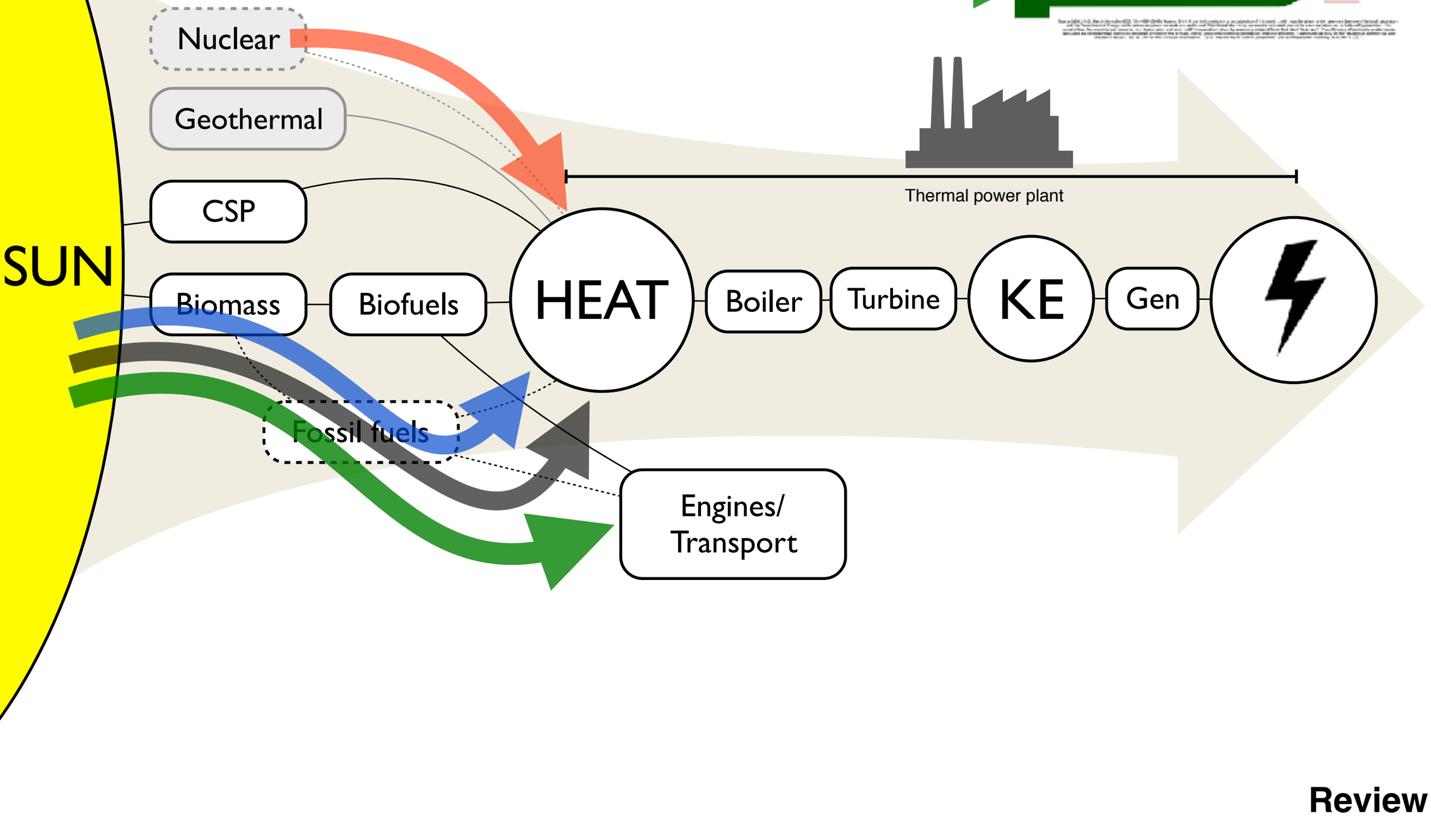
Review



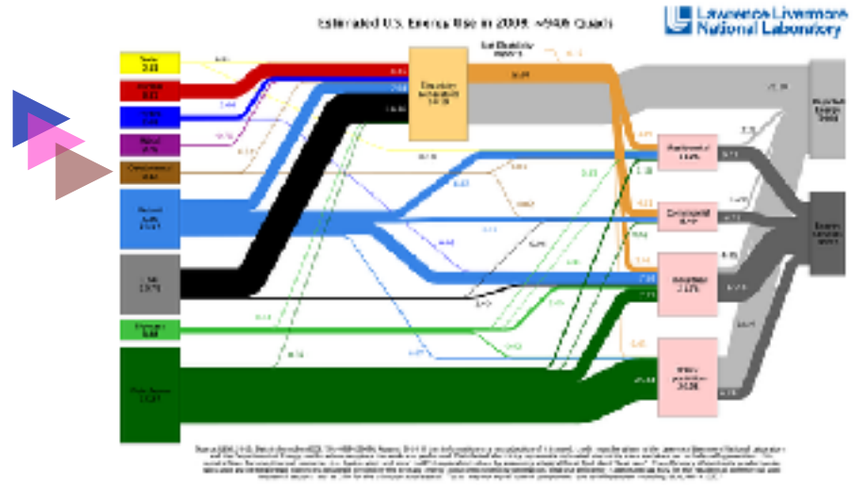


Review


Lawrence Livermore National Laboratory


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

Review



SUN

Tides

Weather

Hydro

Wind

Waves

Nuclear

Geothermal

CSP

Biomass

Biofuels

HEAT

Boiler

Turbine

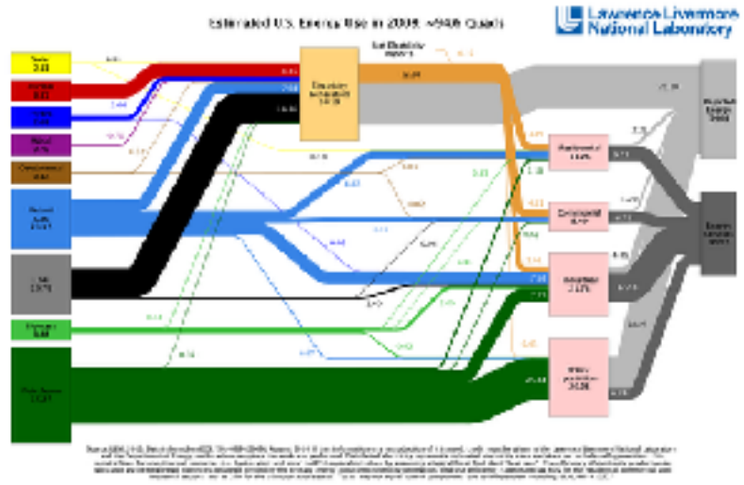
KE

Gen

Fossil fuels

Engines/
Transport

Review



SUN

Weather

Hydro

Wind

Waves

Tides

Nuclear

Geothermal

CSP

Biomass

Biofuels

Fossil fuels

HEAT

Boiler

Turbine

KE

Gen

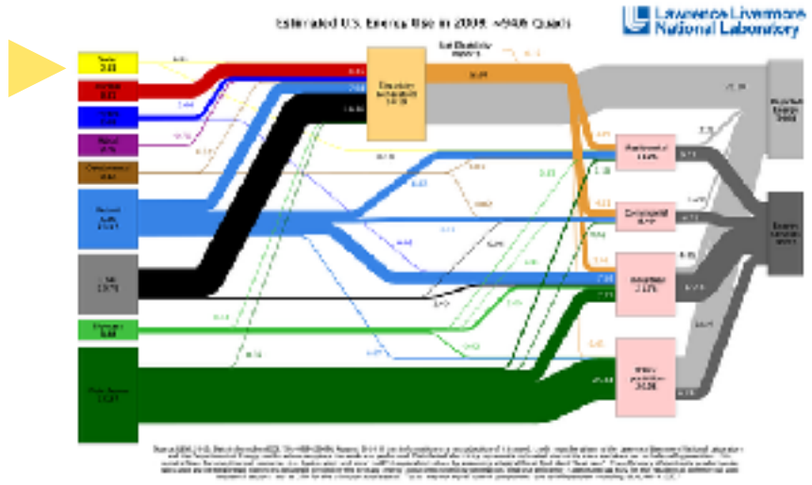
Chemical

Piezo

TC

Engines/
Transport

Review



SUN

Weather

Hydro

Wind

Waves

Tides

Nuclear

Geothermal

CSP

Biomass

Biofuels

Fossil fuels

HEAT

Boiler

Turbine

KE

Gen

Chemical

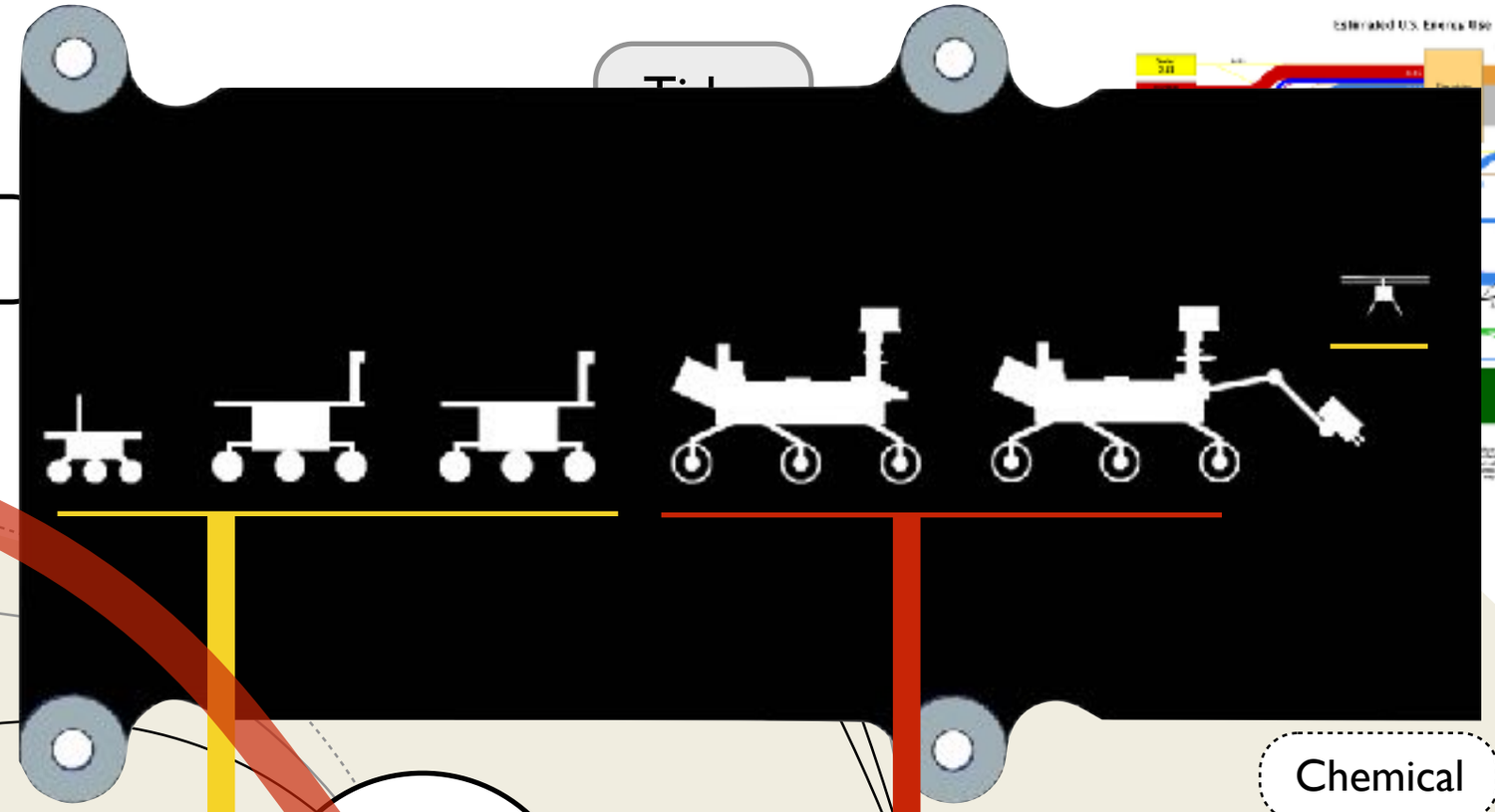
Piezo

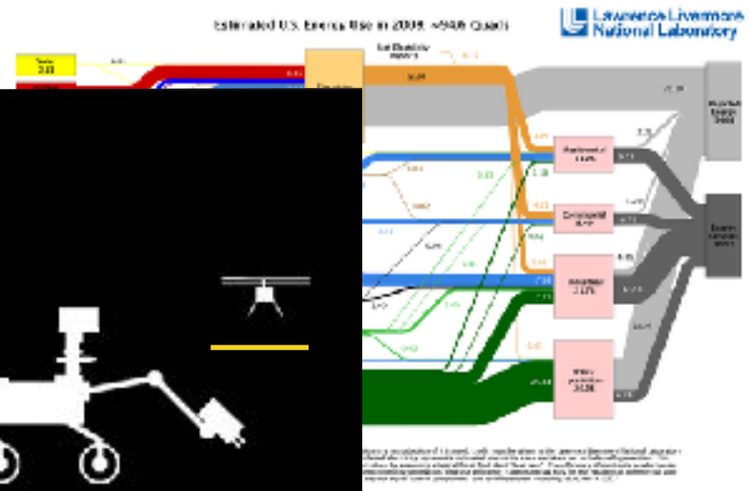
TC

Engines/
Transport

PV

Review





SUN

Weather

4.8kg Pu

Nuclear

Geothermal

CSP

Biomass

Biofuels

Fossil fuels

HEAT

Boiler

Turbine

KE

Gen

Chemical

Piezo

TC

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

Sojourner:
16W peak PV output

Spirit & Opportunity:
140W peak PV output

Curiosity & Perseverance

110W constant
electrical output + heat
Multi-Mission Radioisotope
Thermoelectric Generator

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 x 10^{26} Watts (385 yottawatts!)

Solar constant in space at Earth locale:

1368 W/m² ← Remember this number!

Global solar power:

87 PW (~7000x fossil fuel use)

IMMENSE POTENTIAL BUT…

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/m² ← Remember this number!

Global solar power:

87 PW (~7000x fossil fuel use)

IMMENSE POTENTIAL BUT…

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

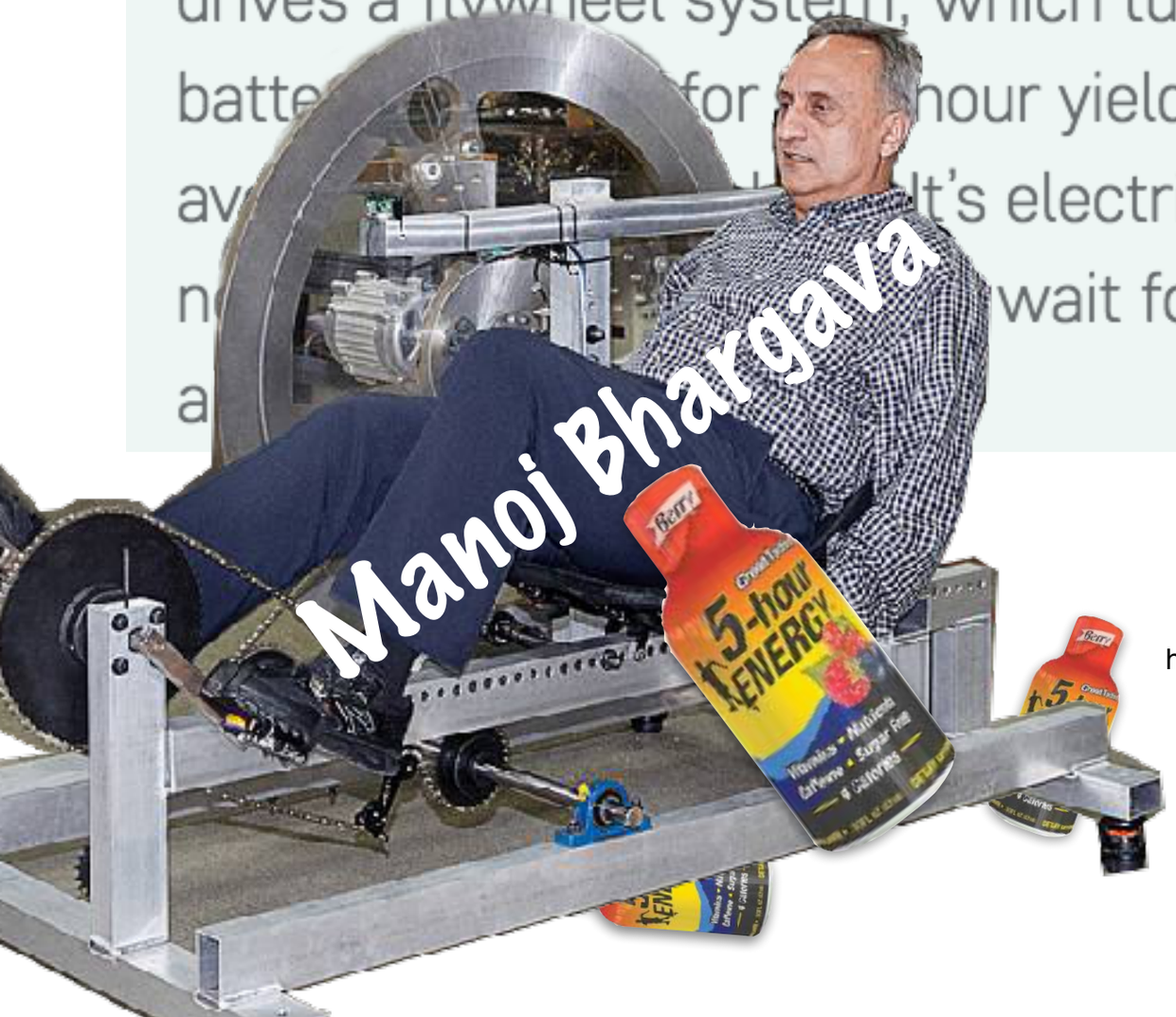
BUT REALLY . . . SOLAR

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 lt'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

GLOBAL TRANSFORMATION

2018

BUT REALLY . . . SOLAR

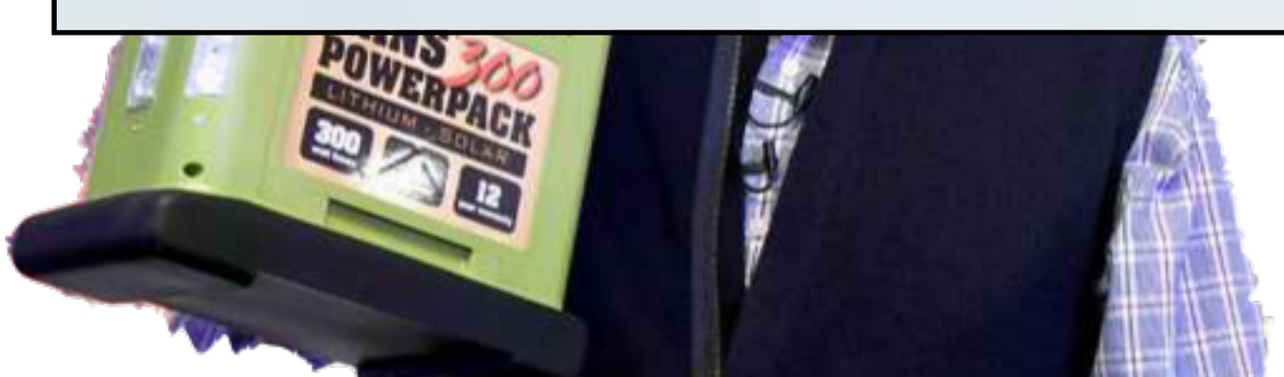
HANS™ SOLAR BRIEFCASE

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.

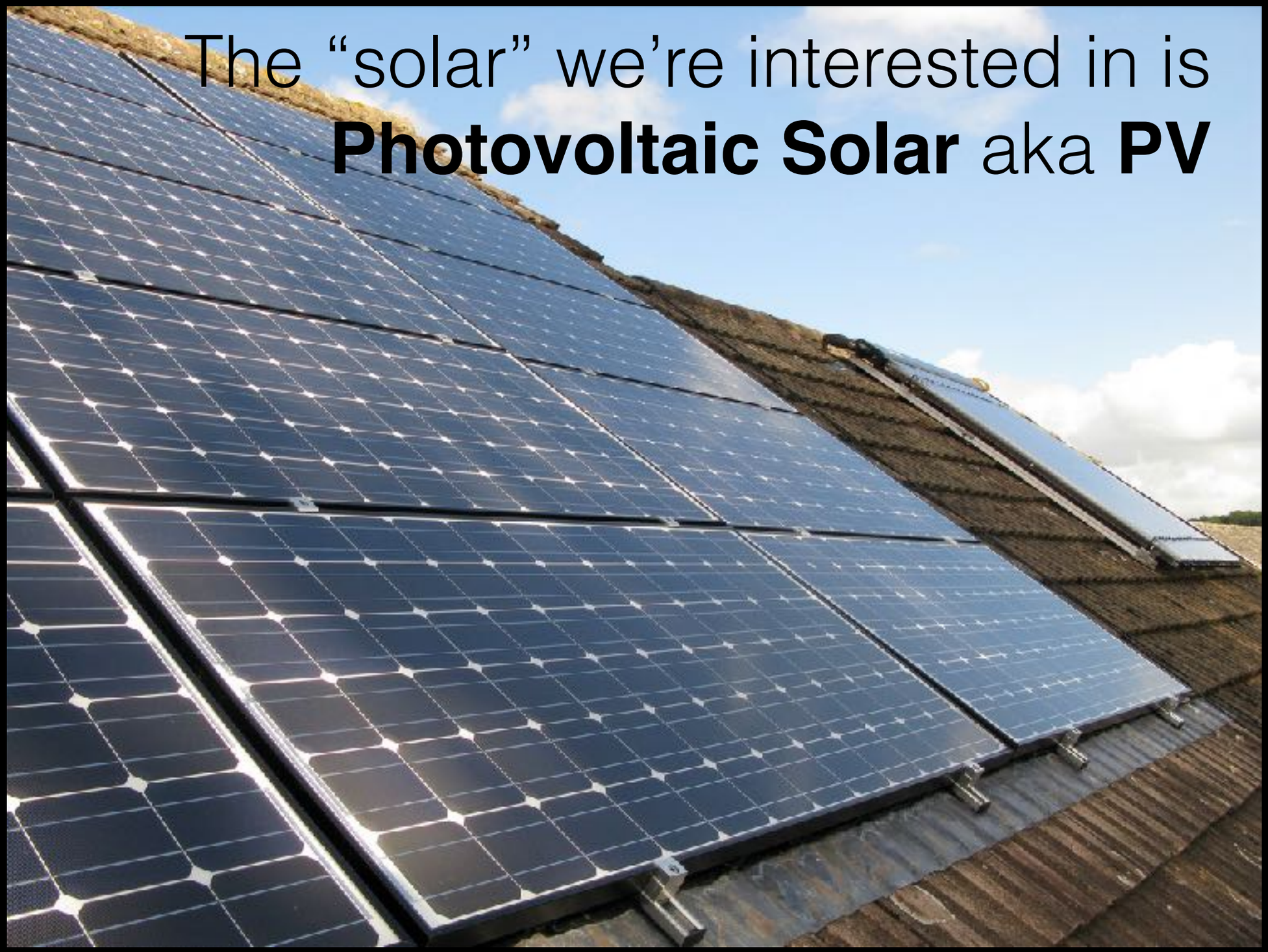
However, after multiple field tests showed that the bike needed modifications, as did the battery, Stage 2 went back to the drawing board. Through the process of making these improvements, two completely new inventions emerged. The HANS™ PowerPack and HANS™ Solar BriefCase quickly leapfrogged the bike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



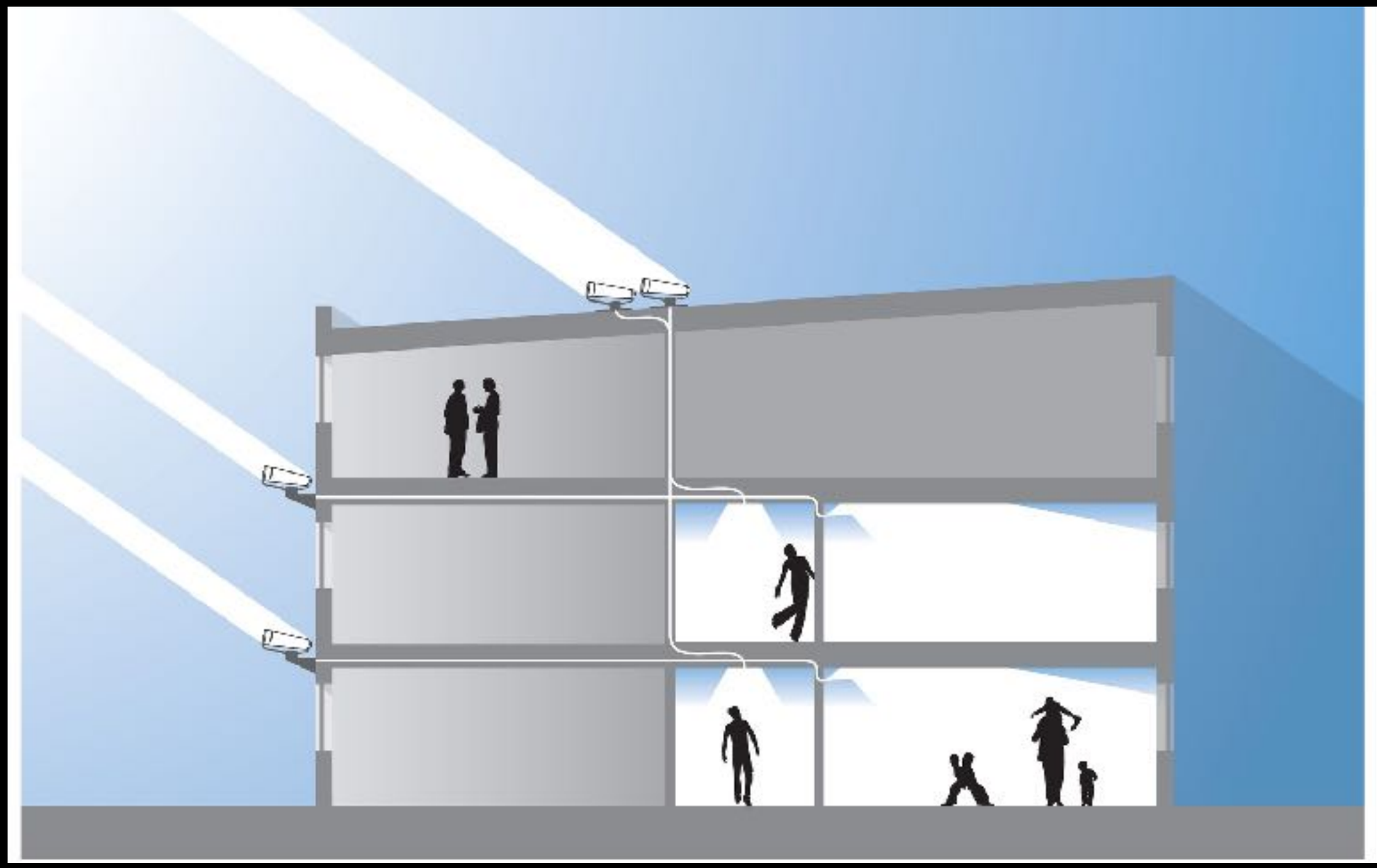
GLOBAL TRANSFORMATION

WHAT IS SOLAR?


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

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

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

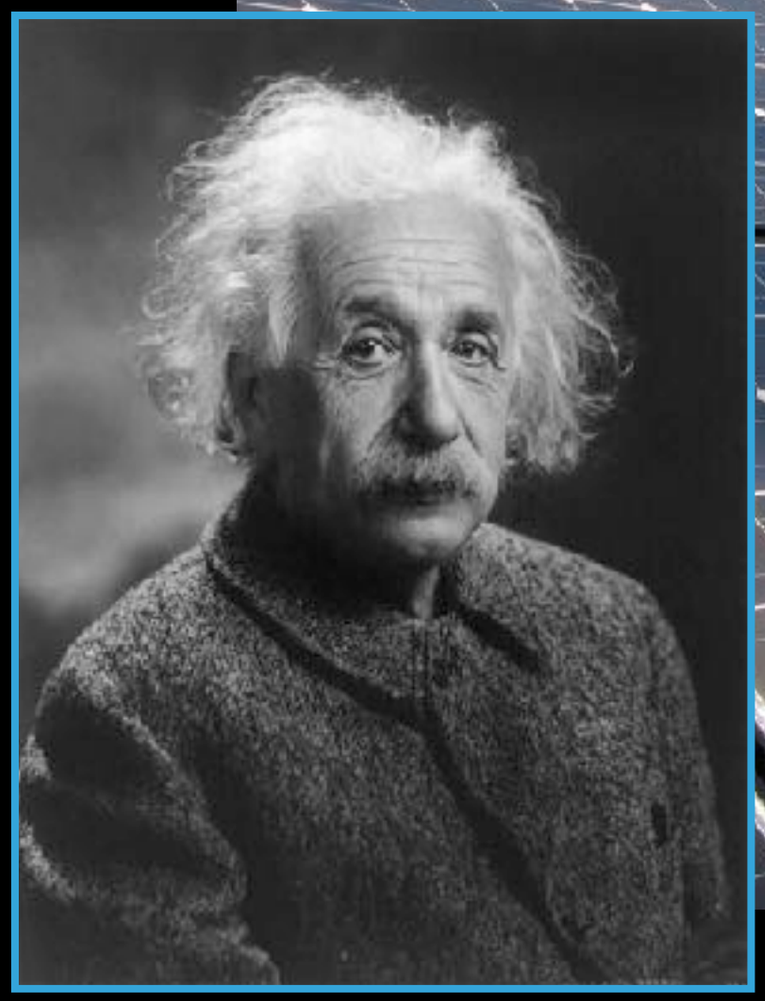


Parans

(Not indirect solar lighting, heliostats, etc…)

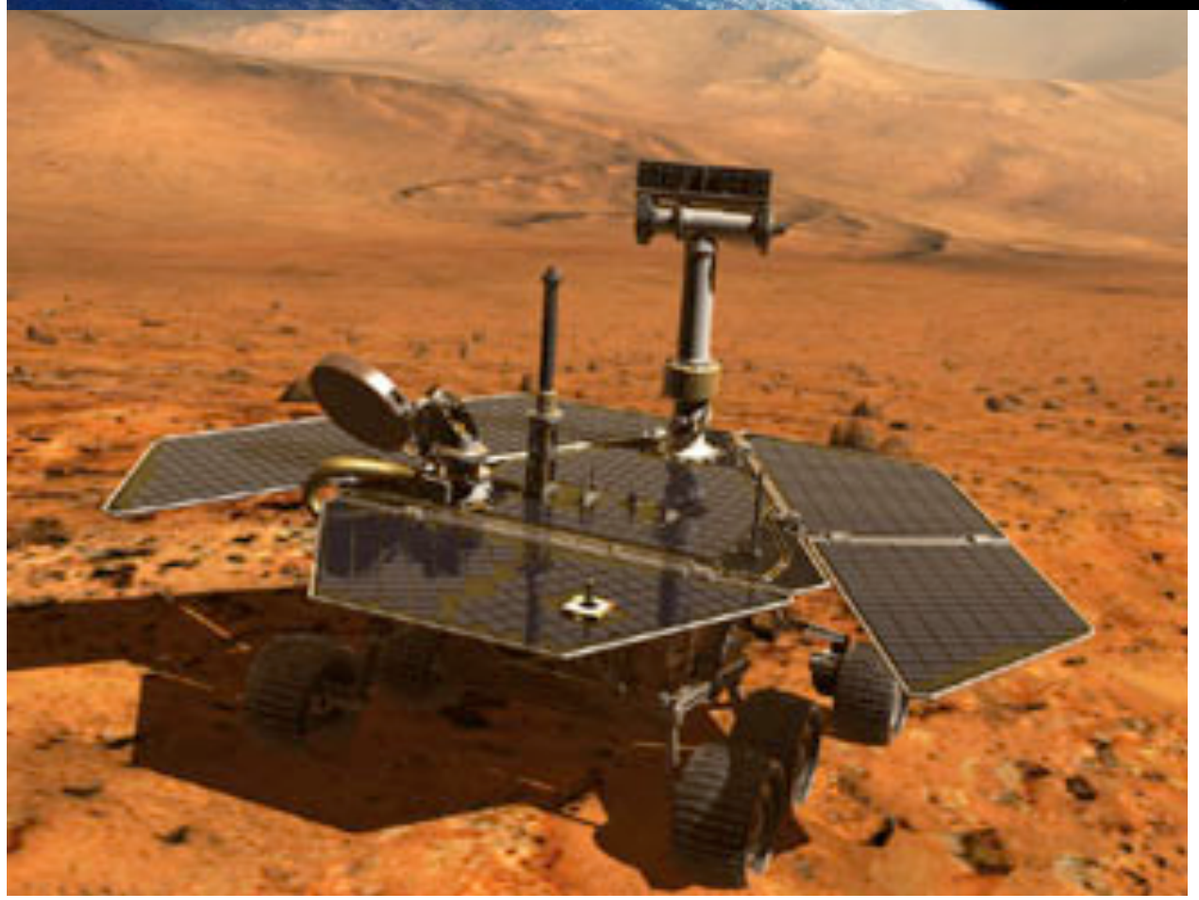
The “solar” we’re interested in is **Photovoltaic Solar** aka **PV**

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/



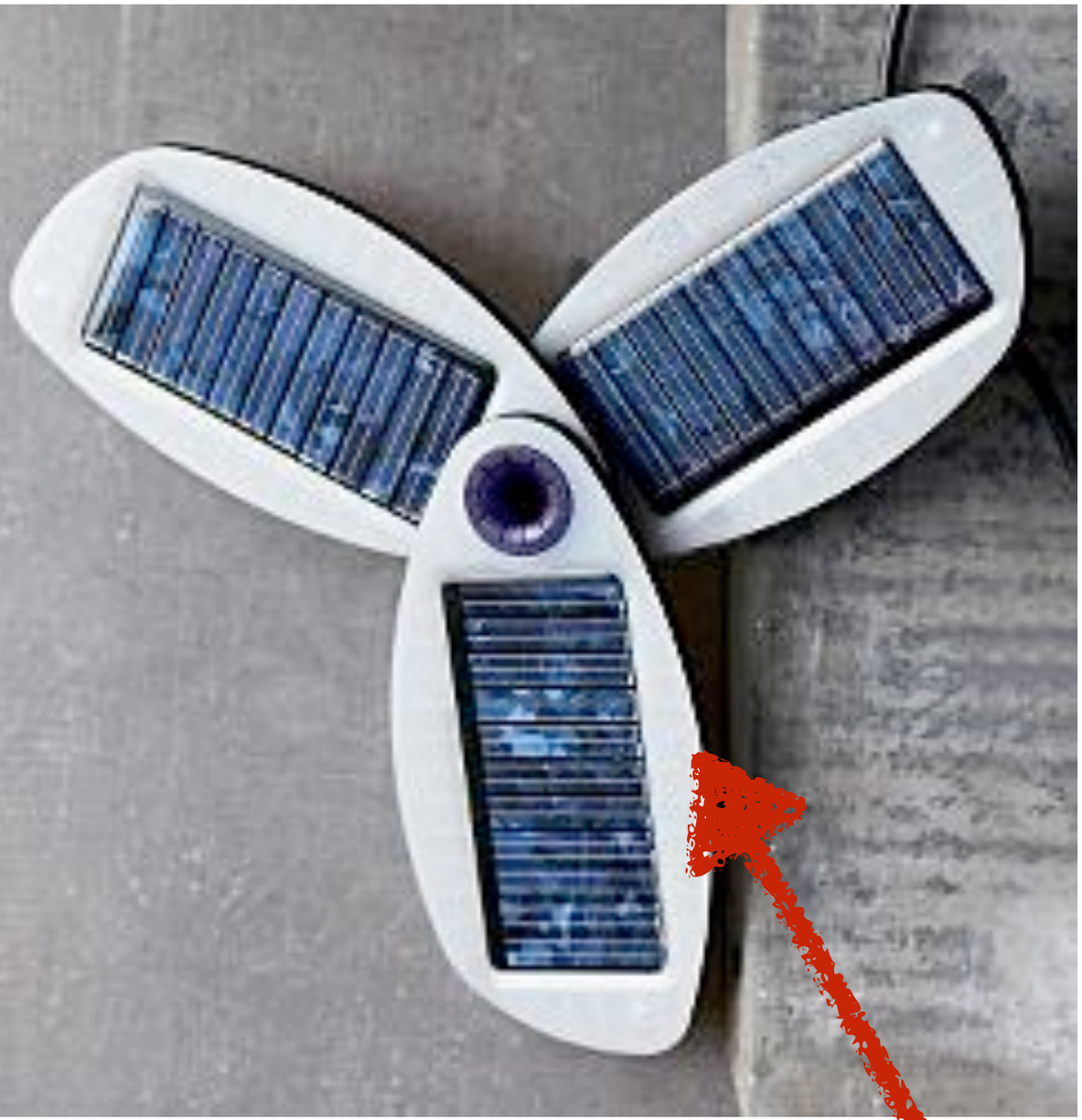
PV works everywhere!
Enabling technology for telecom and space exploration

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

Terrestrial applications

Overview

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

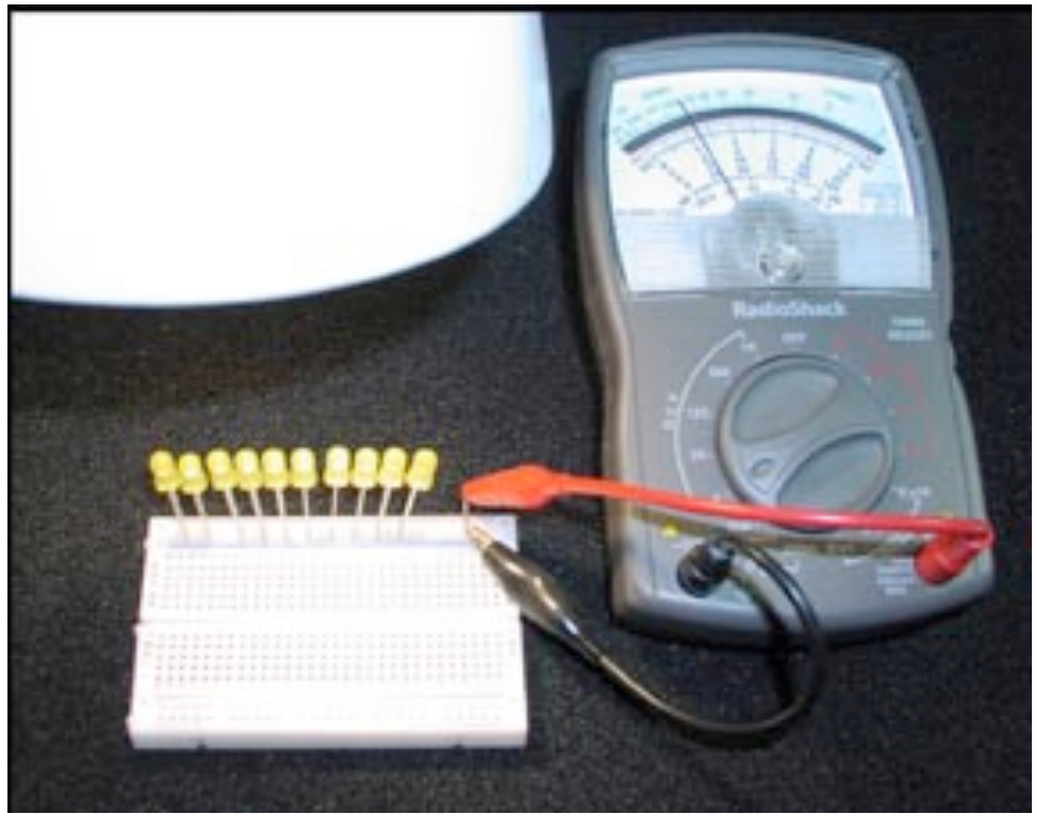


THE SAME STUFF!!!

Small and large commercial applications

HOW DOES SOLAR WORK?

All PV is similar in that:

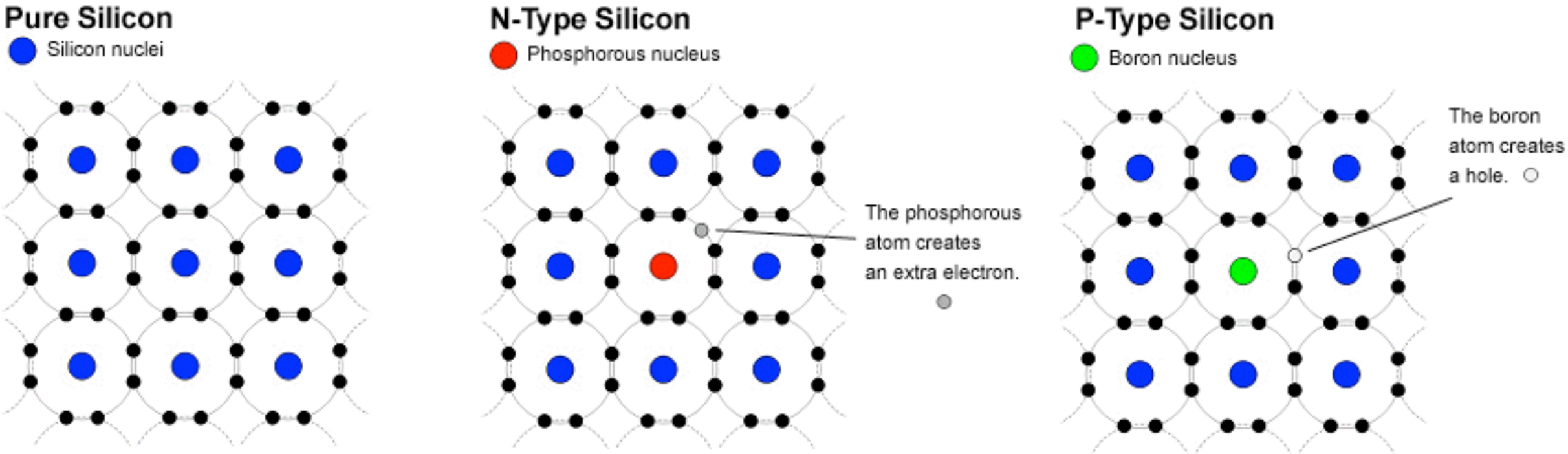


Photovoltaic materials directly convert light into electricity.

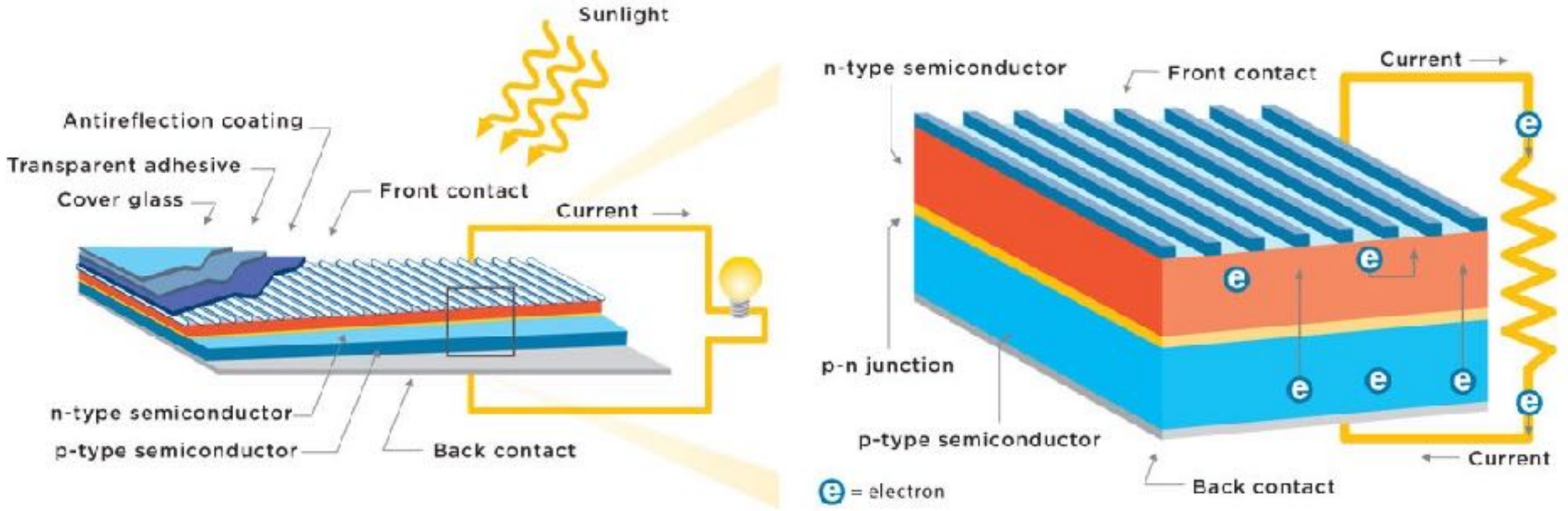
Most semiconductors (including LEDs) do this to some extent.

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

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

Cell

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

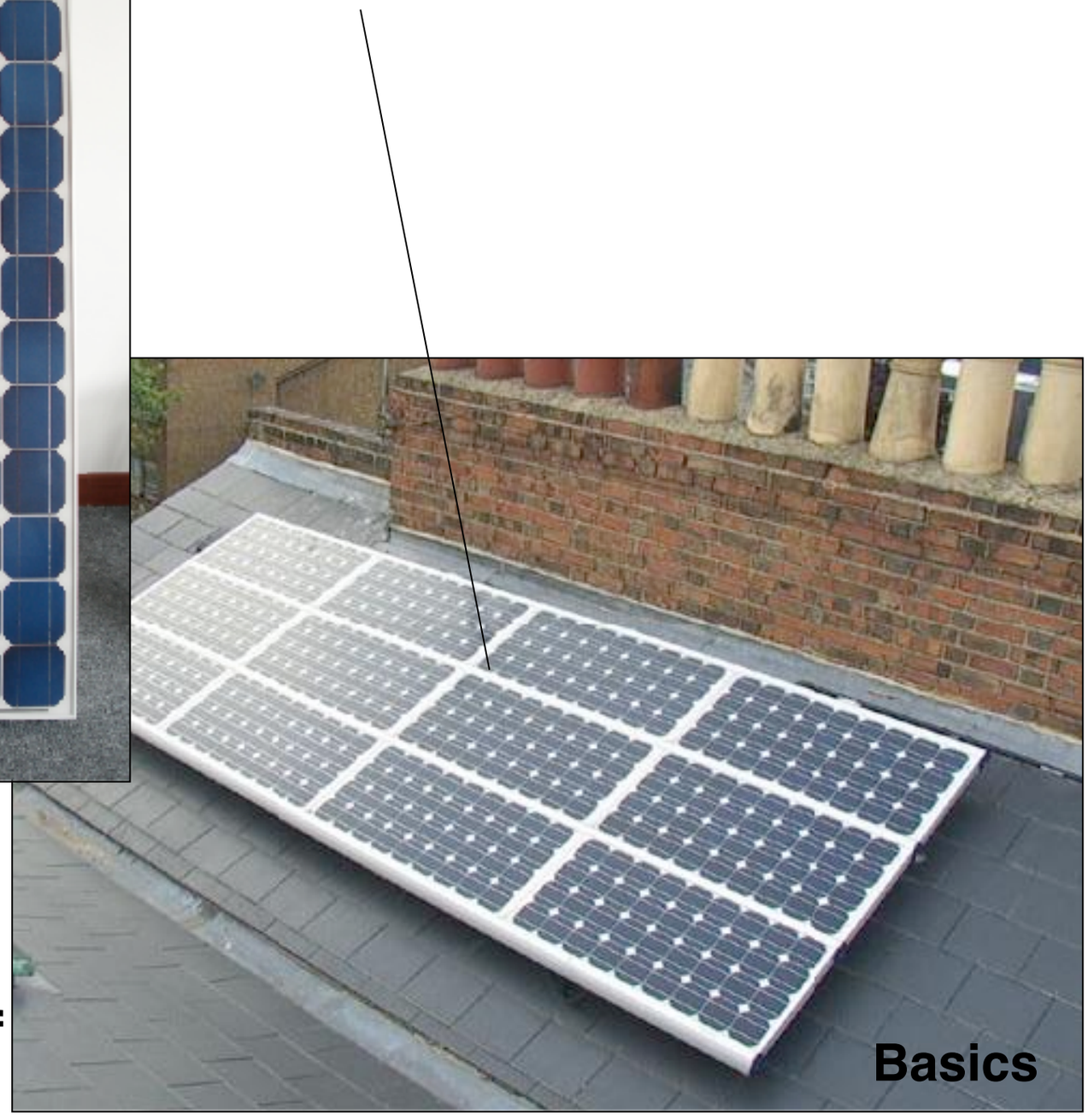
Module: group of cells

Array: group of modules

Cell

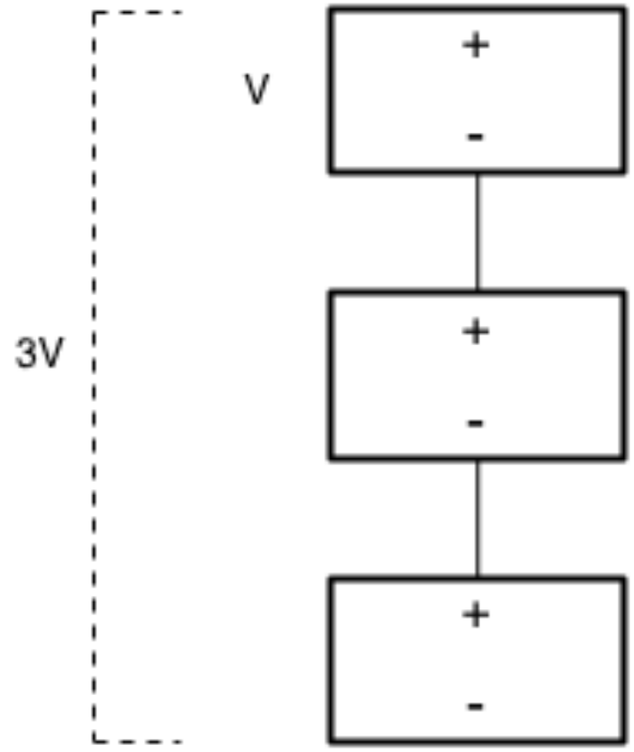
Module: group of cells

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



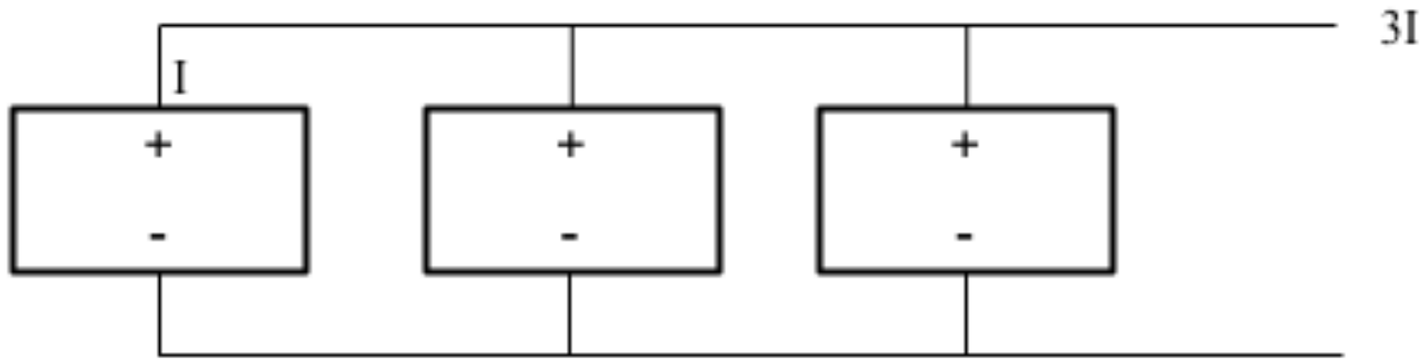
Array: group of modules

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



(Cell or module)

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

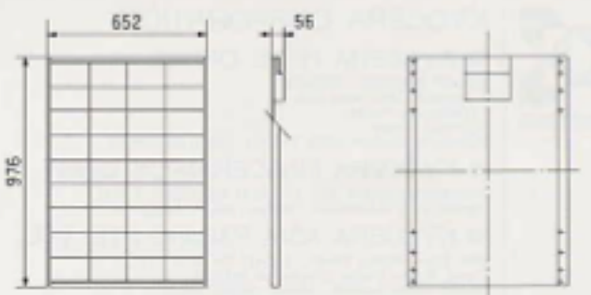
SP

■ 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

Kyocera reserves the right to modify these specifications without notice.



"Nameplate capacity"

=

80W

Basics

DIFFERENCES

Different types of PV are distinguished by:

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

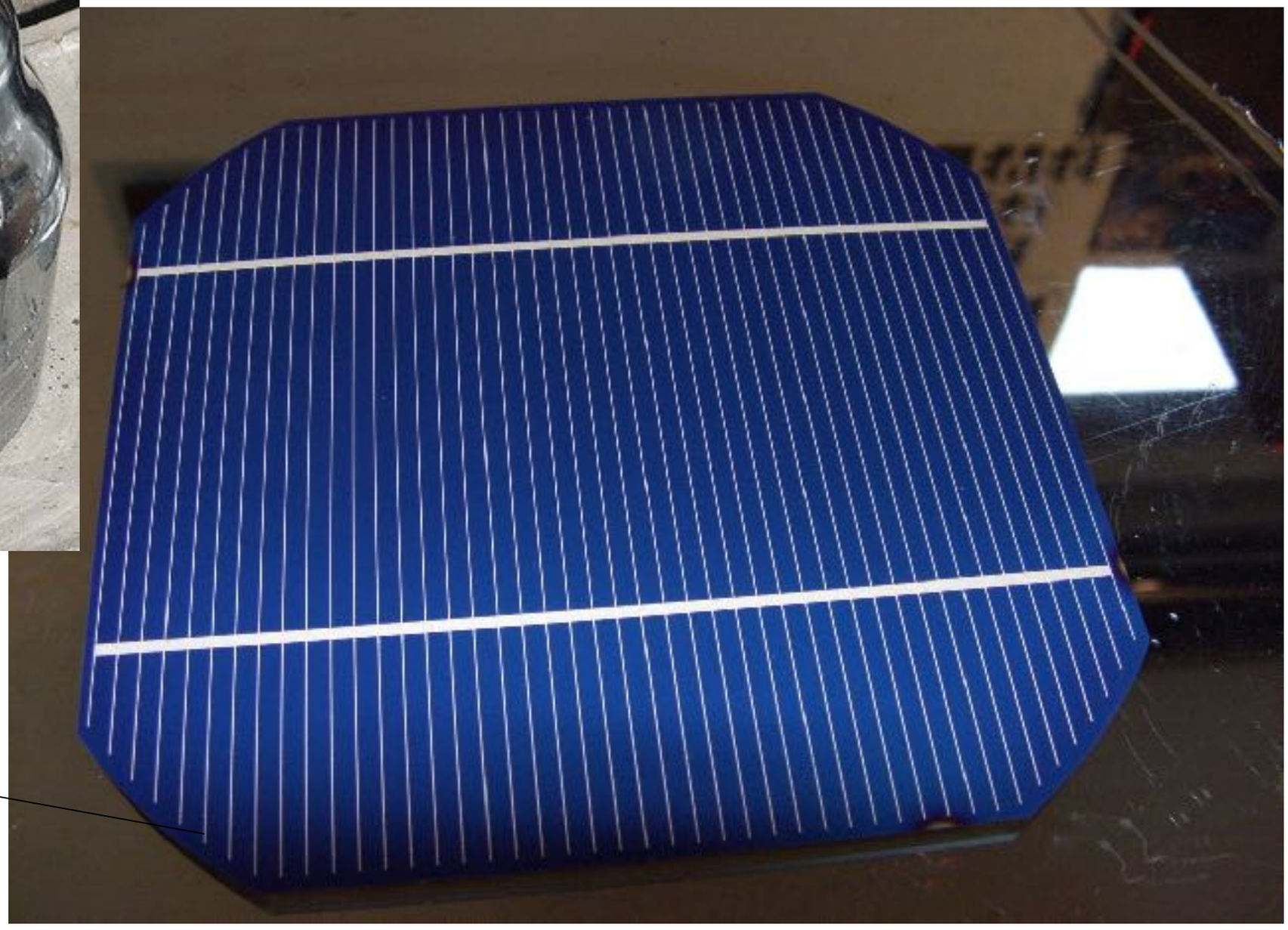
- Type of material (Si vs. CIGS vs...)

- Number of layers (“junctions”)

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

Differences

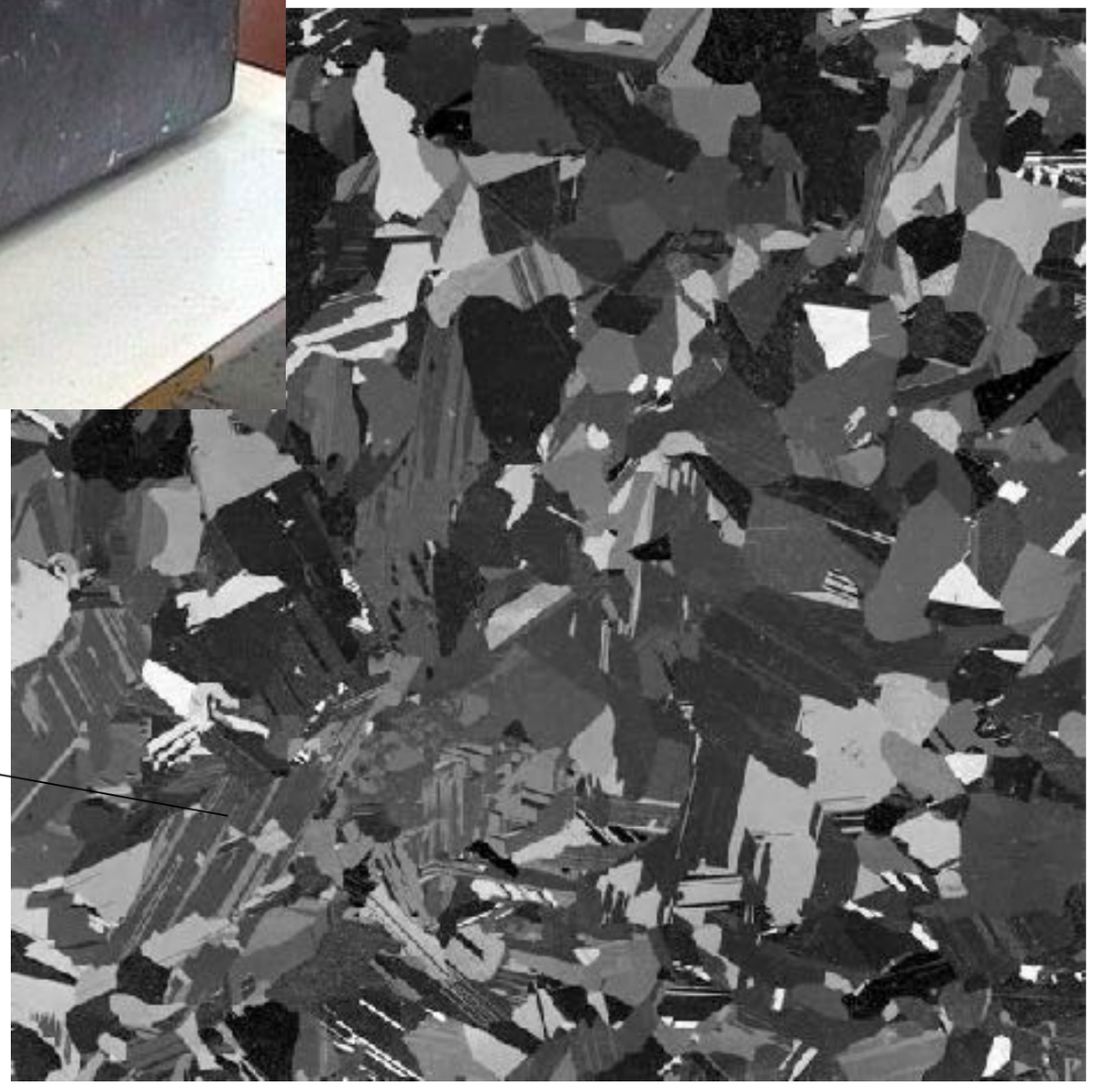
Mono-crystalline Si ingot and cell



Circa 300 um thick
Si layer

Differences

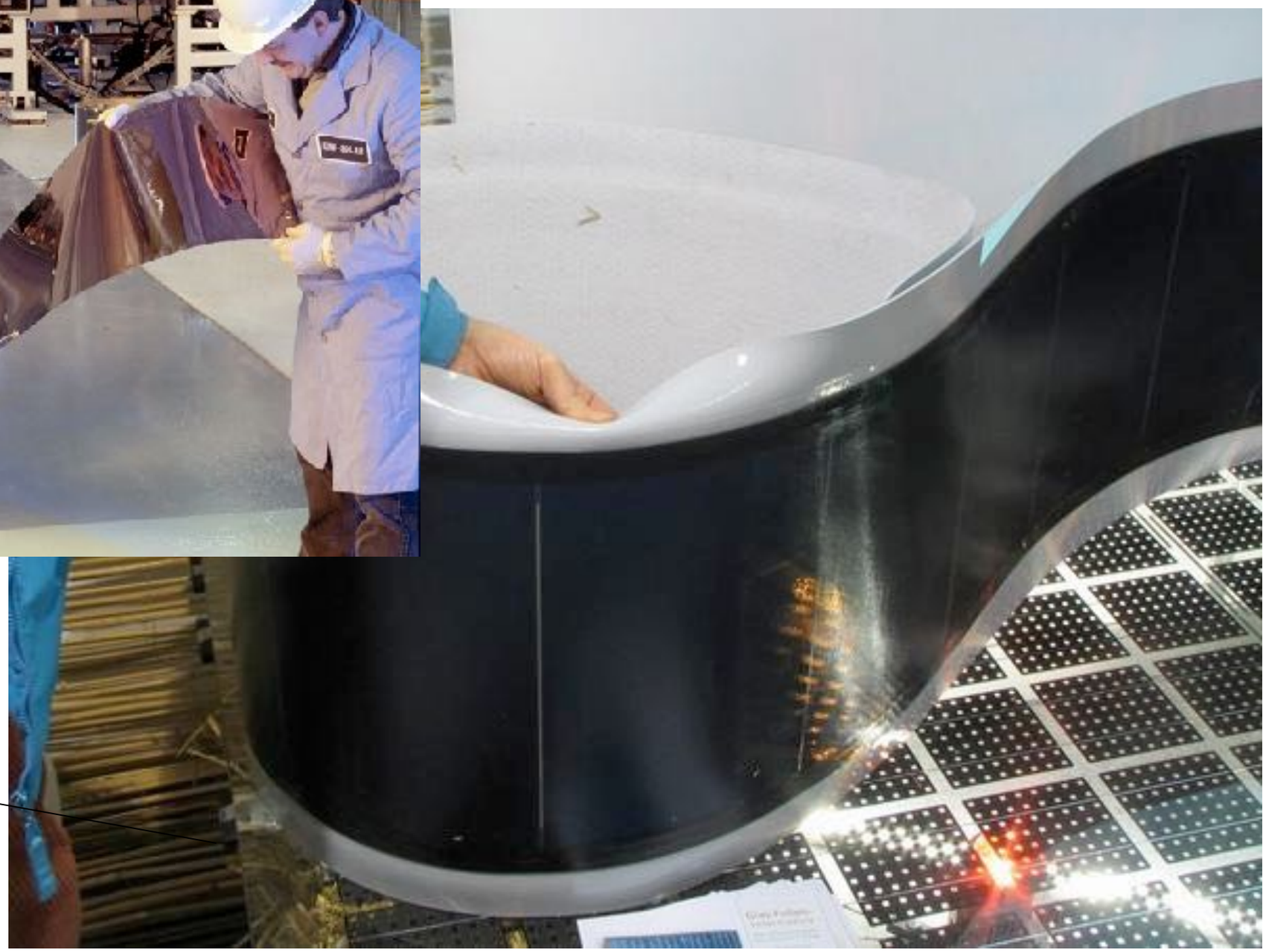
Polycrystalline Si
ingot and cell



Circa 300 um thick
Si layer

Differences

Amorphous or thin film PV

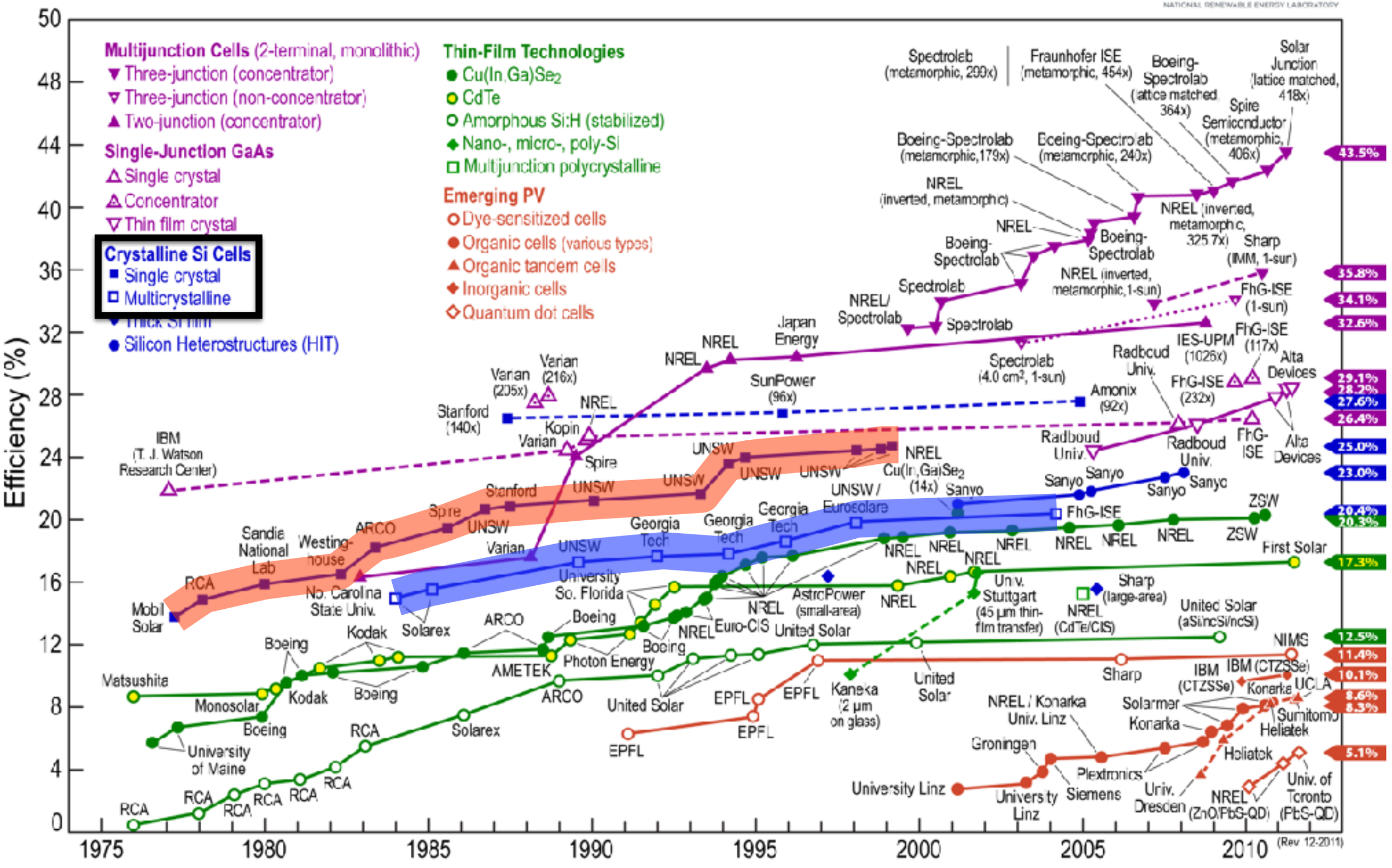


Circa 30 um thick
Si layer

Differences

Best Research-Cell Efficiencies

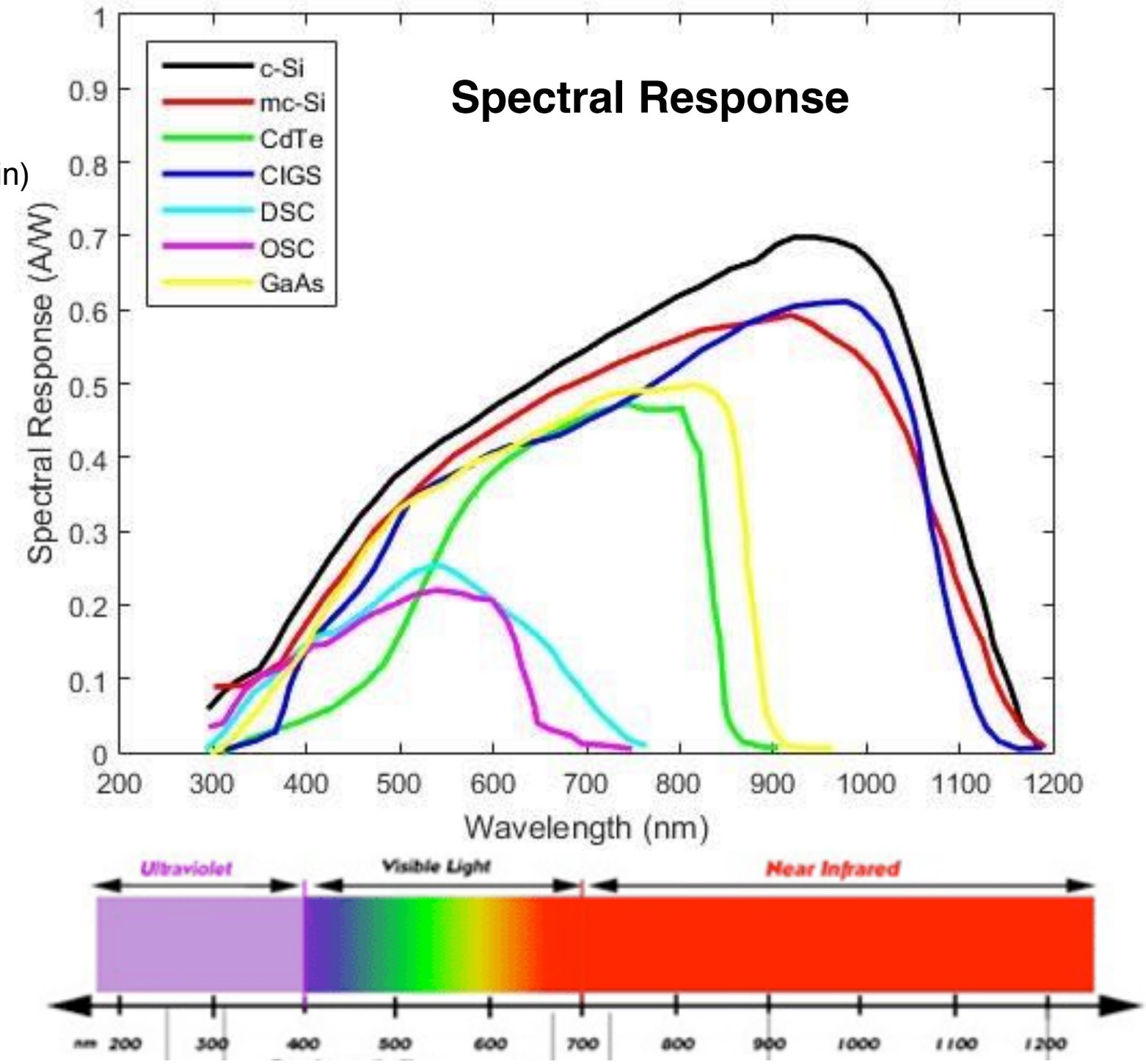
NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Source: DOE NREL

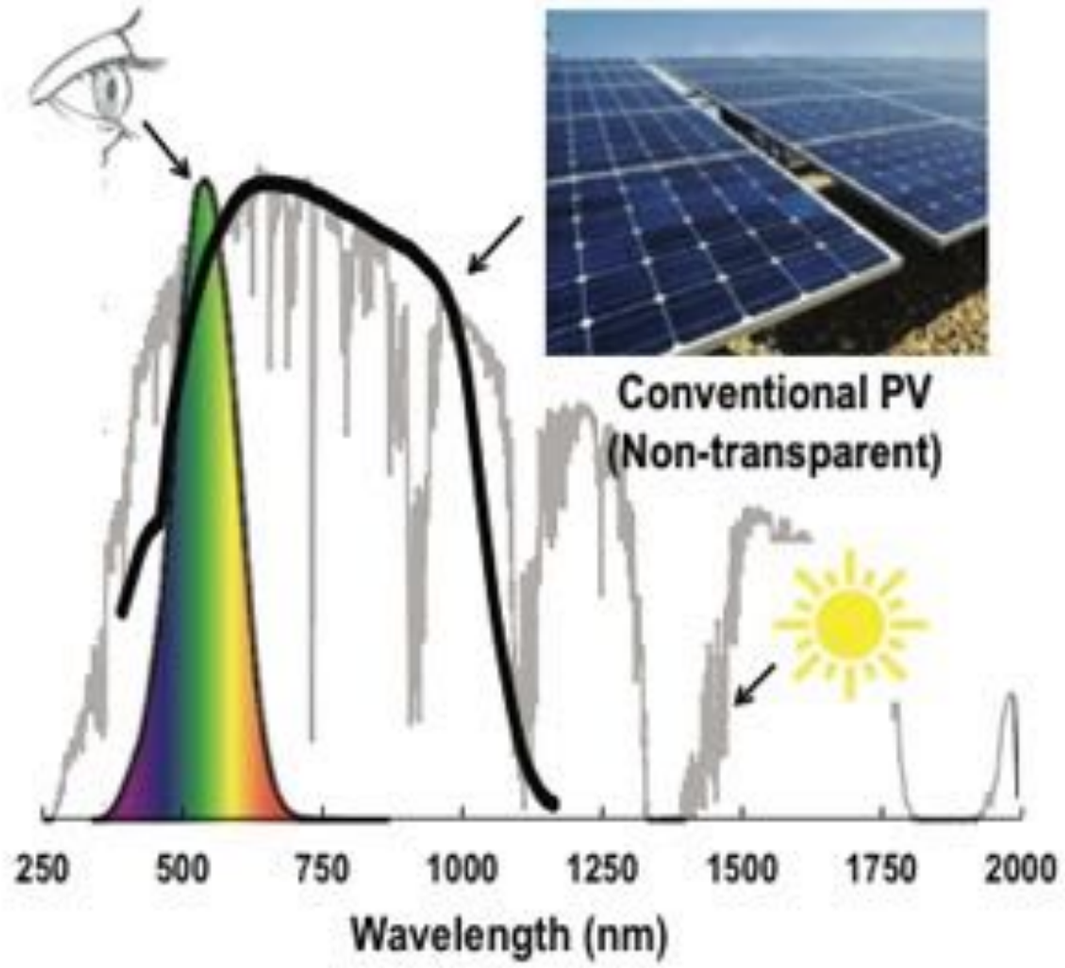
Differences

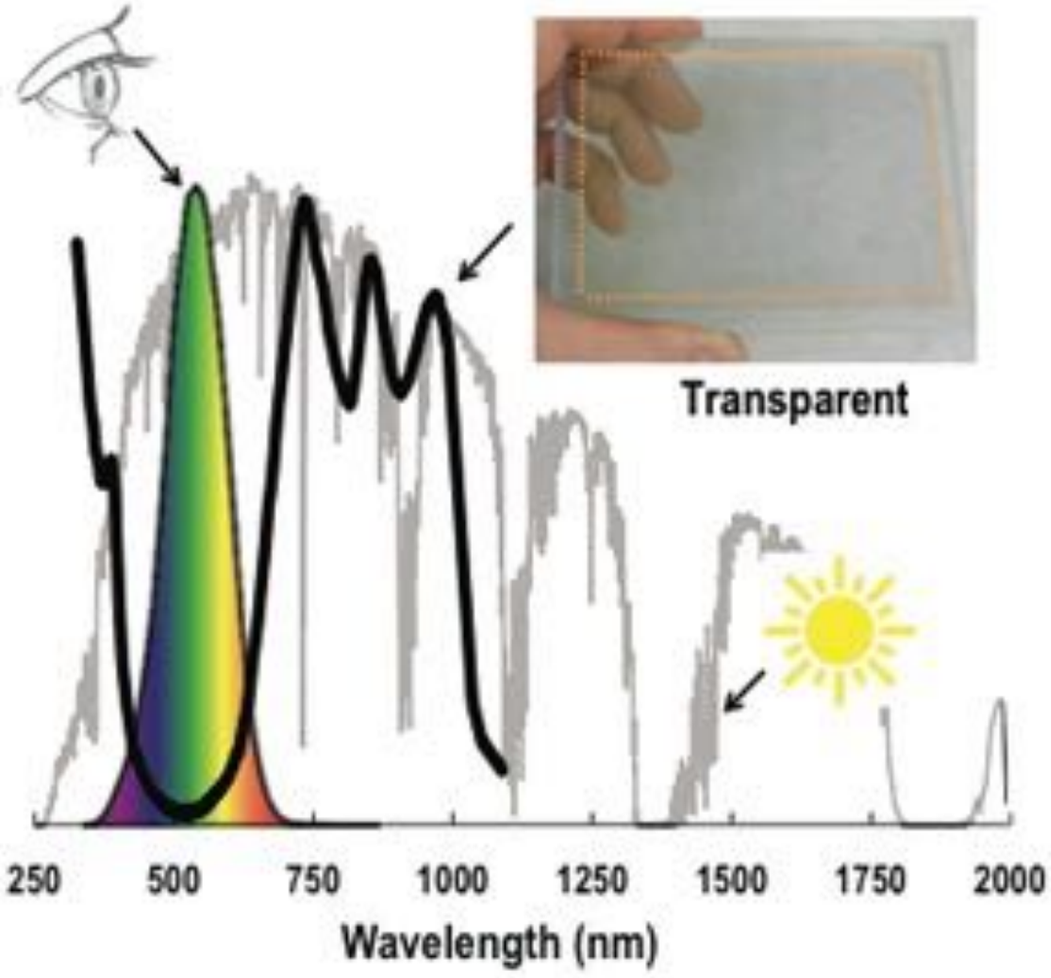
(Mono) Crystalline Si
Multi-crystalline Si
Cadmium Telluride (thin)
Copper-Indium-Gallium (thin)
Dye-Sensitized
Organic
Gallium Arsenide



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

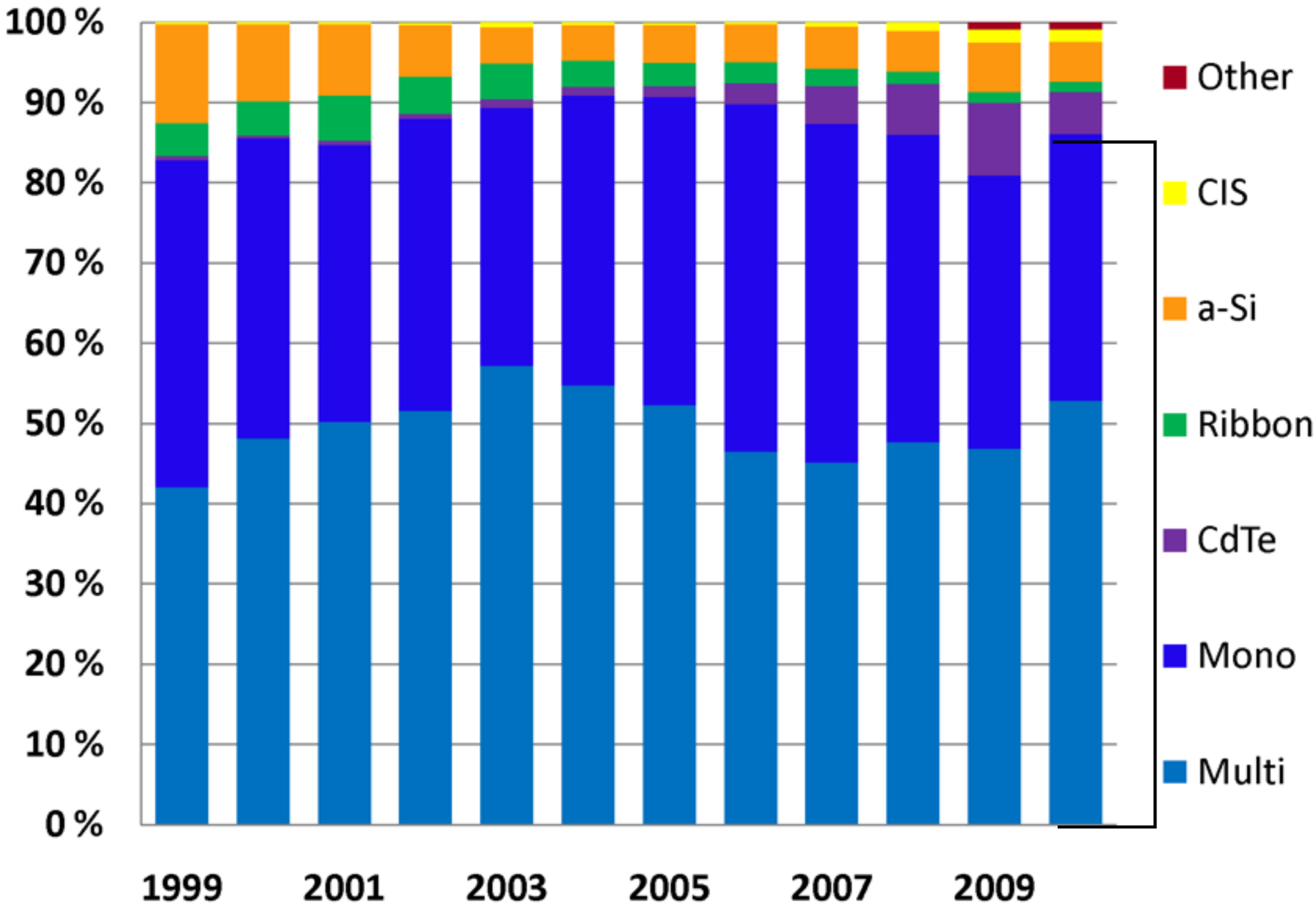
Differences



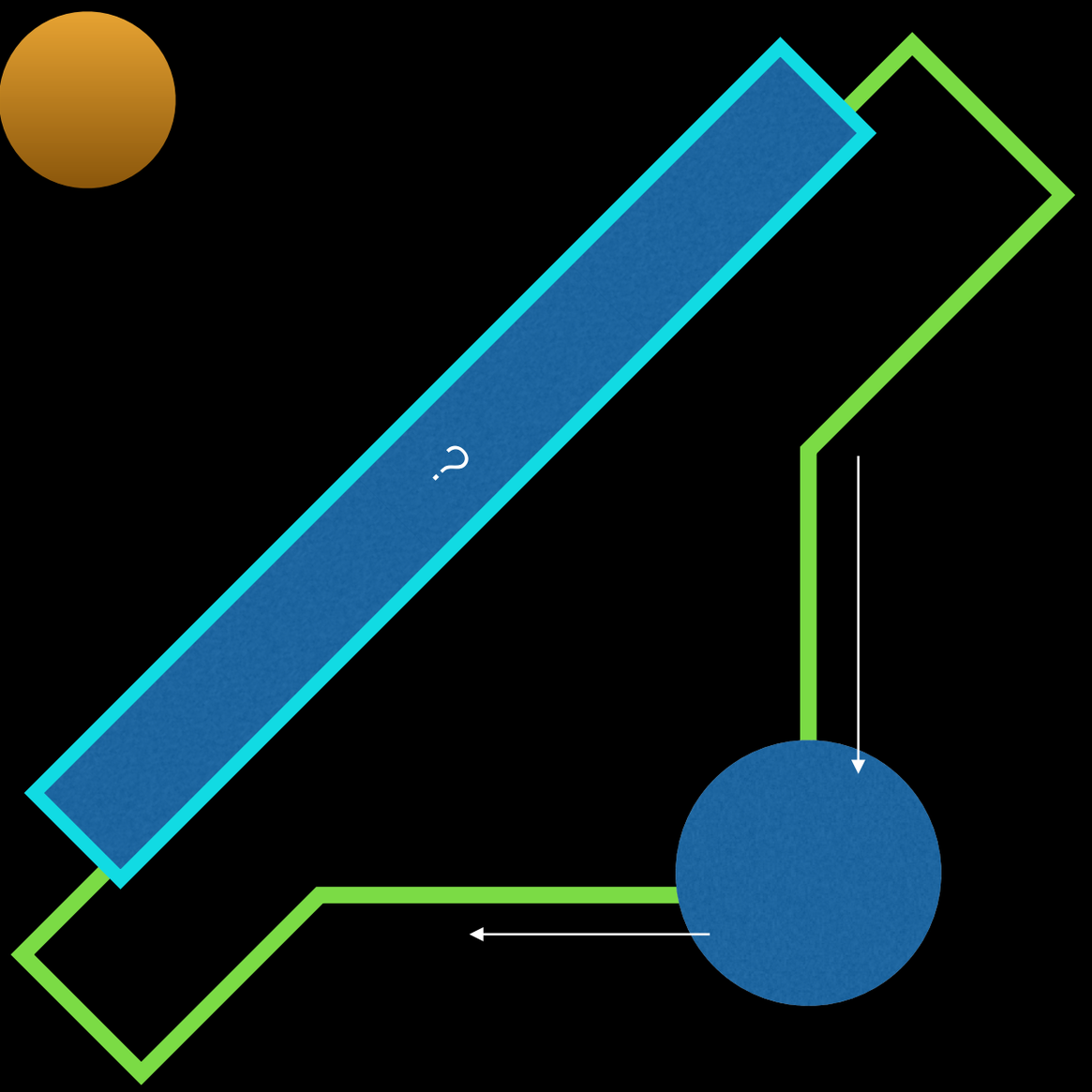


source: http://energy.mit.edu/news/transparent-solar-cells/

Differences

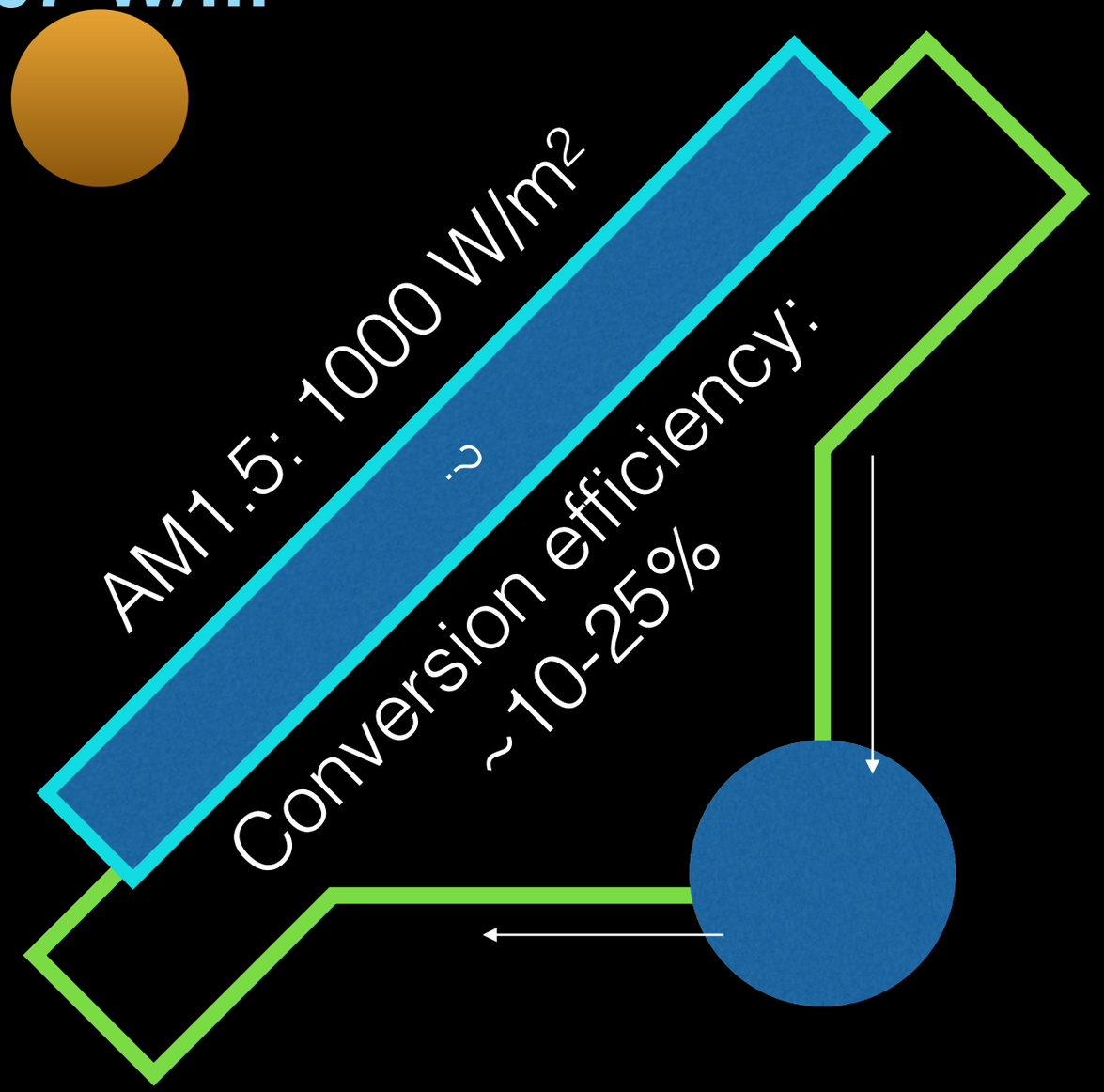


Source: Cleanenergy



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

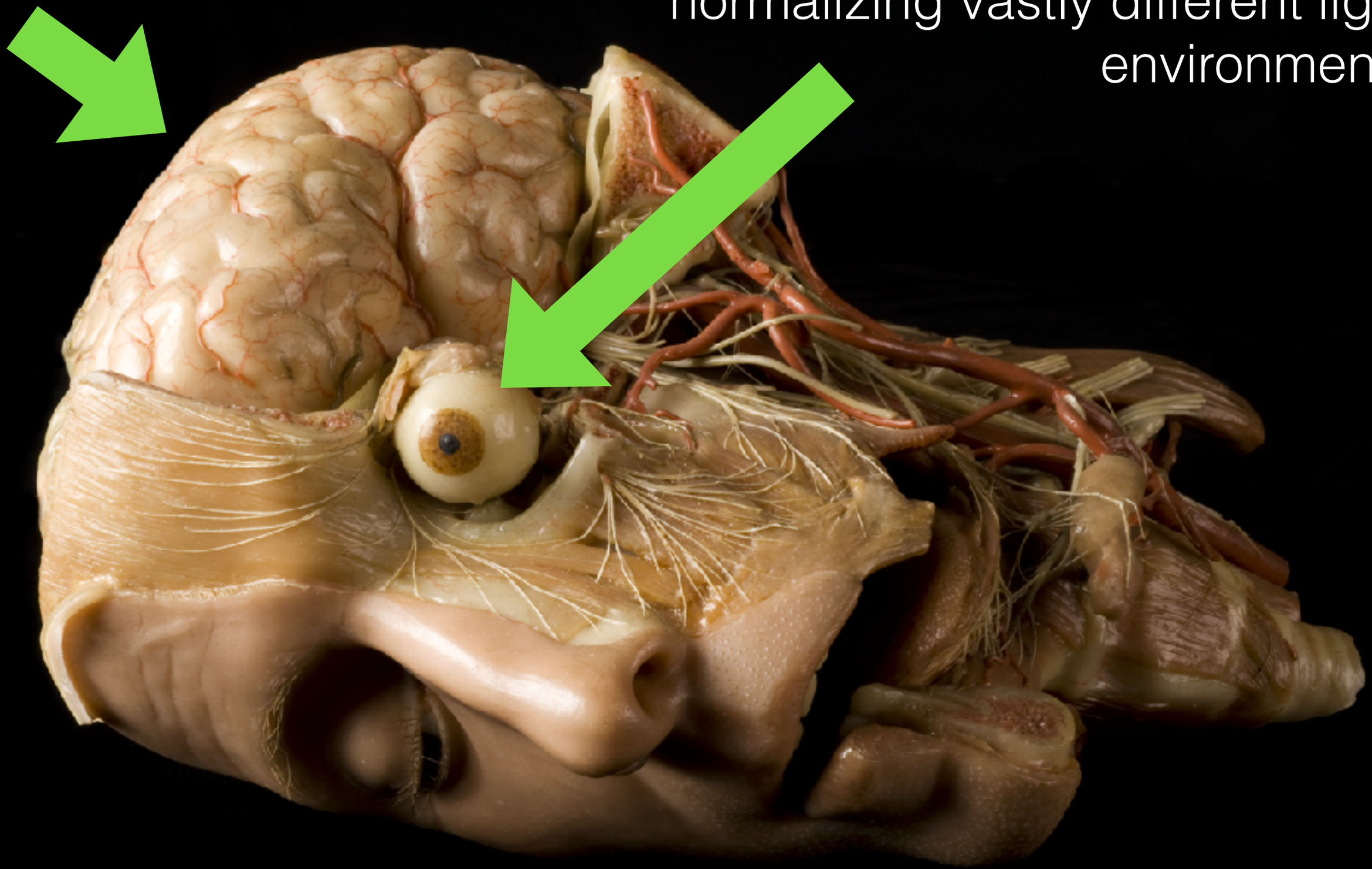
Random solar panel from
www.solar-electric.com
AXITEC AC-290M/156-60S

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 <u>wild</u>!

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

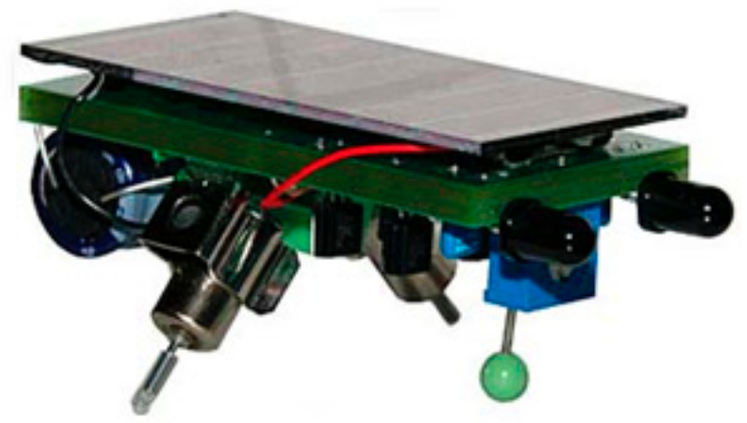
Differences

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.



B.E.A.M.

Feddersen

“Trimet Solar Engine” type

<1W

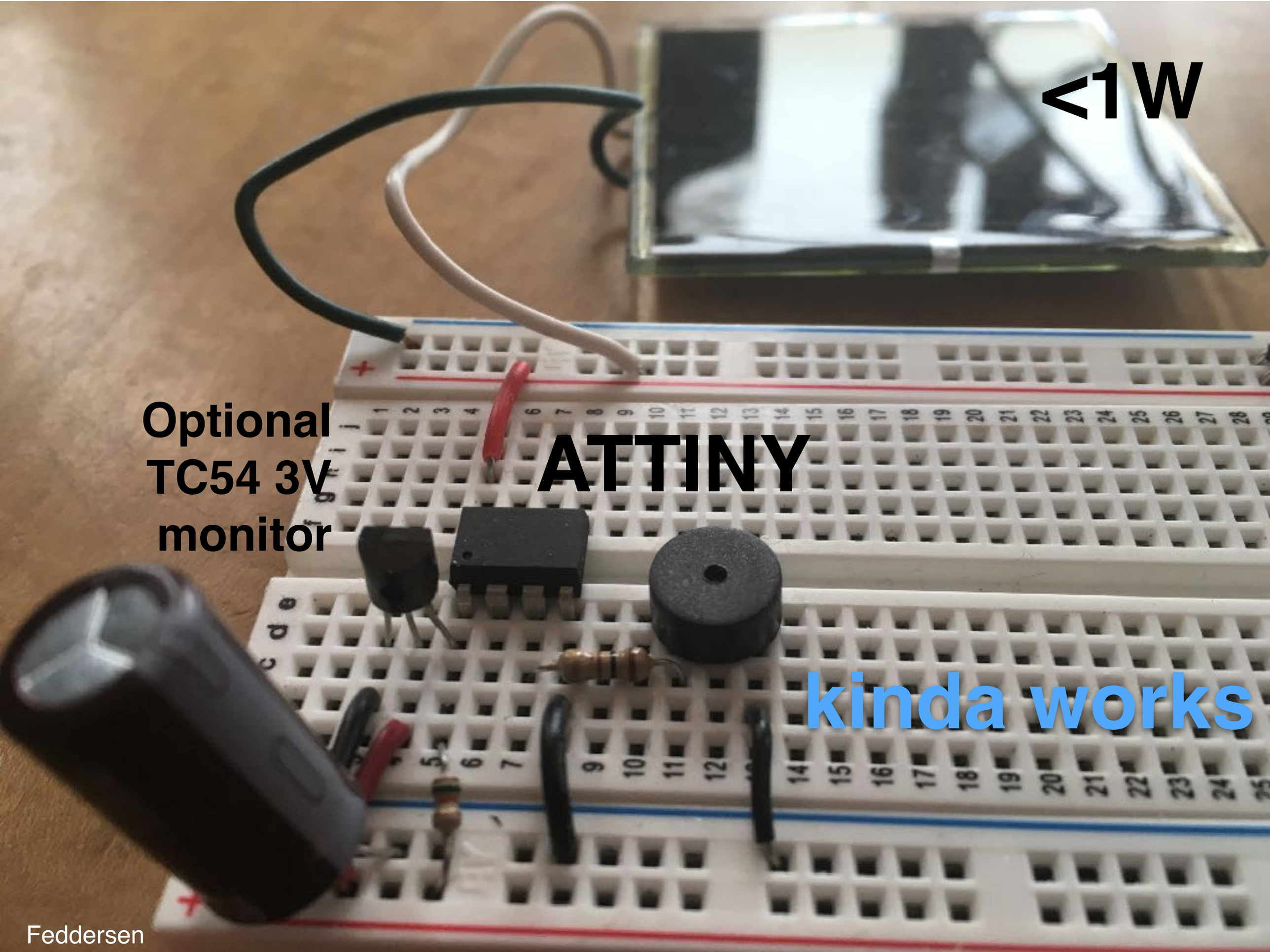
Mohit Bhoite: https://www.bhoite.com/

<1W

Super simple

Solar + microcontroller

Optional: Capacitor; manual reset (not shown - button) or voltage trigger reset eg TC54



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.

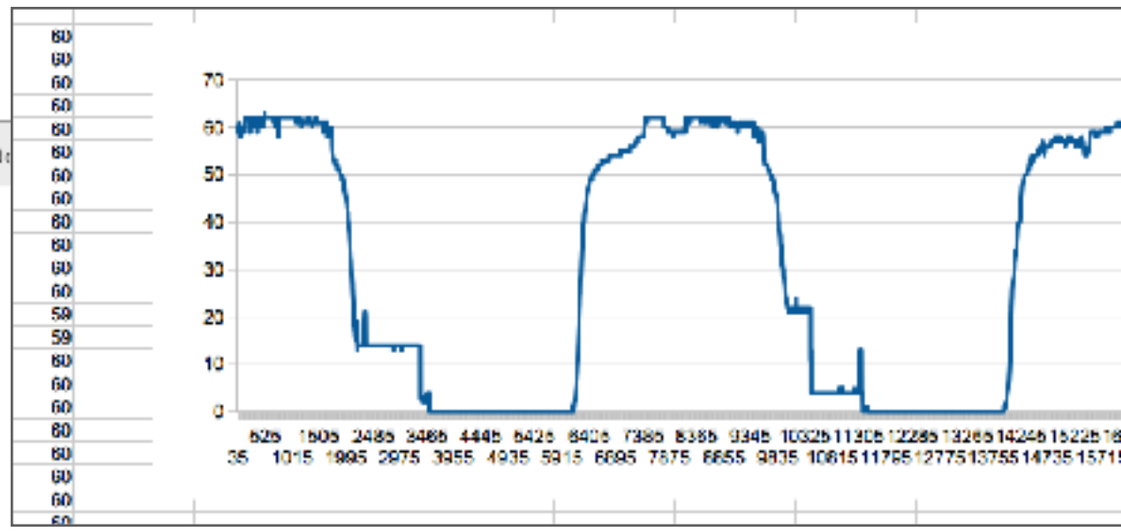
DataLogger1 | Arduino 1.6.8

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]");
  capacity = flash.
  if(!capacity) erro
```

/dev/cu.usbserial-A800cCDM

```
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
60
60
59
59
60
60
60
```



1-10W

Size: Small to Medium

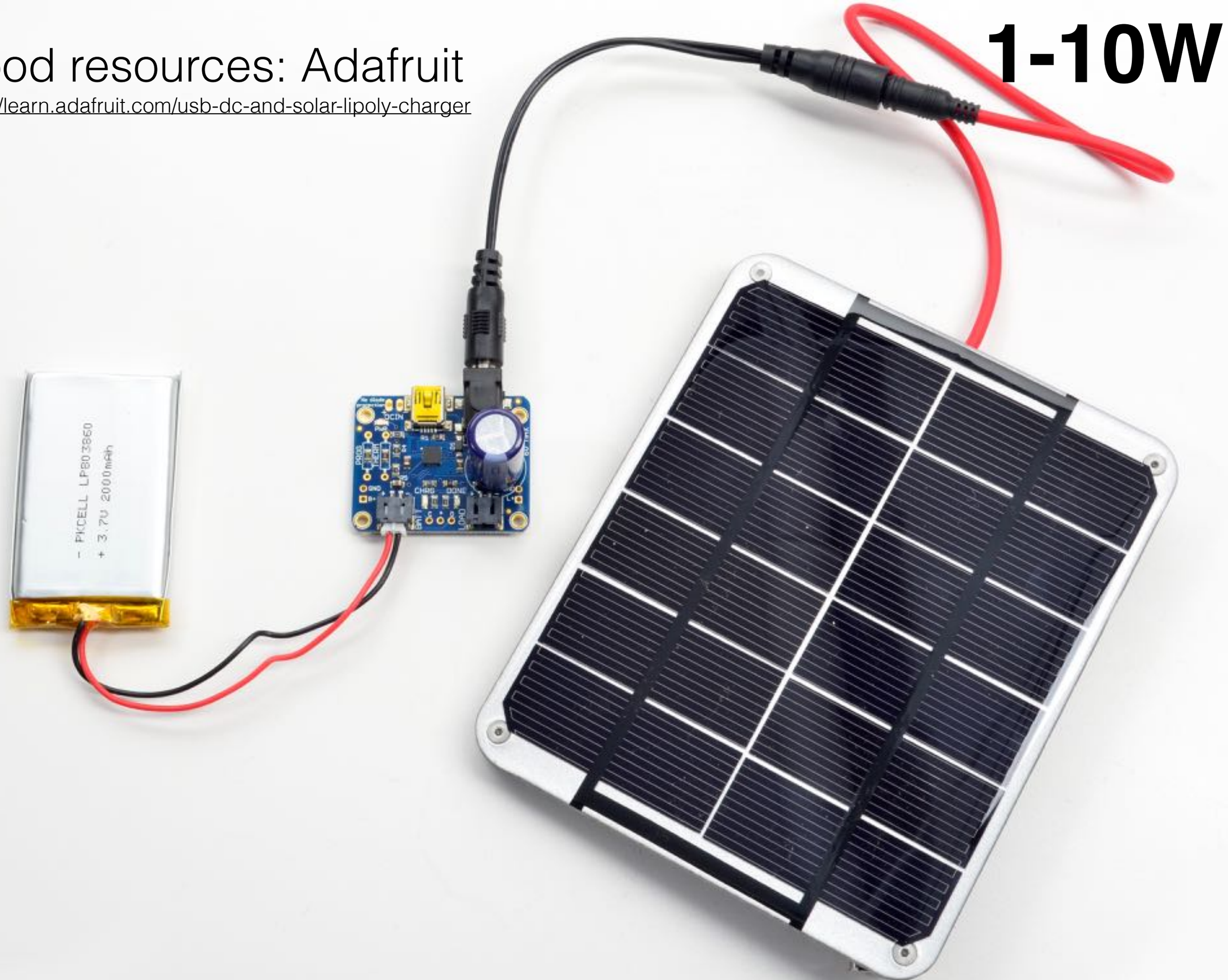
Can you directly power what you want? See SolaSystem amplifier from class notes.

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.

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)

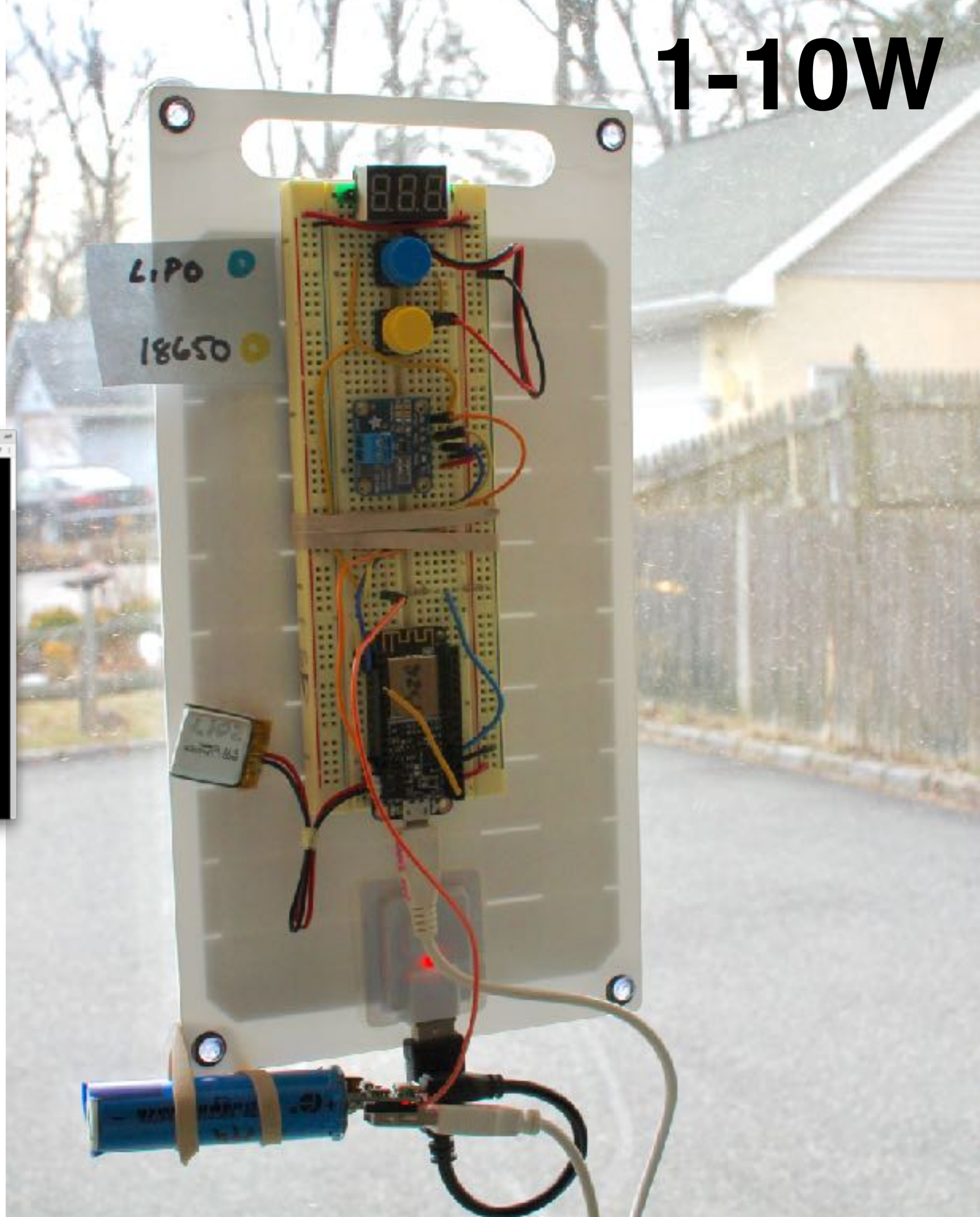
3W panel,
DC-DC 5V USB output
powering USB load directly

ESP32 Feather
+ peripherals,
battery optional

Feddersen

Off-the-shelf

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

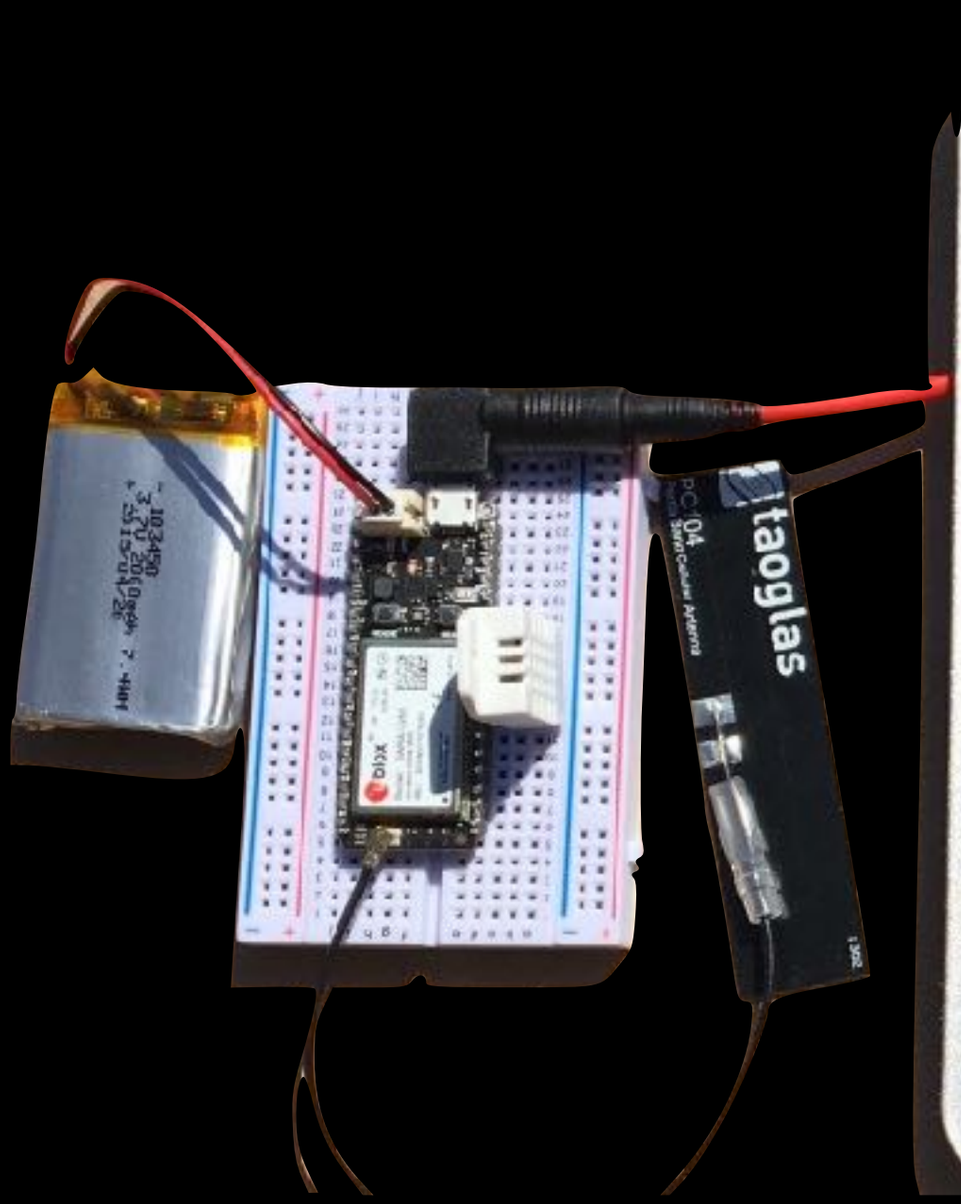


Good resources: Voltaic

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.

>50W

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

Patrick Marold, “Solar Drones”, 2016

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

CASE STUDY

Case study: Earth Speaker

Solar powered sound installation

Case Study

Case study: Earth Speaker

Power system prototype: 5x ~4.5V solar modules in series connected directly to a 12V 1.5 F capacitor.

Helped asses time required to charge at locale.

Case study: Earth Speaker

Load prototype. Tested run-time / energy stored for different frequencies, amplifiers, and speaker configurations.

Class-D Amp

Audio source

Capacitor

Speaker

Case study: Earth Speaker

Final electronics