Powering IoT sensors, kits and gateways

AfricaConnect Meeting and Workshop on IoT-Based Acquisition of Research Data for Scientific Computing, Trieste, 21-25 October 2024

Ermanno Pietrosemoli

ICTP 1964–2024

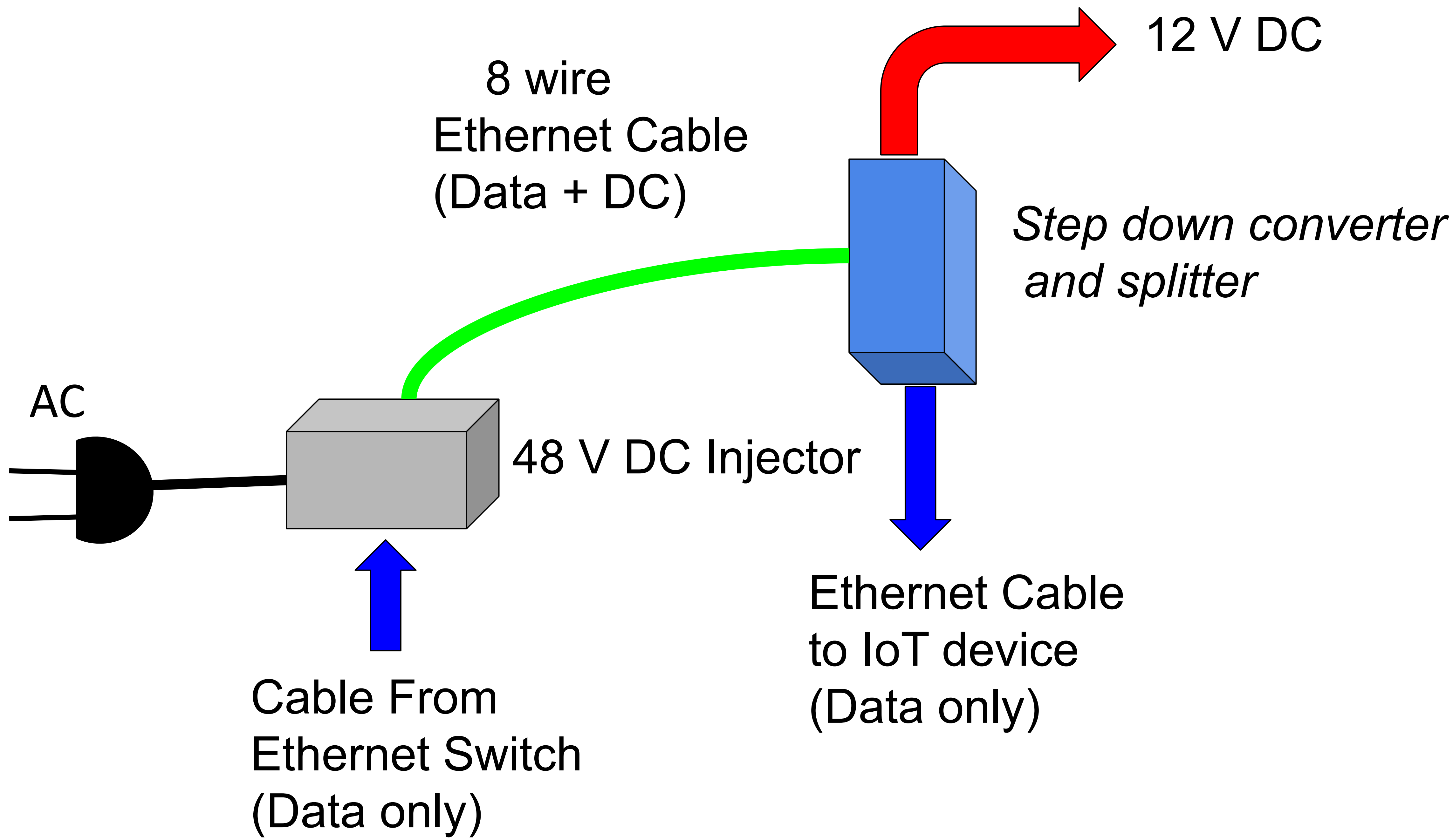
Science, Technology and Innovation unit

Goals

•Examine some of the alternative energy sources that can be used to power IoT devices powering.
•Realize that to calculate the electrical power consumption of IoT devices all the possible states must be considered, since the best power saving technology is to have the device sleep as muc as possible.
•Analyze the components of a photovoltaic system and estimate the requirements to supply a given load.

PoE (Power over Ethernet)

Very often used to power gateways



IoT Powering considerations

- Gateways can be grid connected.
- End nodes can consume little power and be fed by energy scavenging.
- Have node sleeping as much as possible is the best energy saving strategy
- Photovoltaic is widely used. We will cover it in detail
- Many other sources of energy can be harvested
- Most alternative energy sources are intermittent and will require storage devices like batteries or (super)capacitors.

Combined energy sources

Wind and solar generators in Galapagos

- Many energy sources are intermittent, so energy storage devices are required, the most common are batteries and (super)capacitors.
- Some of the sources produce a very small voltage that must be transformed into a higher voltage before it can be utilized

Energy sources in the environment

- Mechanical energy from movement and vibration
- Thermal energy from temperature gradients
- Radiant energy from sunlight and electromagnetic waves
- Biochemical energy from biochemistry such as sweat or bacterial activity

Energy harvesting sources

Energy harvesting is the process by which light, thermal, kinetic, chemical and radio frequency energy can be converted into electrical energy to power some device.

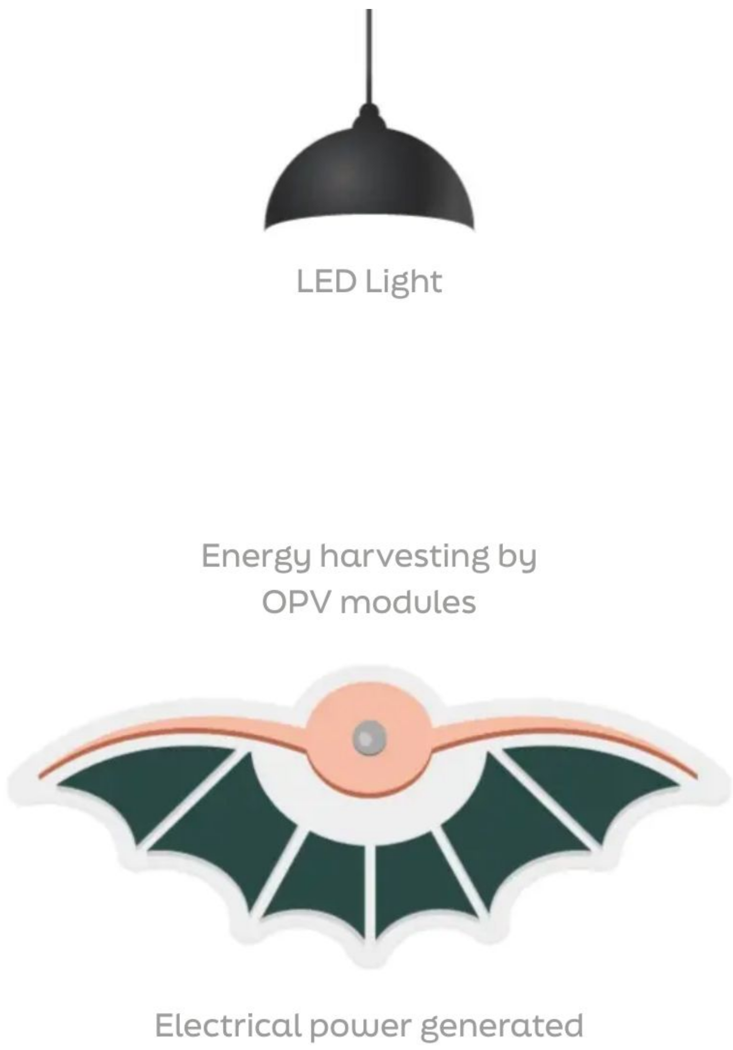
Kinetic energy in the form of wind, vibration, ambient noise, piezoelectric, triboelectric, electrostatic, fluid flow, magnetic induction, wave and tides is used in many applications.

Energy Source	Power Density and Performance
Acoustic noise	3 nW/cm^3 @ 75 dB, 0.96 µW/cm^3 at 100 dB
Airflow	1µW/cm^2
Ambient Light	100 mW/cm^2 (sun), 100 µW/cm^2 (office)
Ambient Radiofrequency	1 µW/cm^2
Hand Generators	30 W/kg
Heel Strike	7 W/cm^2
Push Button	50 J/N
Shoe Inserts	330 µW/cm^2
Temperature Variation	10 µW/cm^2
Thermoelectric	60 µW/cm^2
Vibration (micro generator)	4 µW/cm^3 (human, Hz), 800 µW/cm^3 (machine, kHz)
Vibration (Piezoelectric)	200 µW/cm^3

Dracula Technologies OPV

- Dracula Technologies harvests ambient light to generate energy using organic photovoltaic materials (OPV) that can capture both natural and artificial light.

- With an output of 61 to 72 µW for 100 lux (a low level of general indoor lighting), the devices are capable of replacing batteries.



https://www.pv-magazine.com/2024/09/30/dracula-technologies-relaunches-production-of-organic-photovoltaic-modules-in-france/

Soil Microbial Fuel Cell

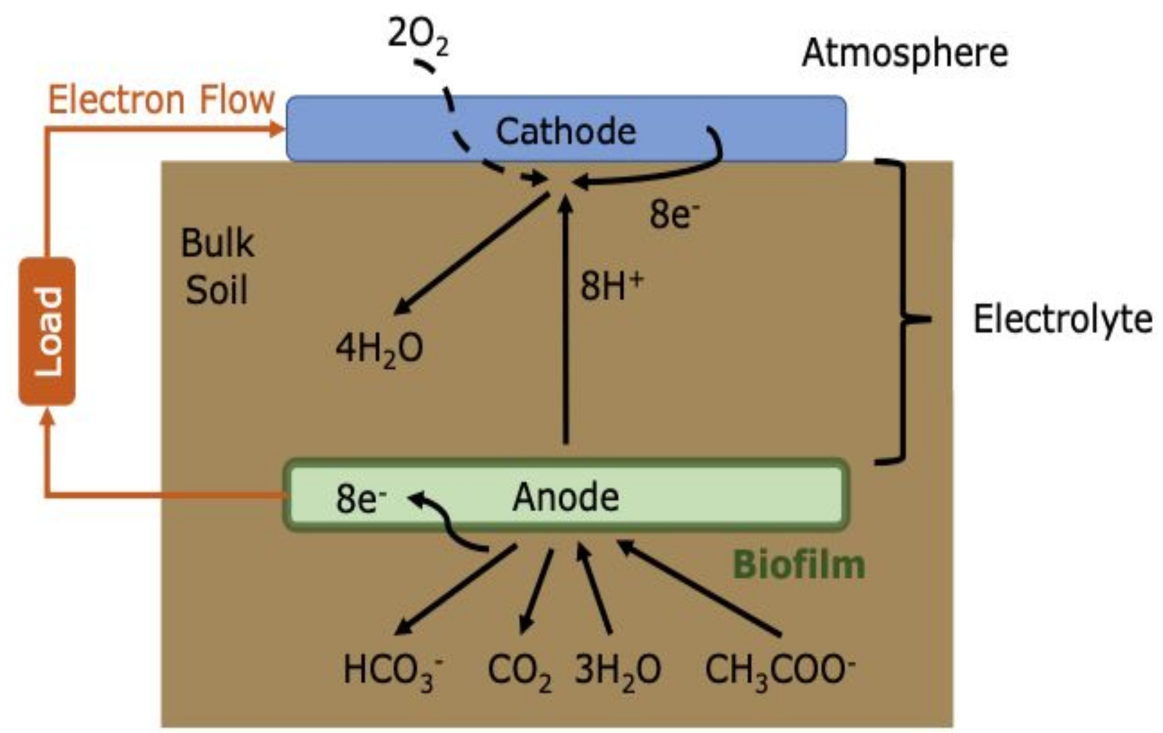


Fig. 2. Basic diagram of a SMFC depicting its anode, cathode, and electrolyte. In a SMFC, the biofilm growing on the anode oxidizes organic matter to release electrons, which becomes the source of electrical power. The cathode performs a reduction reaction to balance out the cell's net charge, which requires oxygen as a reactant. The electrolyte facilitates ion exchange between the anode and cathode while preventing oxygen from penetrating into the anode [80].

Soil-Powered Computing: The Engineer's Guide to Practical Soil Microbial Fuel Cell Design. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. December 2023, https://doi.org/10.1145/3631410

Power Sources Environmental Issues

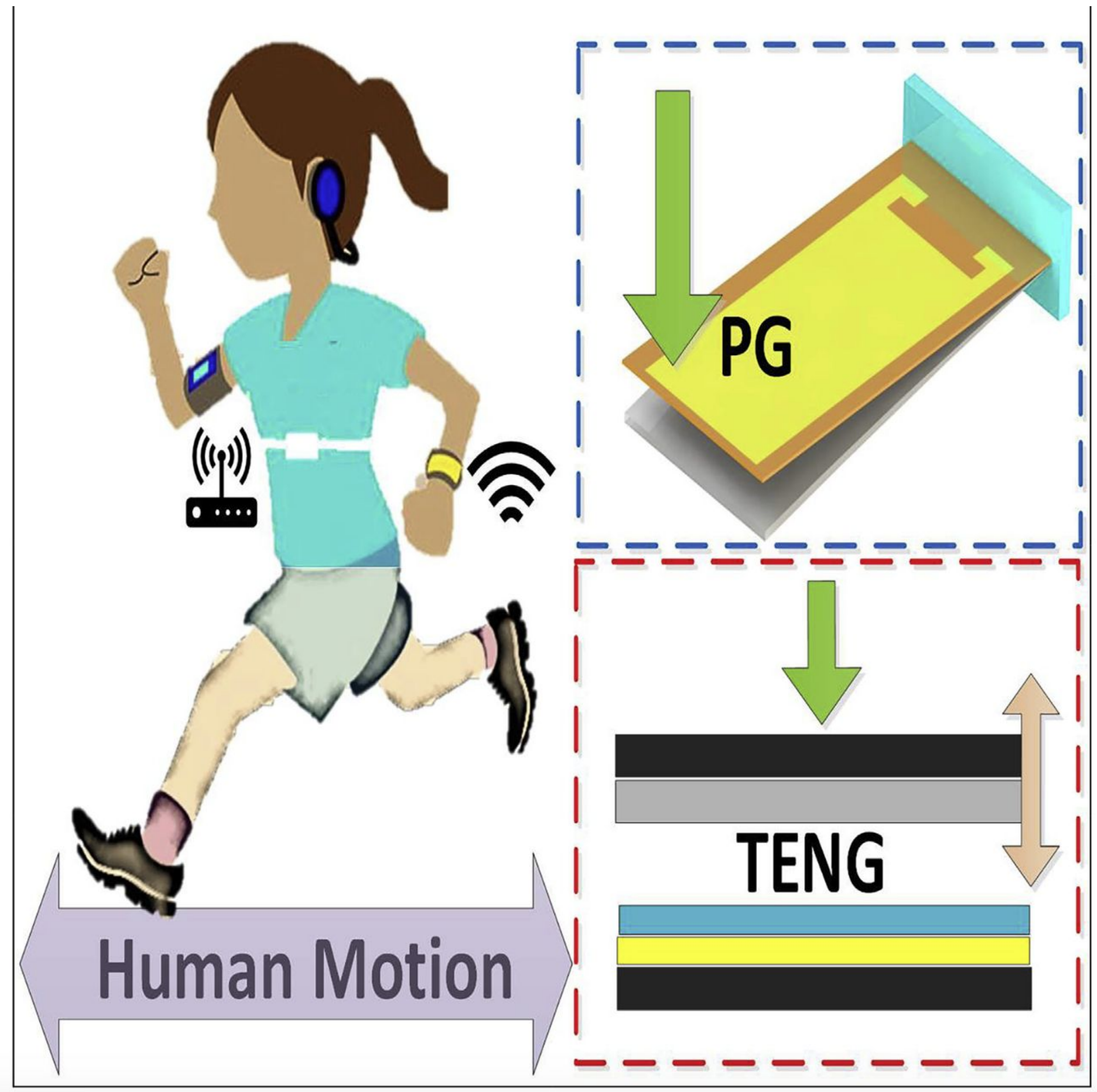
Energy Source	Performance	Hazardous Classification	Core Materials + Extraction Source
Solar cell	100 μW/cm^2 [73] in illuminated office	EPA: Hazardous [4]	Tin, Silver, Silicon [1, 15, 38, 41] (Open/underground mine)
TEG	0.233 μW/cm^2 [40] average	DOT: Poison [69] (Bi_2Te_3)	Bismuth, Tellurium [29, 42, 65] (Mining byproduct)
Piezoelectric	2400 μW/cm^3 [104] 3 m/s airflow	EPA: E-waste [3]	Quartz, Lead, Zirconium [8, 27, 82, 102] (Open/underground mine, mining byproduct)
SMFC	1.74 μW/cm^2 (see Section 3)	No known hazards	Carbon fiber [62] (Petroleum/biomass)
$LiCoO_2$ battery	1363 mAh/cm^3 [68] theoretical capacity	EPA: Hazardous [39]	Lithium, Cobalt [34, 74, 94] (Salt-flat brine, open/underground mine)

Soil-Powered Computing: The Engineer's Guide to Practical Soil Microbial Fuel Cell Design. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 7, 4, Article 196 (December 2023), 40 pages. https://doi.org/10.1145/3631410

Piezoelectricity and Triboelectricity

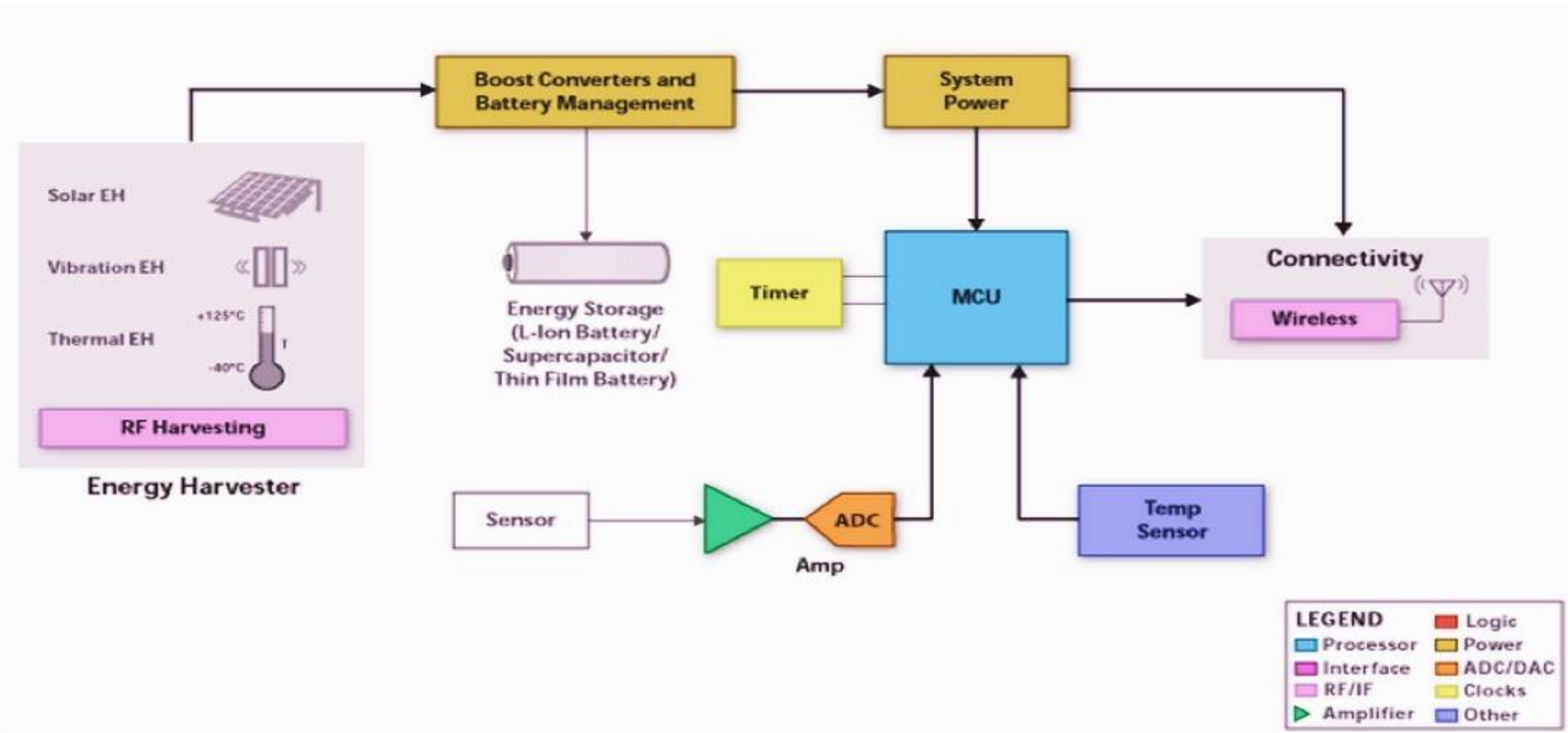
Piezoelectricity is the electric charge that accumulates in certain solid materials in response to applied mechanical stress.

Triboelectricity is electrical charge caused by friction.



https://www.cell.com/iscience/pdf/S2589-0042(20)30473-9.pdf

Energy harvesting for IoT



http://eu.mouser.com/applications/benefits_energy_harvesting/

Example of modern IoT powered system

SenSys '24, November 4–7, 2024, Hangzhou, China — Kai Geissdoerfer and Marco Zimmerling

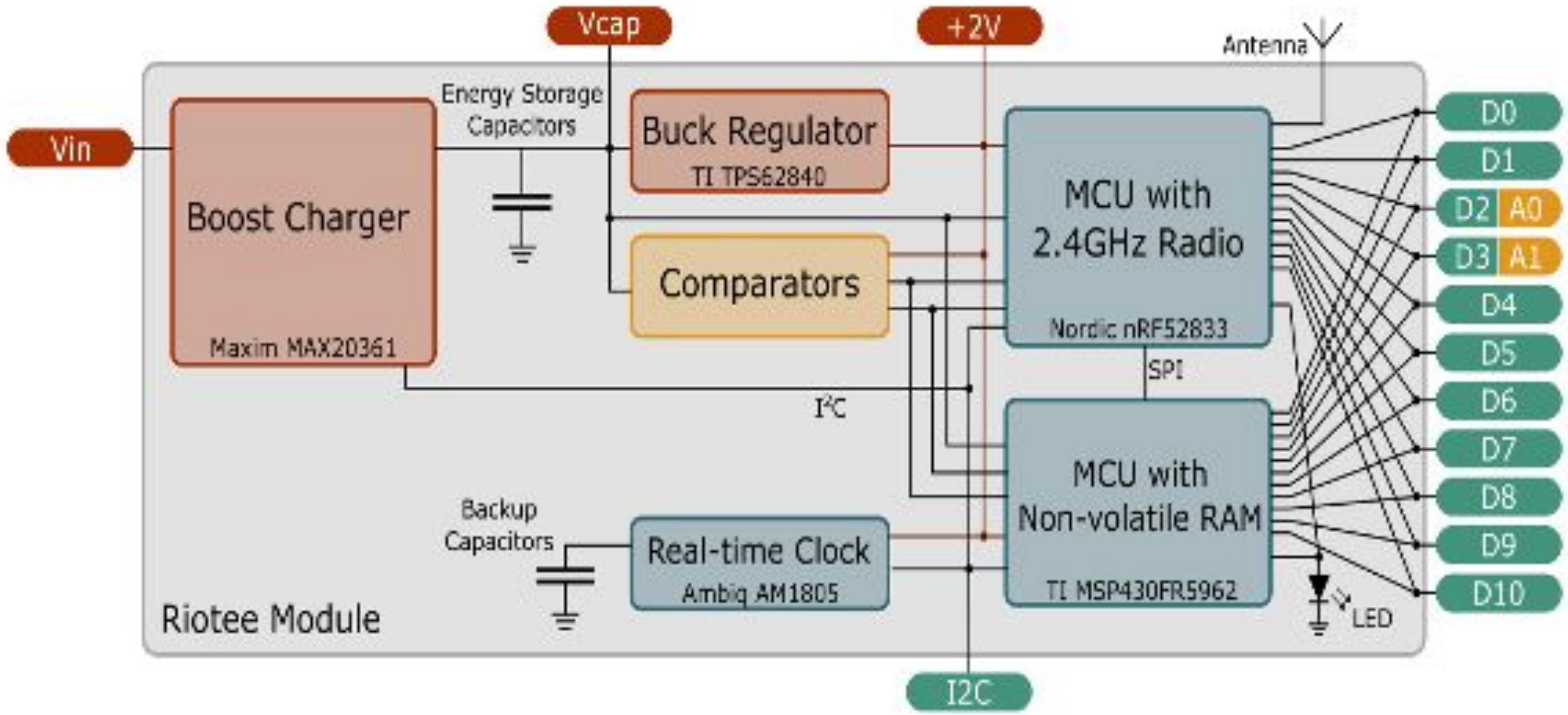


Figure 2: Architecture of Riotee Module. *The Riotee Module integrates energy harvesting, energy storage, power management, non-volatile memory, a powerful Cortex-M4 processor, and a 2.4 GHz BLE-compatible radio into a stamp-sized hardware unit.*

KaiGeissdoerferandMarcoZimmerling. 2024.
Riotee:AnOpen-sourceHardware and Software Platform for the Battery-free Internet of Things. In Proceedings of the 22nd ACM Conference on Embedded Networked Sensor Systems (SenSys).

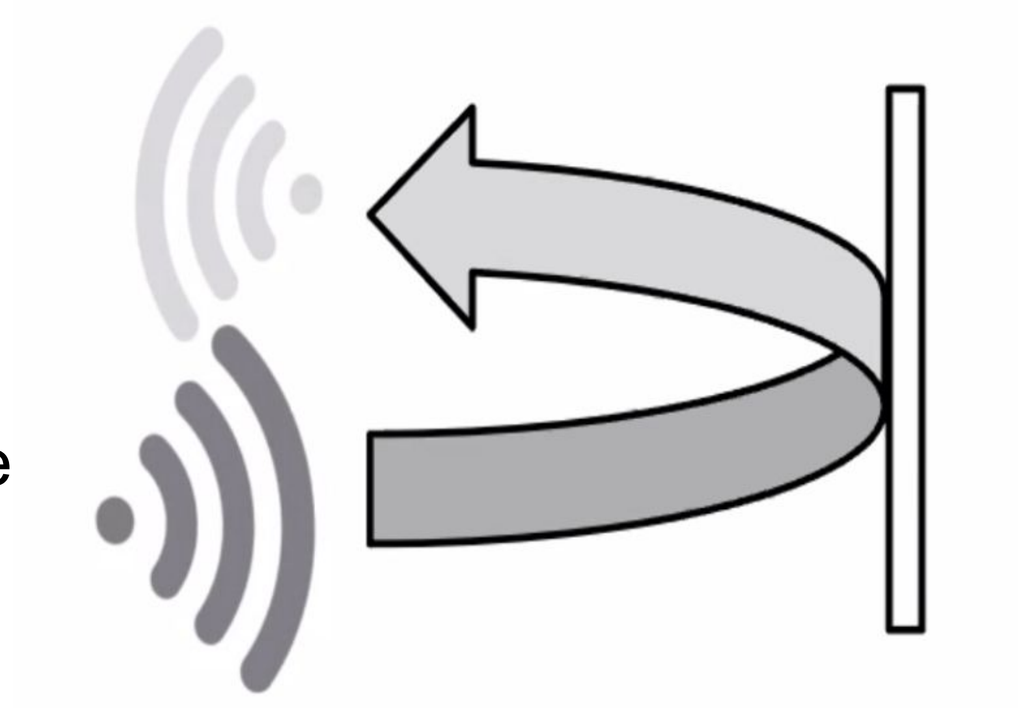
RF Energy

RF energy has been leveraged in RFID in which the reader transmits a powerful enough wave so that a passive tag can use it to power its receiver and transmitters stages.

This idea has been applied to other RF sources like WiFi with discouraging results, due to the quadratic decay of RF power with distance.

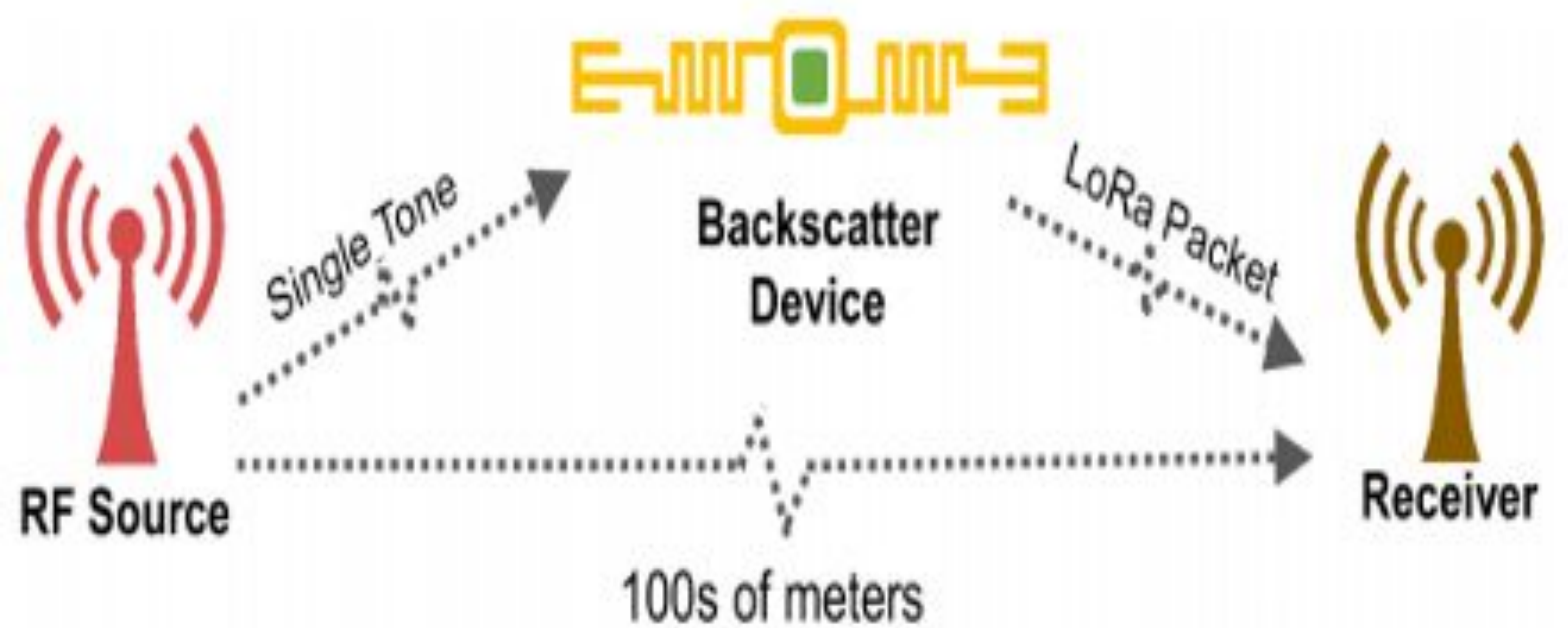
Backscatter

- Backscatter leverages changes in the reflecting surface.
- Information contained in the reflecting tag can be conveyed by changing its impedance and therefore its reflection coefficient.
- Signal reflection merely consumes microwatts since it only changes the information that modulates the carrier.
- But the reflected signal is very low power and can be interfered.
- Shifting the carrier frequency at the reflector helps in alleviating this issue.



LoRa Backscatter Implementation

- Piggybacking data on an existing RF signal with very low power backscattering device
- Self interference handled by frequency shifting and harmonic cancellation



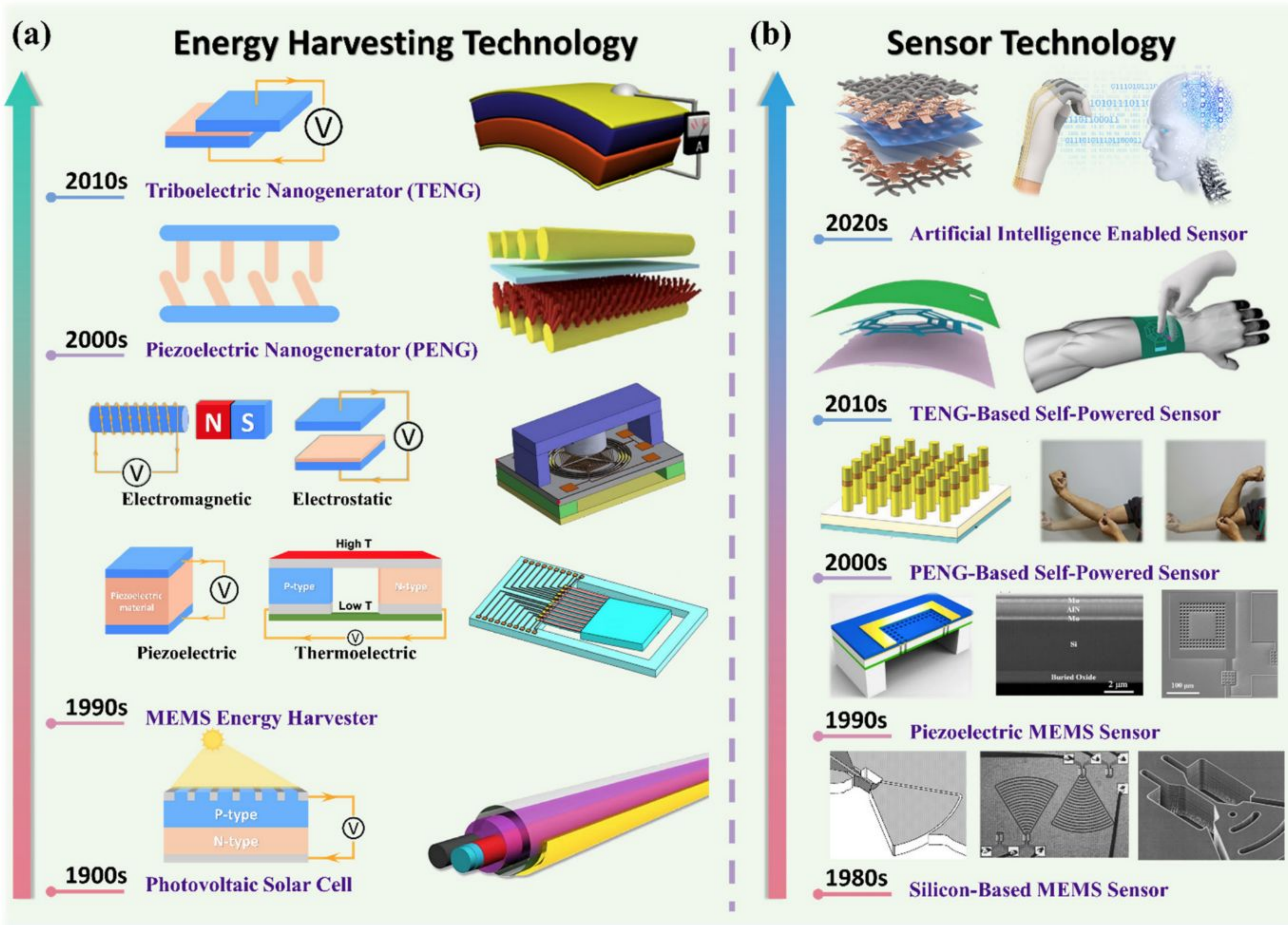
https://arxiv.org/pdf/1705.05953.pdf 16 May 2017

A self-powered integrated fingertip-microgrid sensing system

Sweat-powered electronic finger wrap generate its power using special biofuel cells. These biofuel cells can extract energy from compounds like lactate and oxidants found in sweat to generate electricity.

Can track health biomarkers like glucose, vitamin C, lactate, and drugs.

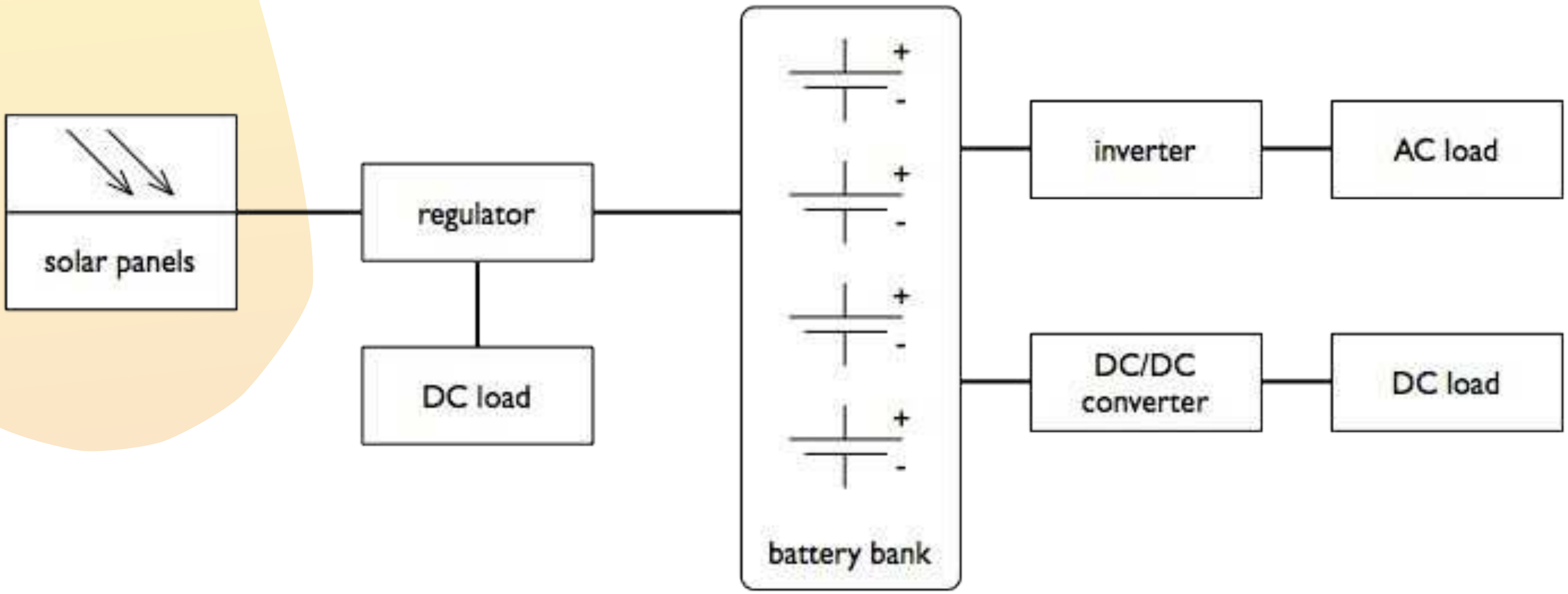
Mahato, K., Saha, T., Ding, S. et al. Hybrid multimodal wearable sensors for comprehensive health monitoring. Nat Electron 7, 735–750 (2024). https://doi.org/10.1038/s41928-024-01247-4



https://www.researchgate.net/publication/355991802_Recent_Progress_in_the_Energy_Harvesting_Technology-From_Self-Powered_Sensors_to_Self-Sustained_IoT_and_New_Applications/link/657b1dd1cbd2c535ea2900da/download

Photovoltaic system

A basic photovoltaic system consists of five main components: the **sun**, the ***solar panel***, the ***charge controller***, the ***batteries***, and the ***load***. Many systems also include a ***voltage converter*** to allow use of loads with different voltage requirements.

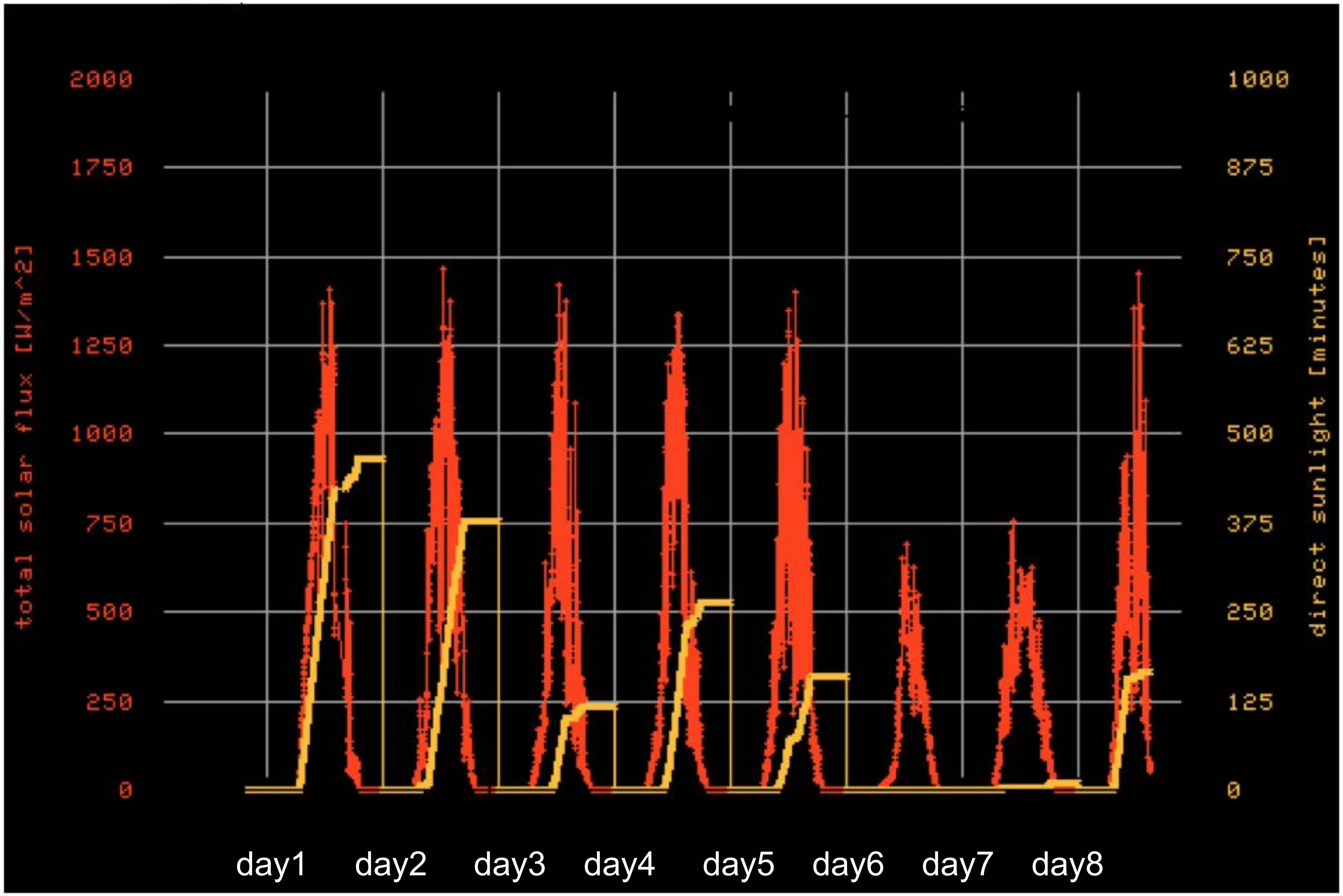


Terms definition

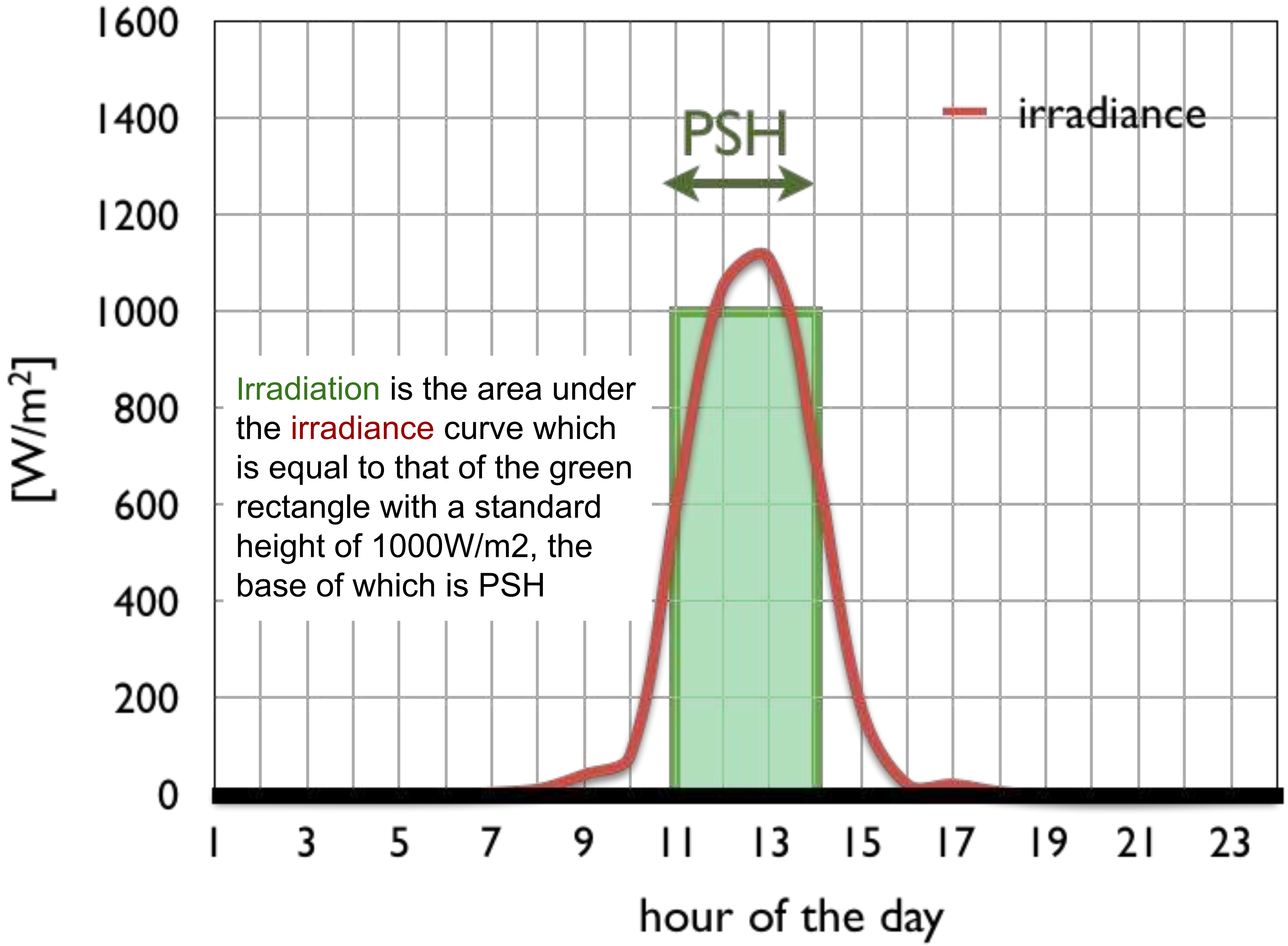
- Solar Irradiance: intensity of solar power per unit area (W/m^2).
- Solar Irradiation: amount of solar energy collected per unit area over time (Wh/m^2).
- Insolation: amount of solar irradiation collected during one
day ($kWh/m^2/day$).
- Solar Constant : average amount of solar irradiance that arrives above the Earth's atmosphere, which is around $1353 W/m^2$.

The atmosphere absorbs about a third of this irradiance, so 1000W/m2 is taken as reference value at sea level.

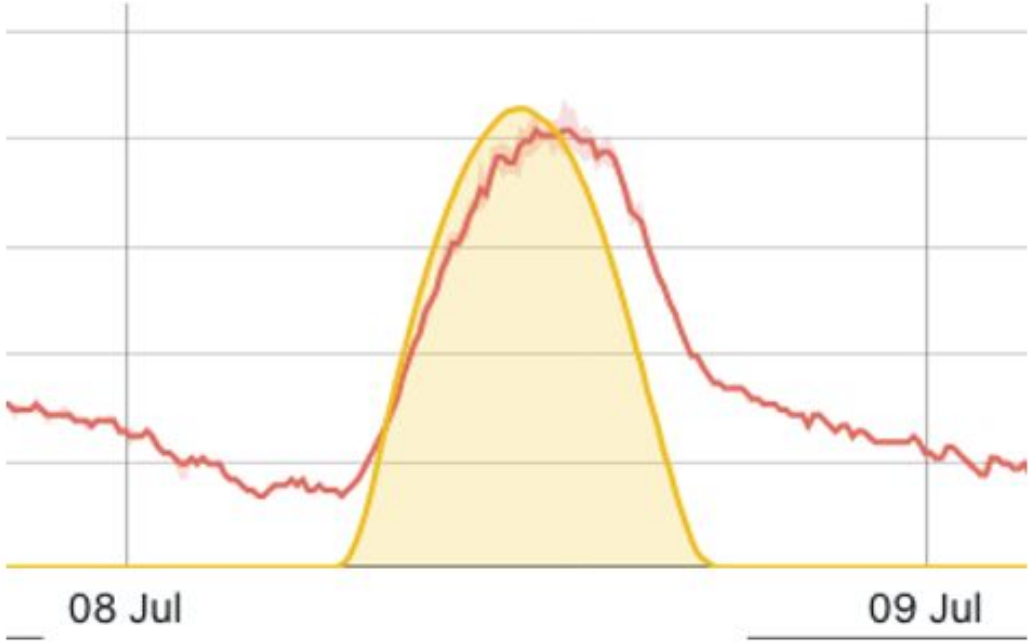
Irradiance and insolation at 4800 m



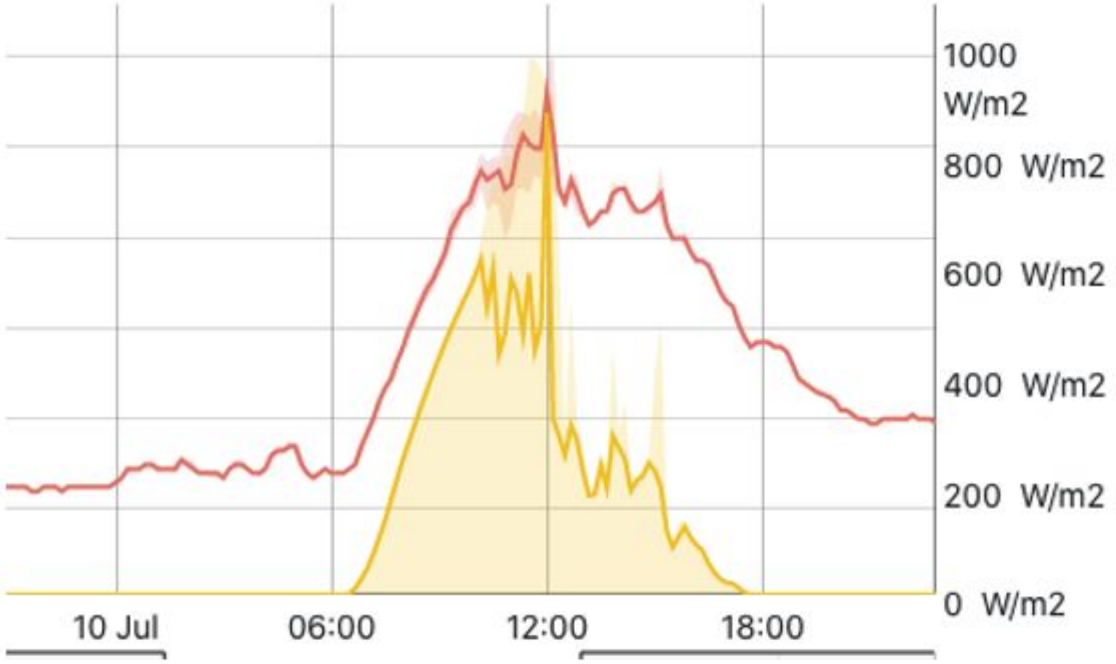
Peak Sun Hours = kWh/m^2



Real example: Harare, Zimbabwe



Temperature in red, Irradiance in yellow, cloudless day



Temperature in red, Irradiance in yellow, cloudy day

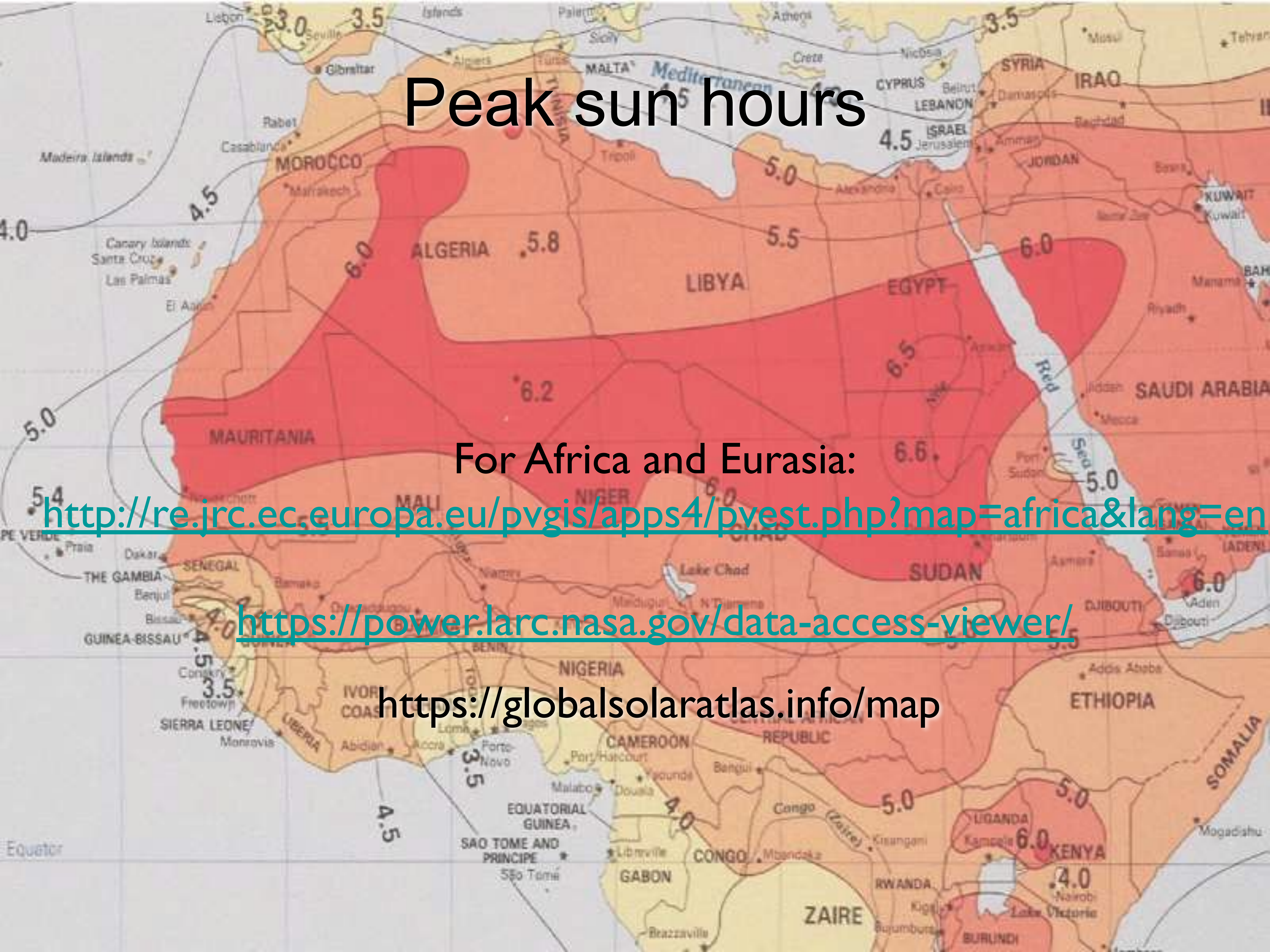
Peak sun hours

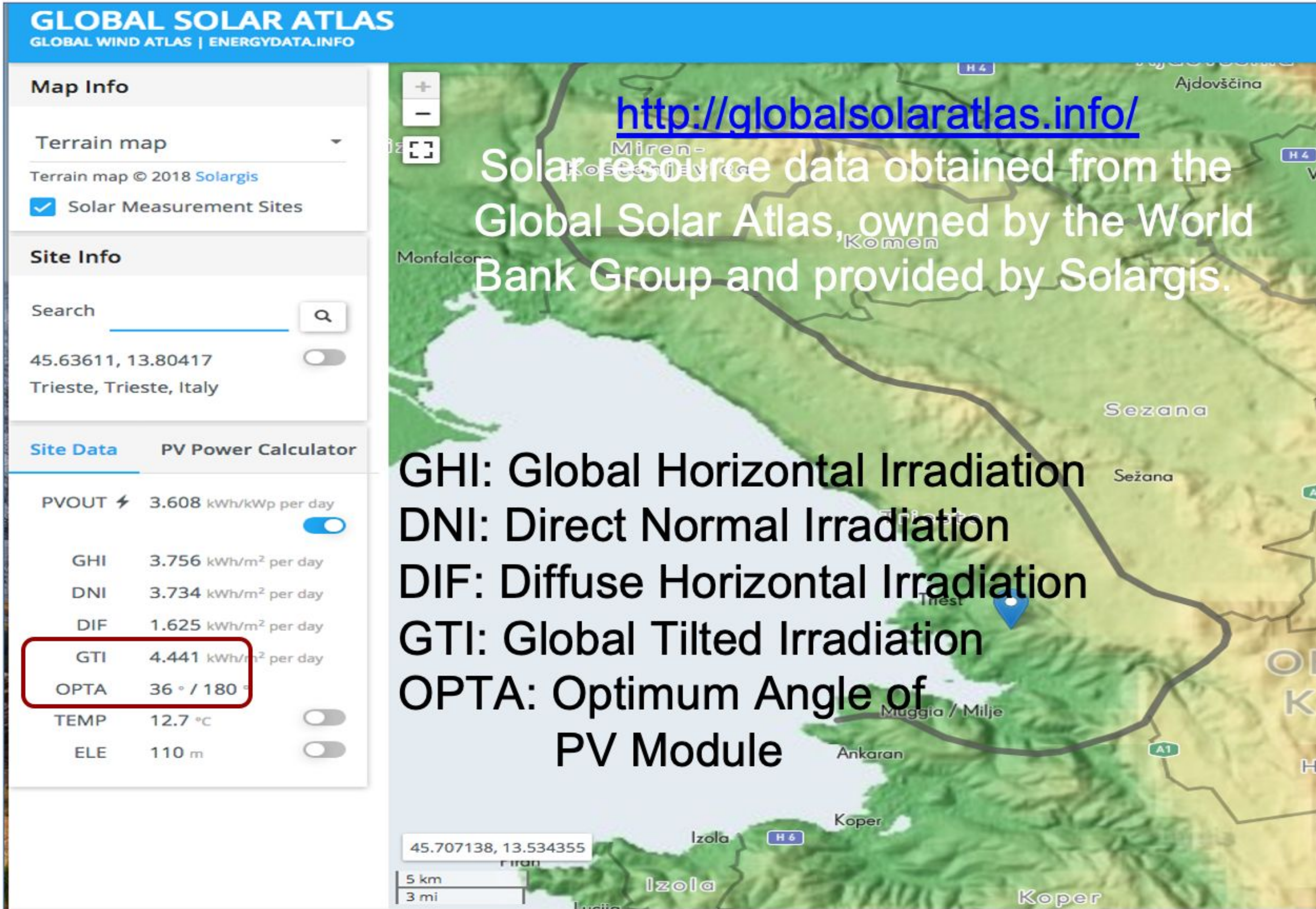
For Africa and Eurasia:

http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa&lang=en

https://power.larc.nasa.gov/data-access-viewer/

https://globalsolaratlas.info/map





http://globalsolaratlas.info/

Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.

GHI: Global Horizontal Irradiation

DNI: Direct Normal Irradiation

DIF: Diffuse Horizontal Irradiation

GTI: Global Tilted Irradiation

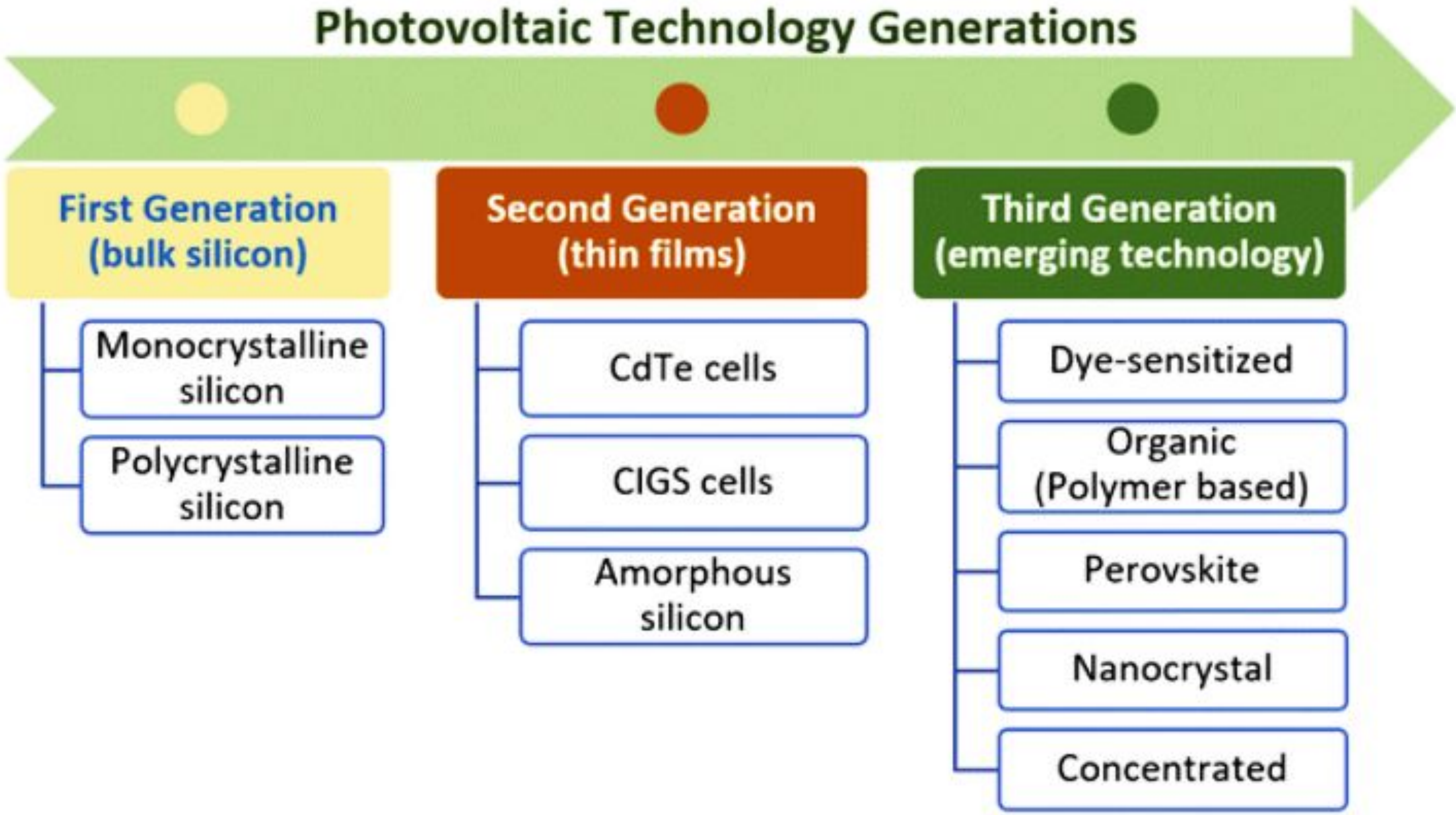
OPTA: Optimum Angle of PV Module

Solar panel

A solar panel is made of many solar **cells**

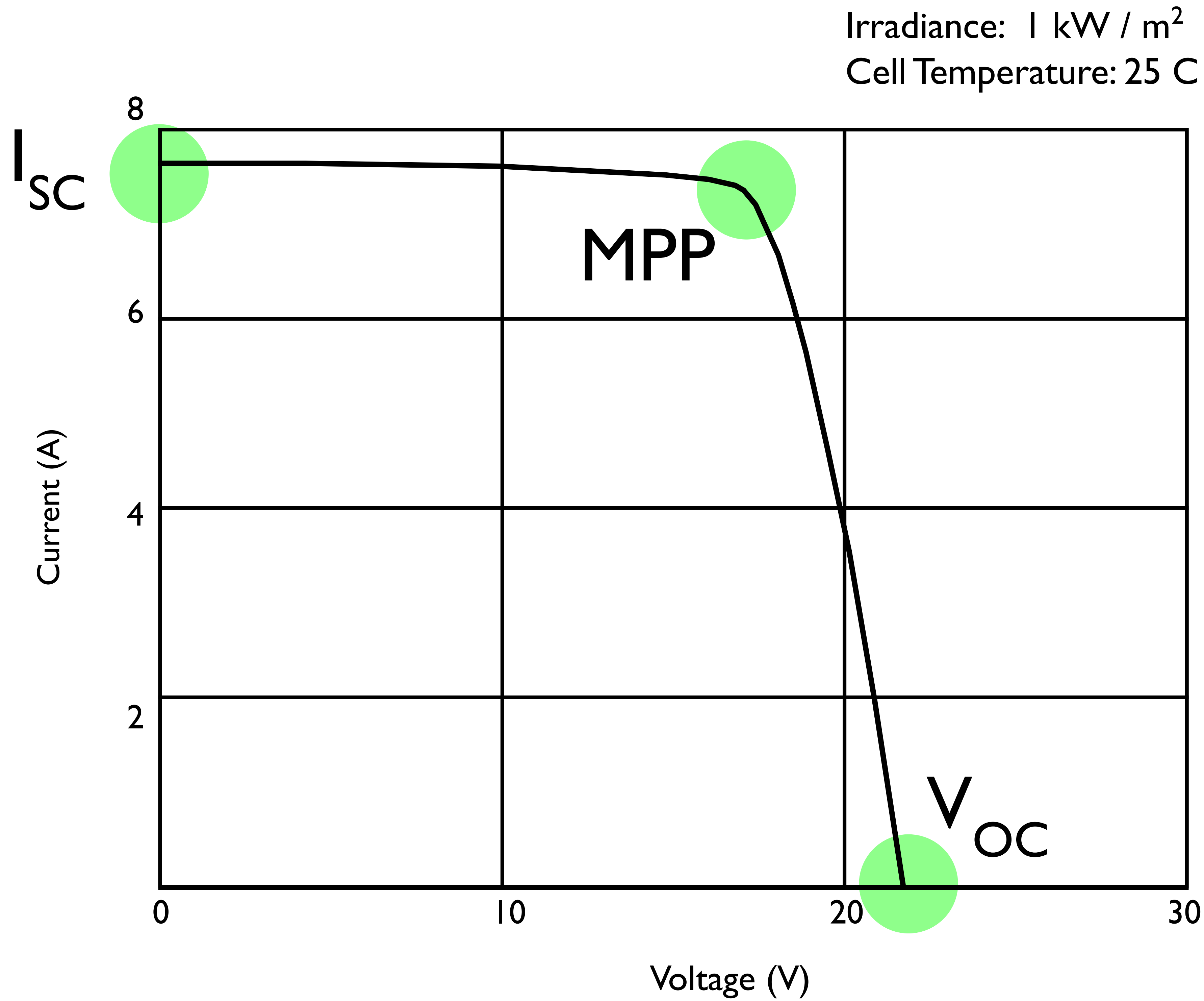
There are many types of solar panels:

- **Monocrystalline**: expensive, best efficiency
- **Polycrystalline**: cheaper, less efficient
- **Amorphous**: the cheapest, worst efficiency, short lifespan
- **Thin-film**: less expensive, flexible, low efficiency, special uses
- **CIGS**: Copper Indium Gallium Selenide
- **Perovskite:** efficieny reaching 28 % in combination with silicon

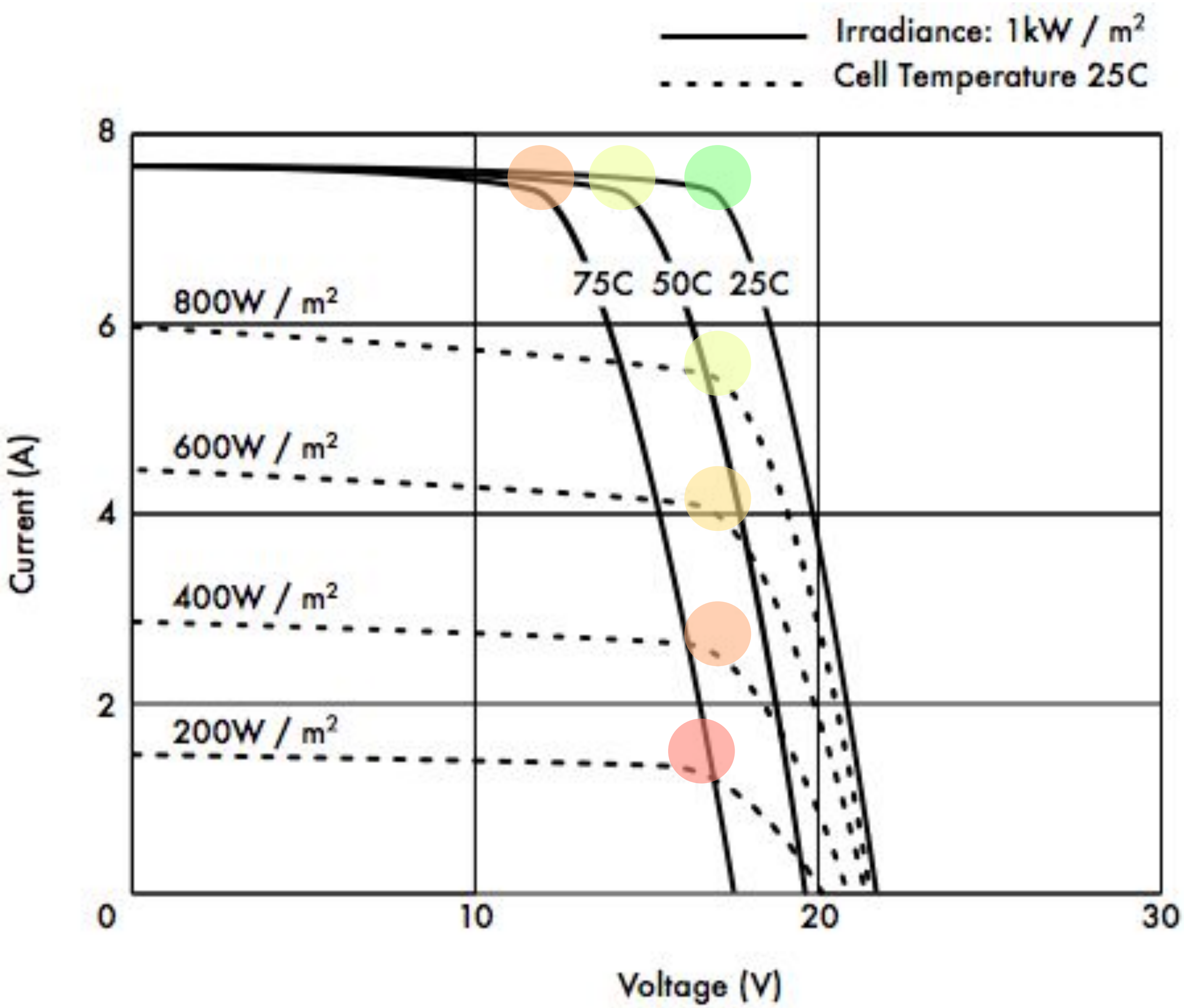


https://pubs.rsc.org/en/content/articlelanding/2023/ra/d3ra01454a#!

Solar panel IV curve



Solar panel IV curve for different amounts of irradiance and temperature

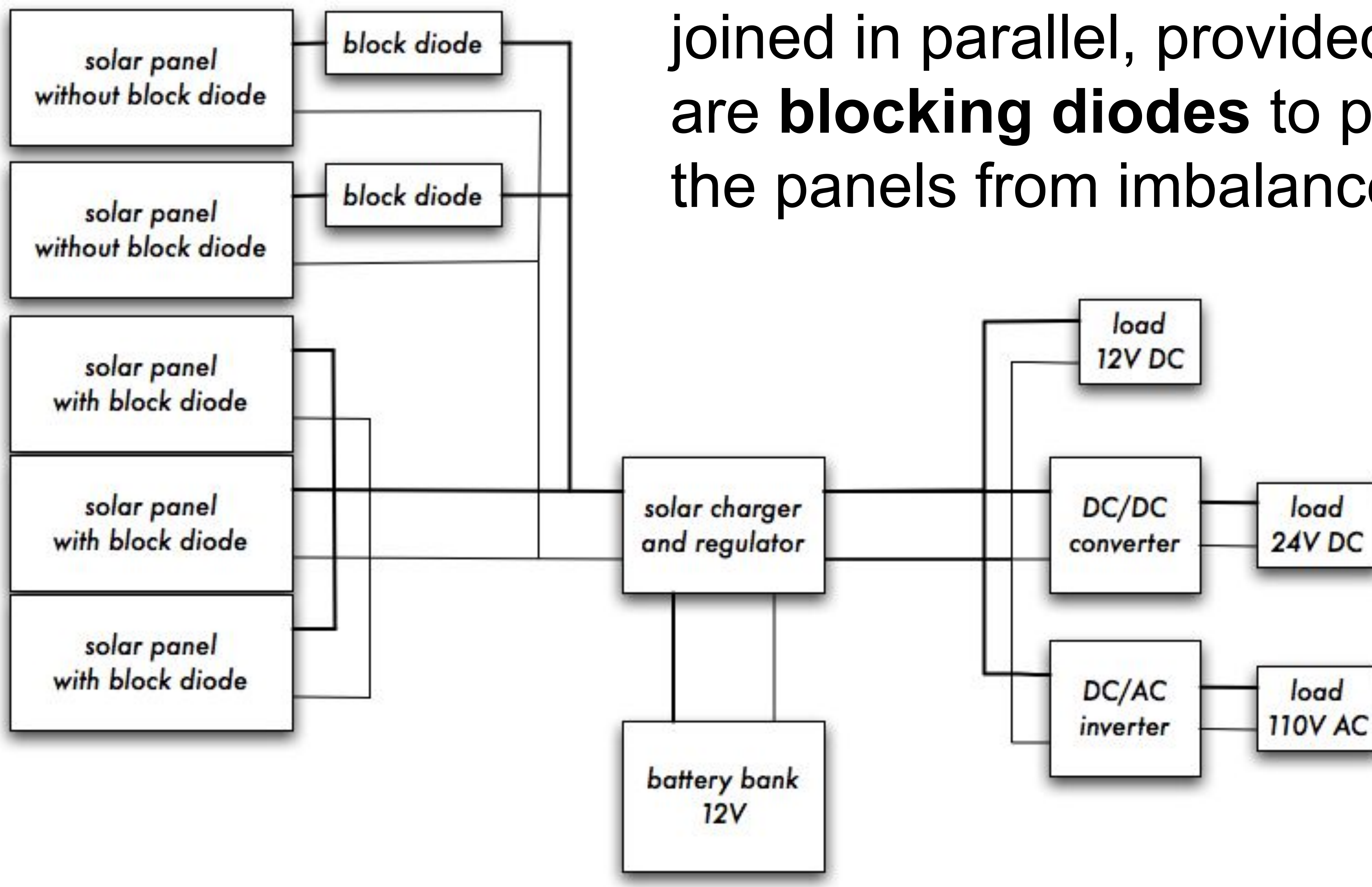


Optimizing panel performances

Optimal elevation angle = Latitude + 5°

Photovoltaic system

If more power is required, multiple solar panels may be joined in parallel, provided there are **blocking diodes** to protect the panels from imbalances.



Batteries

Batteries for solar systems (called deep cycle or stationary batteries) are different from the one used in automotive applications, since the latter must provide high current for short periods of time and their liquid electrolytes are agitated by the vehicle's movement, which. prevents sedimentation of the acid that would happen in stationary usage.

The depth of discharge (DOD) is the percentage a battery is allowed to discharge without sacrificing its performance and is higher stationary batteries.

Batteries

Lithium based are the most used while lead-acid with gel electrolyte are also common.
$LiFePO_4$ have improved perfomance.

Batteries determine the main ***operating voltage*** of your installation, for best efficiency all other devices should be designed to work at the same voltage

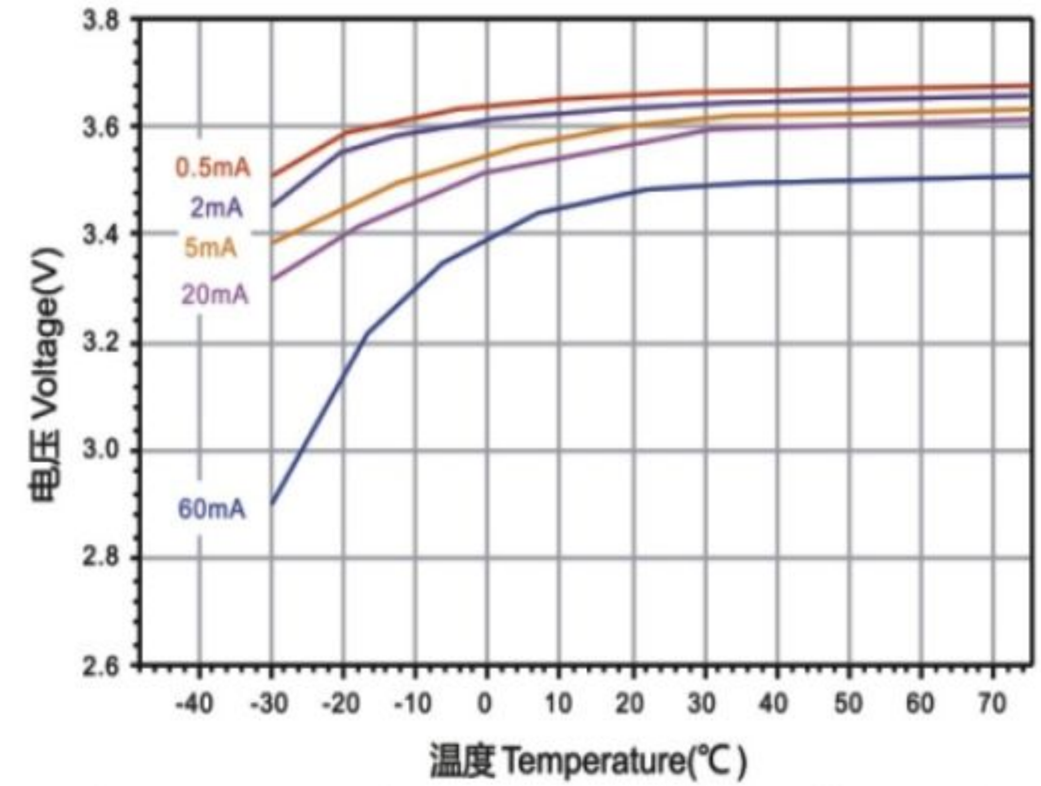
LiPO (Lithium-Polymer) battery

- Each cell will be around 3.7 V when fully charged.
- The minimum voltage is around 3 V per cell.
- Capacity is expressed in mAh, amount of energy stored.
- Handle with precaution, lithium can explode.
- Many IoT modules have LiPo battery chargers built in.

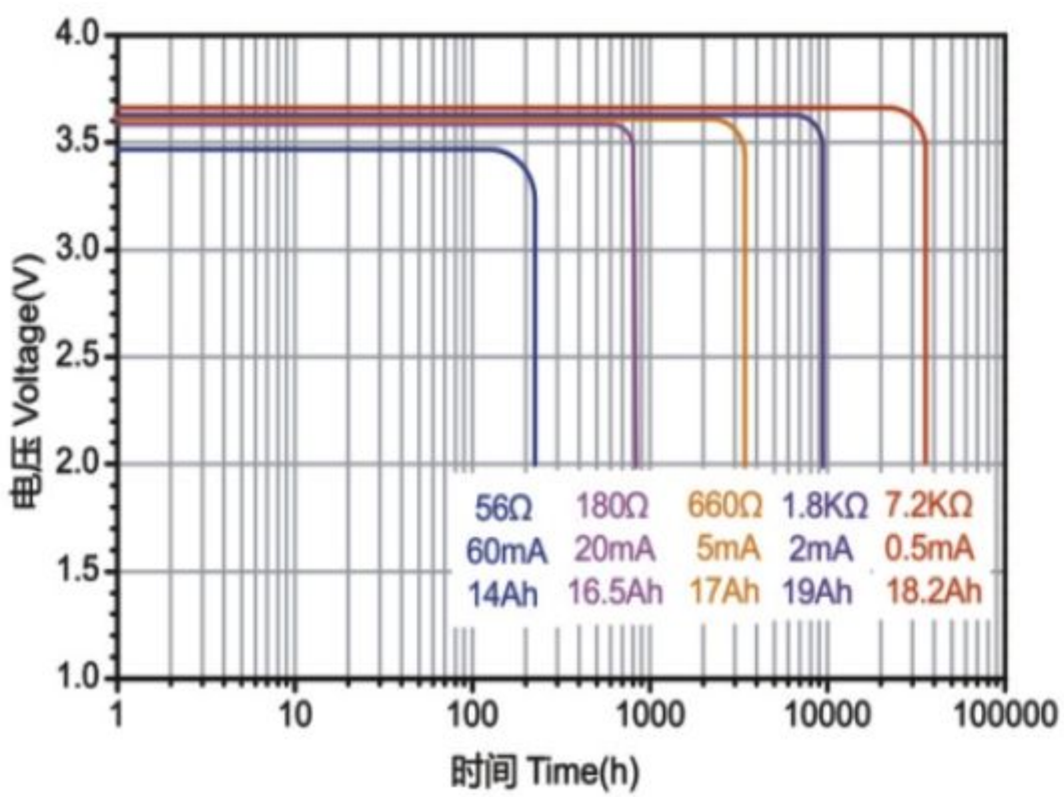
19 Ah $LiFePO_4$ battery features

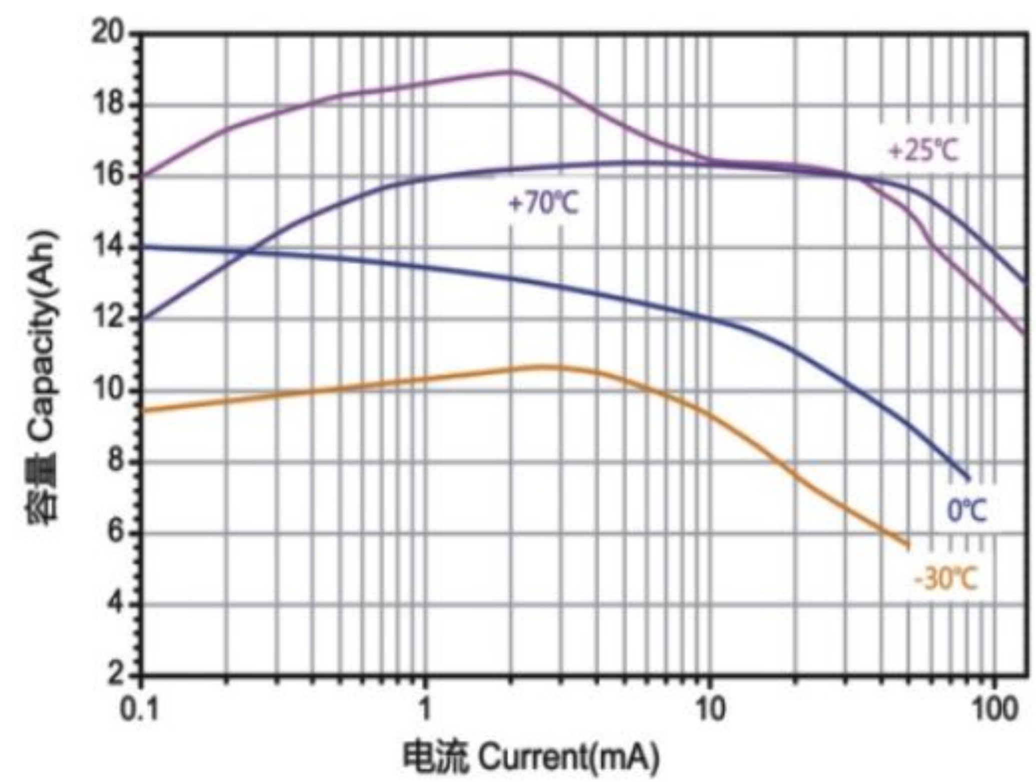
1% self discharge rate per year

Nominal capacity	19000mAh
Nominal voltage	3.6V
Max.continuous current	230mA
Max.pulse current capability	400mA
Weight	Approx.107g
Dimension	Ø34.0*61.5mm
Operating temperature range	-60℃ ~+85℃



25℃放电特性 Discharge Characteristics(25℃)





Batteries comparison

Criteria	Li-Ion	LiFePo4
Voltage	4.2 - 3V	3.6 - 3V
Usage for 3.3V projects	need regulator	direct connection
Capacity measurement	accurate	inaccurate
Availability of charger boards	good	poor
Energy density (Wh/kg)	150-200	90-160
Discharge current	extremely high	high
Charging time	short	longer
Charging cycles (to 80% capacity)	<1000	>5000
Safety	Burn easily	Do not burn

Designing a battery bank

- The size of the battery bank will depend upon: the storage capacity required, the maximum discharge rate, and the storage temperature of the batteries. The storage capacity of a battery (amount of electrical energy it can hold) is often expressed in amp-hours (Ah).
- A battery bank in a PV system should have sufficient capacity to supply needed power during the longest expected period of cloudy weather.

Supercapacitor

- Device with capacitance much higher than normal capacitors but with lower voltage ratings.
- It bridges the gap between rechargeable batteries and electrolytic capacitors.
- Store up to 100 times more energy per mass or volume than electrolytic capacitors, charge and discharge much faster than batteries and tolerate more C/D cycles than batteries.

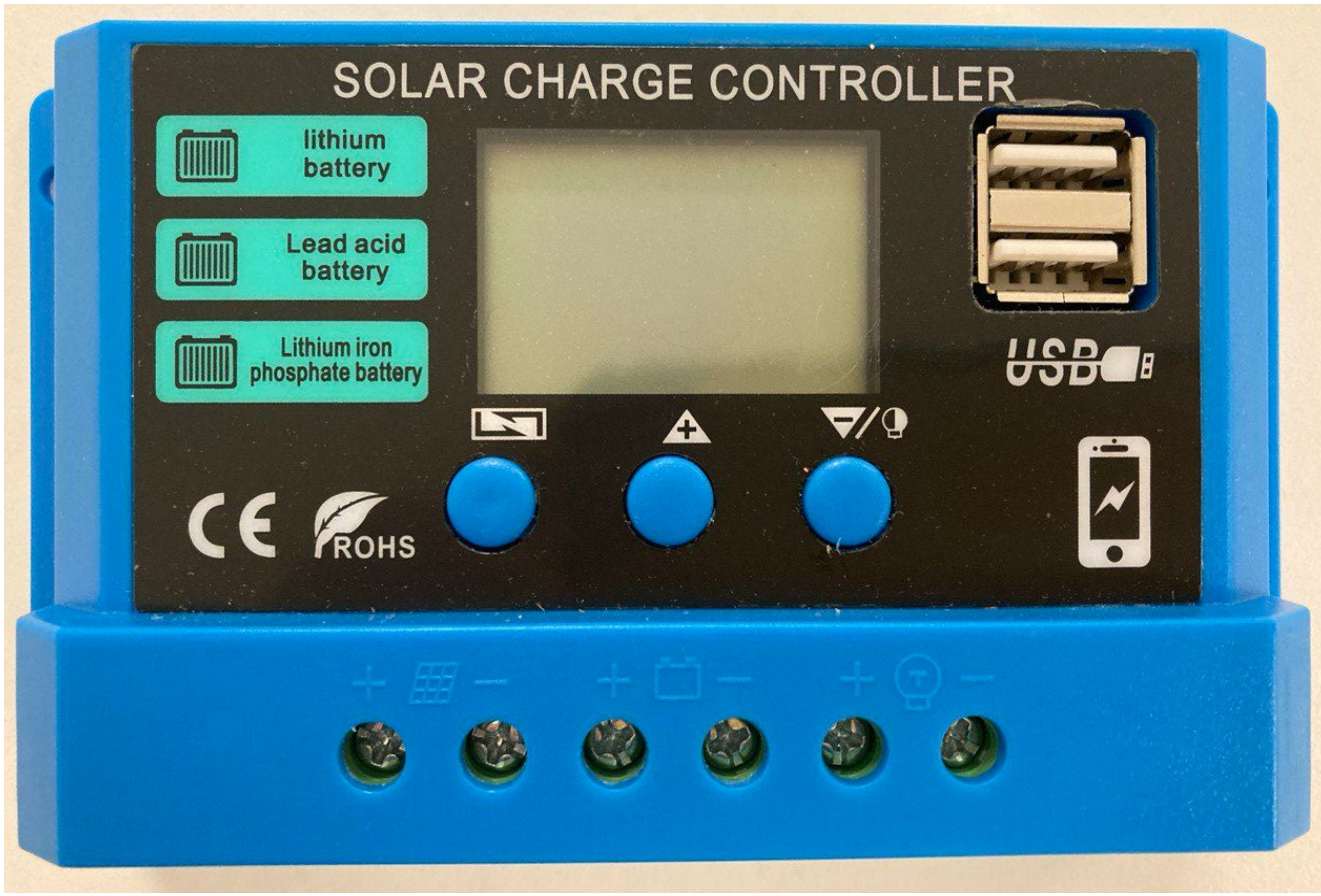
Supercapacitors and batteries

Charge Controller

The ***Charge Controller*** provides the proper voltage and current to charge the battery, and supplies power for the load.
Different types of batteries require different current values during the charging phases.
Initially a higher current is required, then it is reduced.
Finally, when the battery is fully charged a ***trickle charge*** may be applied for some battery types.

IoT devices often have a voltage regulator built in.

Solar Charge Controller



PWM battery charging, for 3 types of batteries
12 or 24 V battery
Maximum photovoltaic panel voltage: 50 V
2 X 5 V USB outlets
rated current: 30 A maximum

Monitoring the state of charge

There are two special states of charge that can occur during the cyclic charge and discharge of the battery. They should both be avoided in order to preserve the useful life of the battery.

- ***Overcharge*** takes place when the battery arrives at the limit of its capacity. If current is applied to a battery beyond its point of maximum charge, the electrolyte begins to break down. This produces bubbles of oxygen and hydrogen, a loss of water, oxidation on the positive electrode, and in extreme cases, a danger of explosion.

Monitoring the state of charge

- ***Overdischarge*** occurs when there is a load demand on a discharged battery. Discharging beyond the battery's limit will result in deterioration of the battery. When the battery drops below the voltage that corresponds to a 50% discharge, the charge controller prevents any more energy from being extracted from the battery.
- The proper values to prevent overcharging and overdischarging should be programmed into your charge controller to match the requirements of your battery system.

Maximizing battery life

Lead acid batteries degrade quickly if they are discharged completely. A battery from a truck will lose 50% of its design capacity within 50 -100 cycles if it is fully charged and discharged during each cycle.Never discharge a 12 Volt lead acid battery below 11.6 volts, or it will forfeit a huge amount of storage capacity. In cyclic use it is not advisable to discharge a truck battery below 70%. Keeping the charge to 80% or more will significantly increase the battery's useful lifespan. For example, a 170 Ah truck battery has a usable capacity of only 34 to 51 Ah.

The Load

The ***load*** is the equipment that consumes the power generated by your energy system.

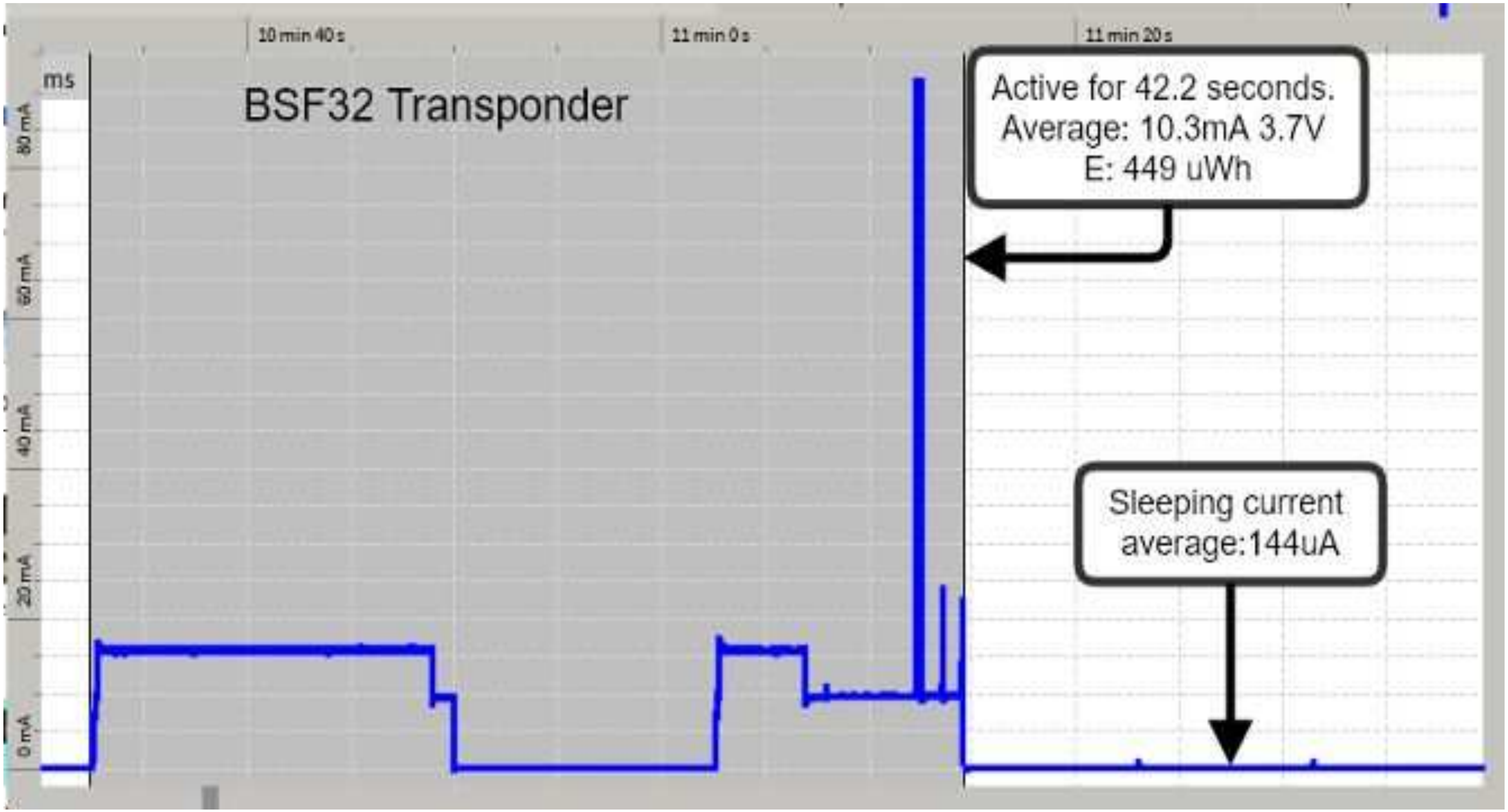
The load is expressed in watts, which are the product of volts time amperes

$$\text{watts} = \text{volts} \times \text{amperes}$$

If the voltage is already defined, the load can be expressed in amperes.

In alternating current circuits the power factor must be used in the power calculation.

Example of IoT device consumption during one cycle



Simplified spreadsheet for photovoltaic calculations

Solar radiation data for a given site available from:

https://eosweb.larc.nasa.gov/sse/RETScreen/ , Worldwide coverage

http://globalsolaratlas.info/ , Worldwide coverage

http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa&lang=en, Africa and Eurasia coverage

Input data framed in red — Intermediate results framed in blue — Final results framed in green

Electrical Load Calculation

Device	Consumption,W	Hours/day	Energy/day, Wh
GPS	1.5	24	36
WiFi Client	8	24	192
Laptop	15	12	180
WiFi AP	3	24	72
Ethernet Switch	4	24	96
Total energy consumption/day, Wh			36

Battery capacity calculation, considering the number of no-sun days and the allowed depth of discharge

Required autonomy, days	Depth of Discharge	Battery capacity,Wh	Battery voltage,V	Battery Capacity, Ah	Number of batteries
4	0.5	288	12	24.0	2

Panel capacity calculation

Panel Peak power, Wp
10

Load energy,Wh	Battery charging allowance	Energy /d, Wh	PSH	Daily Photovoltaic power, W	Number of panels
36	1.5	54	5.5	9.8	1

Conclusions

- Many forms of ambient energy can be harvested.
- For massive IoT end nodes deployment, environmental issues must be considered.
- Solar power is an ever evolving technology but indoor efficiency is low.
- Batteries for energy storage and proper charge controllers are required for intermittent energy sources.
- Battery technologies are continuously evolving.
- Sleeping is the most effective way of energy saving for IoT devices.