Photovoltaic Systems Design

A Ridiculously Short Introduction & Future Outlook.

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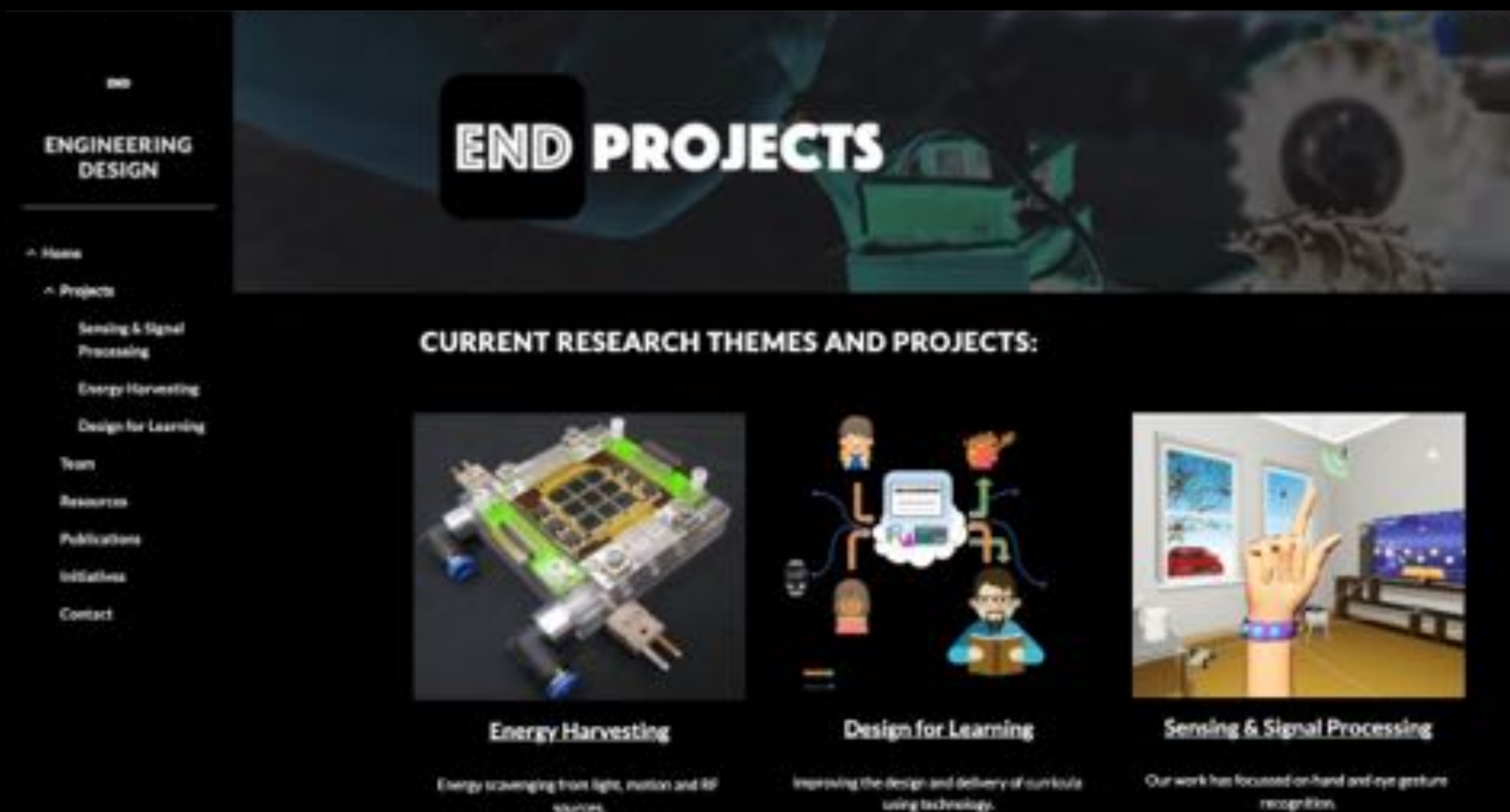
About Me

- Lead the Engineering Interactive Devices (EnD) Group at **Glasgow University**.
- Scotland Chair of the IEEE Education Society.
- Chair of IET's Pedagogy in Engineering and Technology.
- Chair of UK:iLRN Chapter

- I'm interested in **designing** **interactive** technologies that have a **measurable** impact on the way we **learn**.

Research Themes



Why Energy?

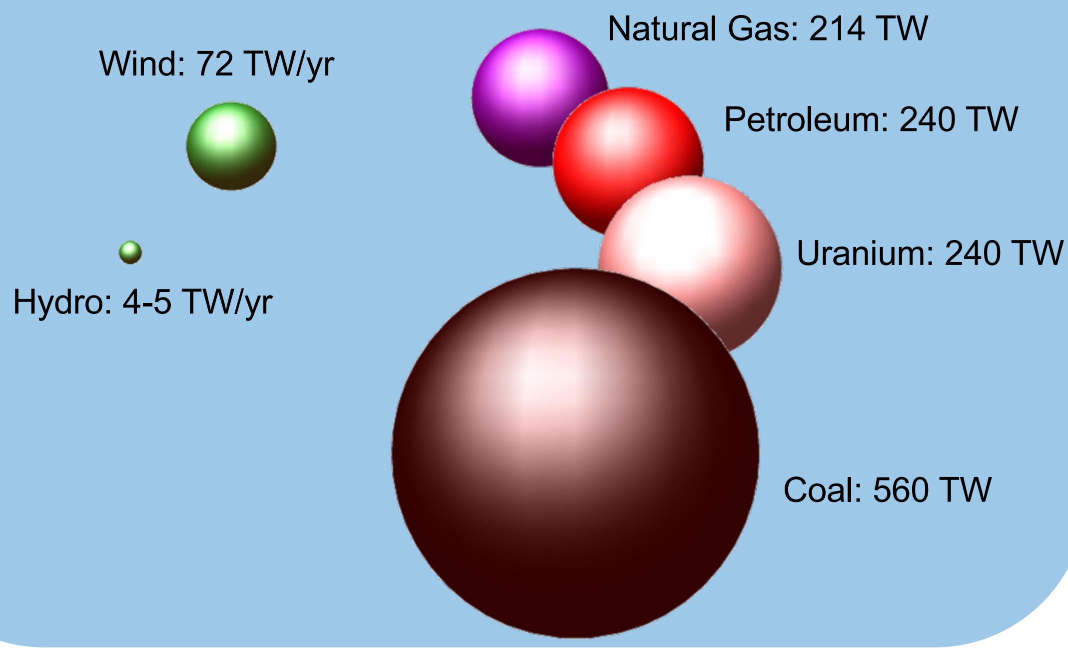
Our Energy Consumption …

- We consume around 20 TW $(10^{12}\ W)$ of power each year.

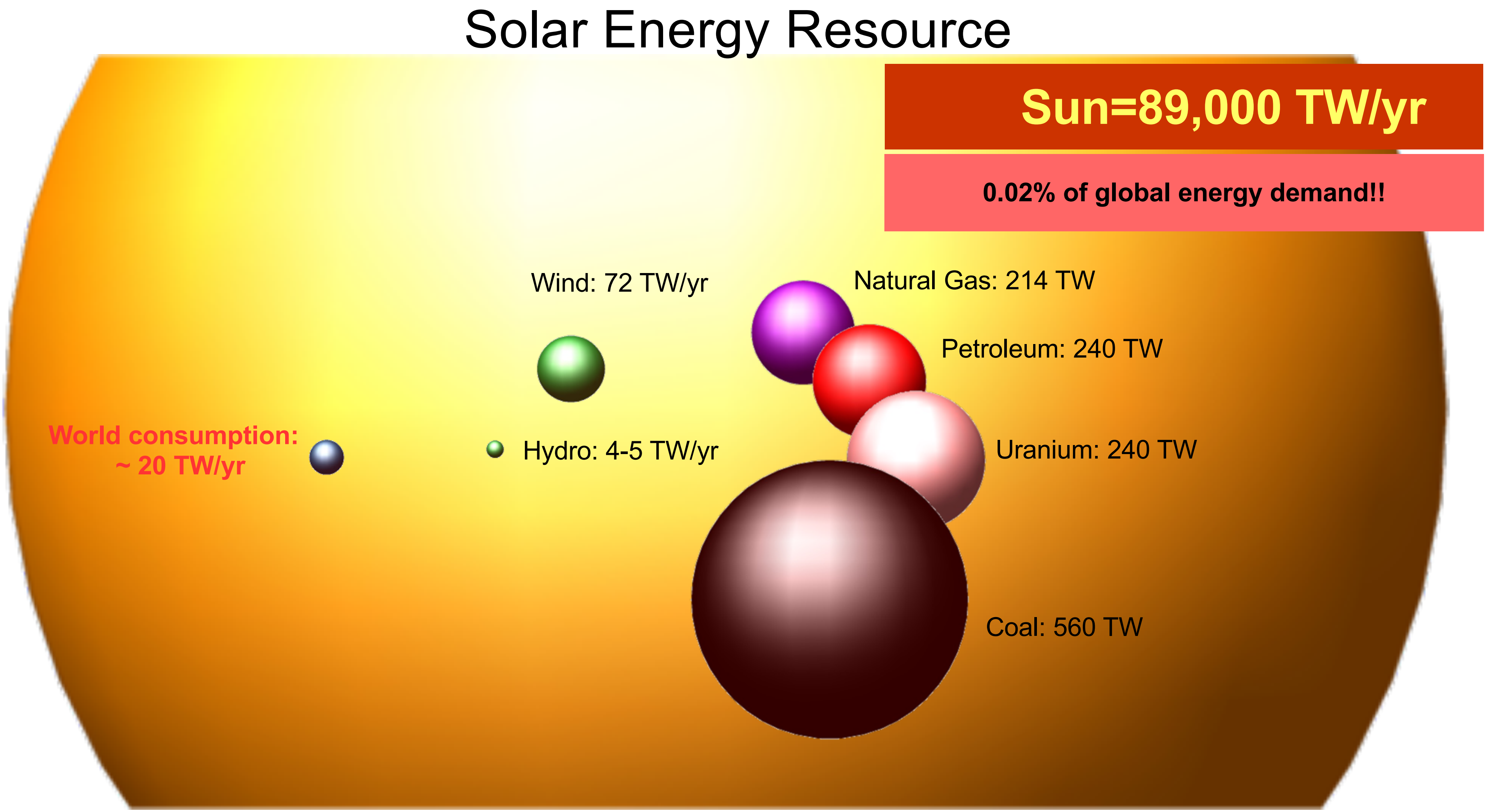
- Around 20 % of that power is consumed by the US.

How much resource is available?

- We have a number of resources to satisfy these needs.



Why Solar?


Solar Energy Resource
Sun=89,000 TW/yr
0.02% of global energy demand!!
Wind: 72 TW/yr
Natural Gas: 214 TW
Petroleum: 240 TW
World consumption:
~ 20 TW/yr
Hydro: 4-5 TW/yr
Uranium: 240 TW
Coal: 560 TW

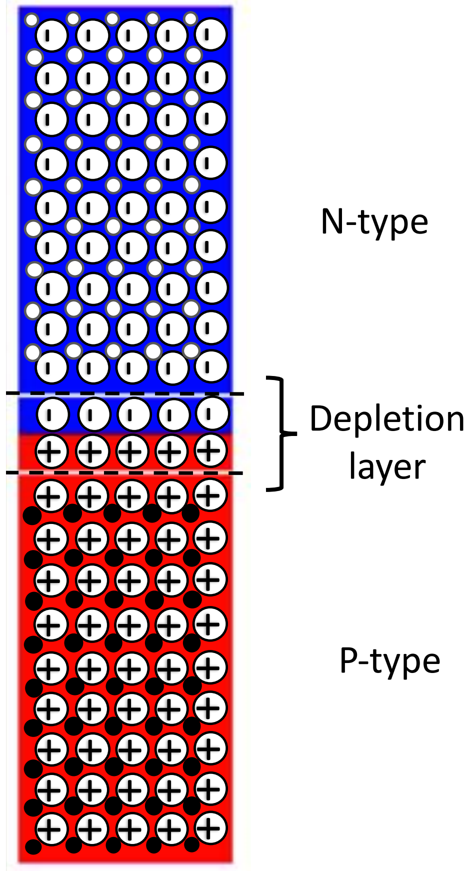
The PN Junction

Solar Cells are made from semiconducting materials such as Silicon.

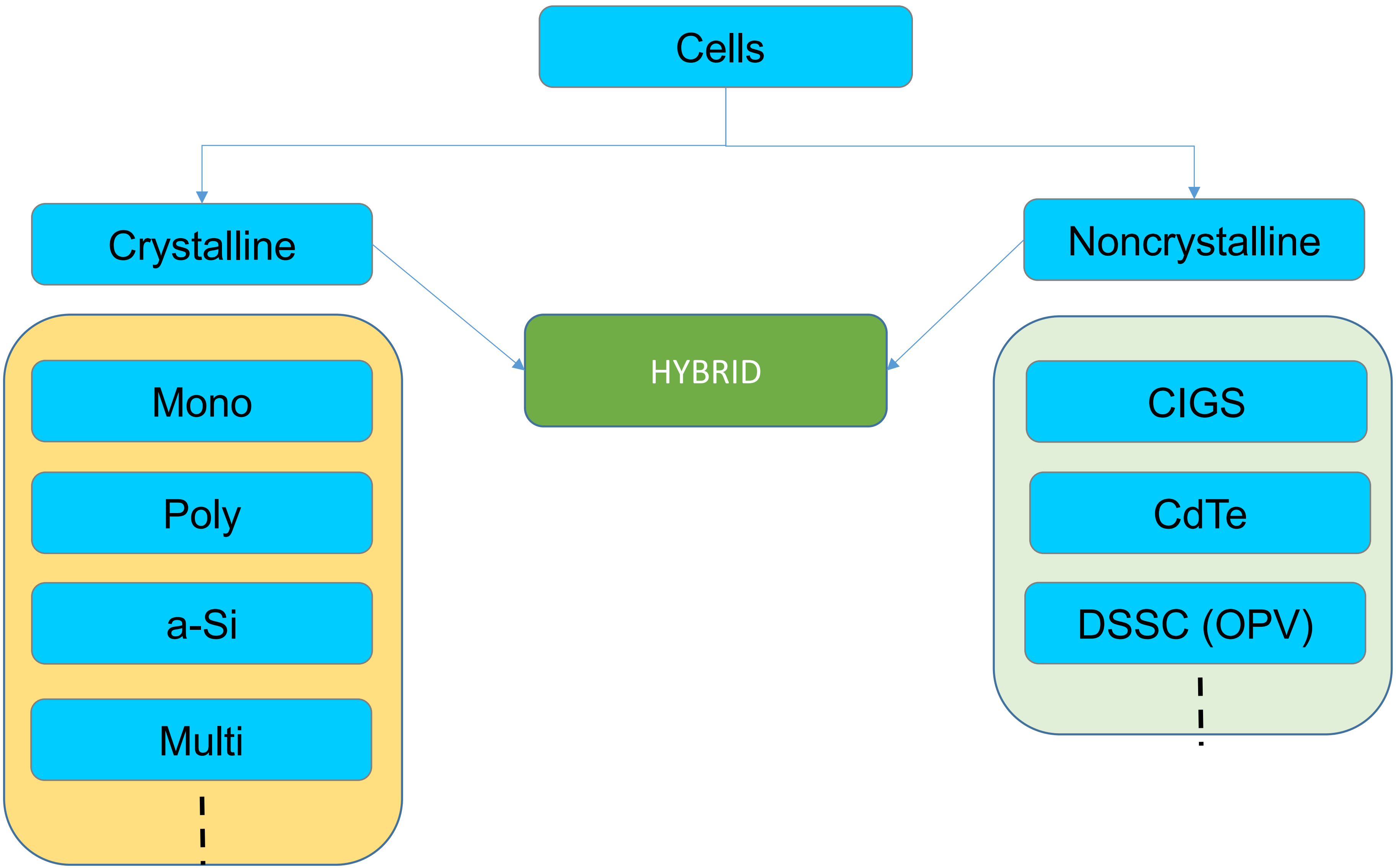
Two types of semiconducting materials are required: an n-type and a p-type semiconductor.

The process of "doping" is used to create *n* and *p* materials, which have excess electrons or holes.

The boundary between the two types of semiconductors is known as the PN junction.



Types of Solar Cells



Crystalline Solar Cells

Mono-crystalline

- Colour = Dark blue/black
- Efficiency = 16-19%
- Thickness = 0.2-0.3mm
- Size = 4-8” (10x10cm – 15x15cm)

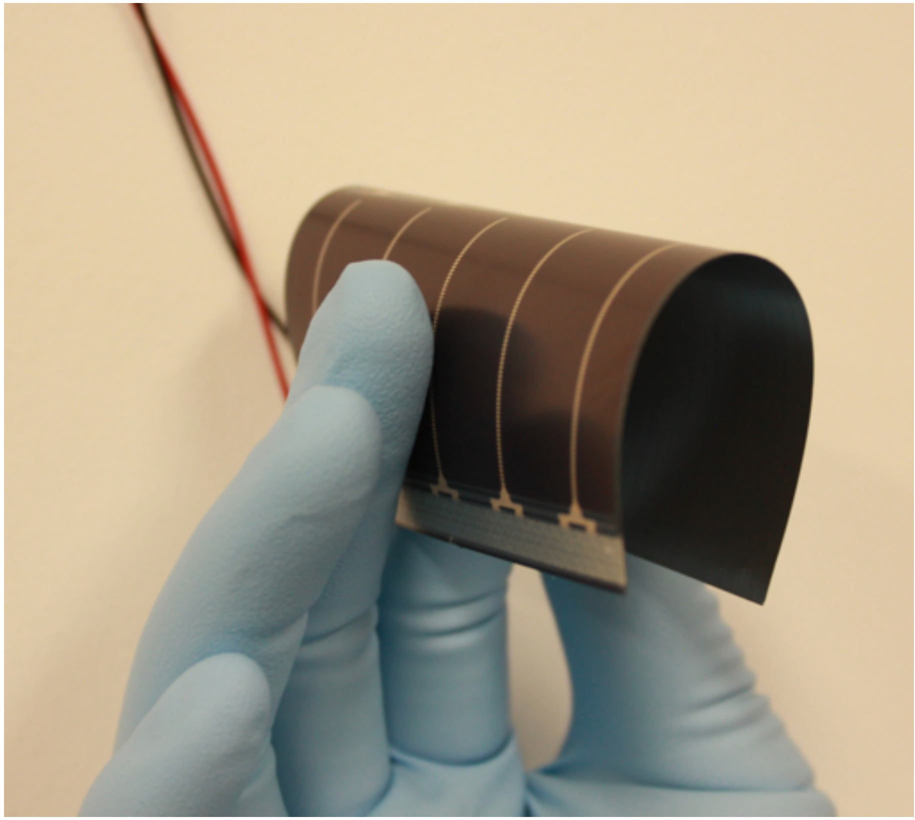
Poly-crystalline

- Colour = blue
- Efficiency = 14-17%
- Thickness = 0.2-0.3mm
- Size = 4-8” (10x10cm – 21x21cm)

Thin Film Solar Cells

Examples include:

- Cadmium Telluride (CdTe).
- Amorphous silicon (a-Si).
- Copper Indium Gallium Selenide (CIGS).



Materials are highly absorptive. Therefore, a small layer is sufficient (1-5 microns).

Thin Film cells are not restricted to any size or shape.

Can be deposited on any substrate.

Can be connected monolithically during coating process.

Principles

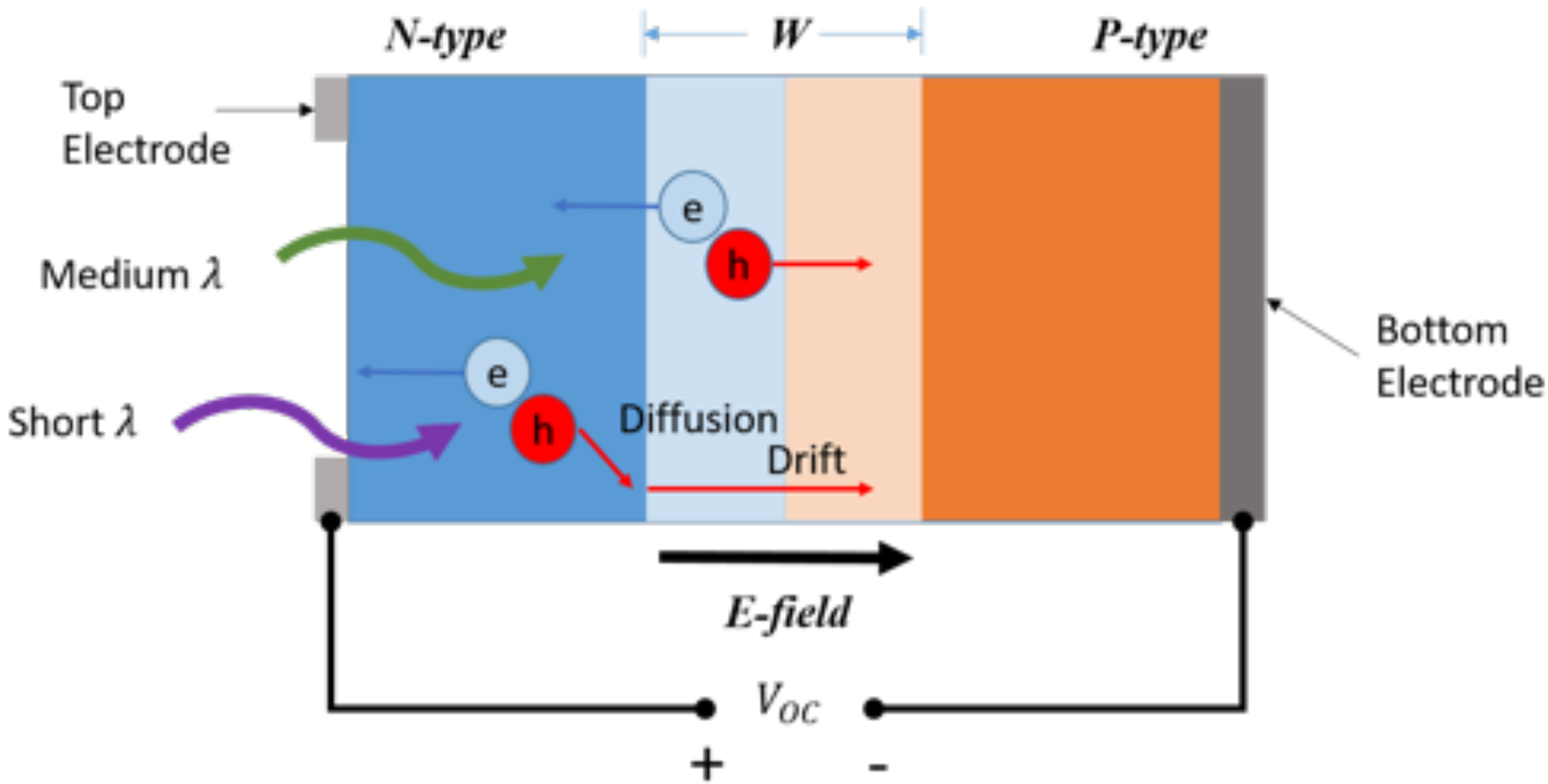
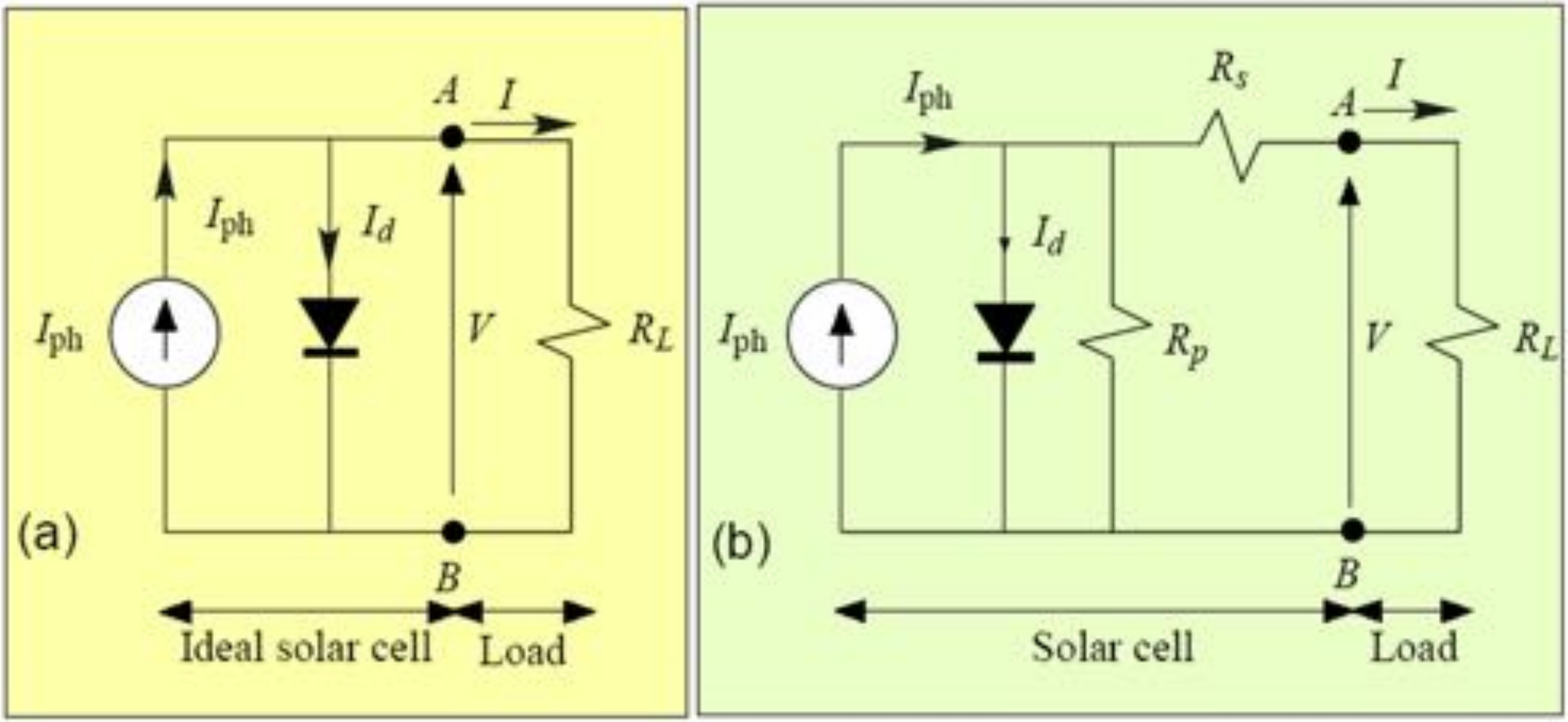


Image from: Ghannam, R. et al. (2019) Artificial intelligence for photovoltaic systems. (doi:10.1007/978-981-13-6151-7_6)

Ideal vs Practical Solar Cells

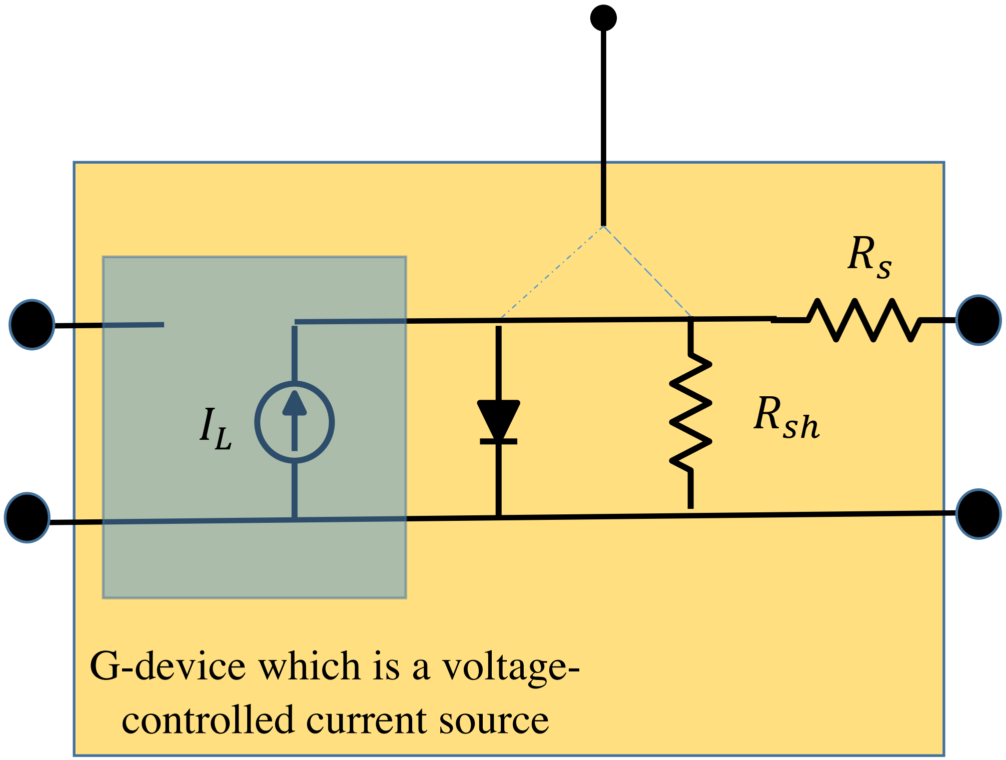


$$I = I_{\text{ph}} - I_o\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

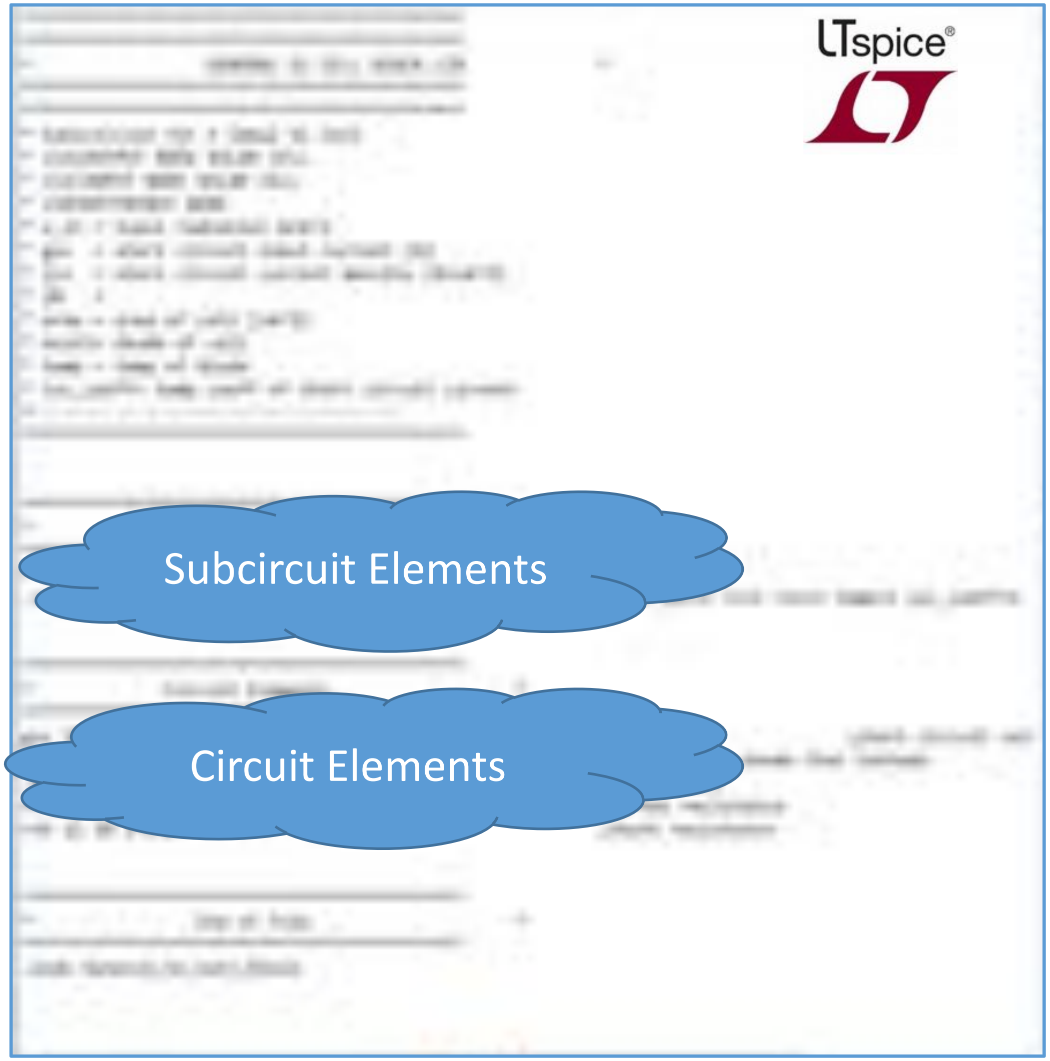
$$I = I_{\text{L}} - I_o\left[\exp\left(\frac{V + IR_s}{\eta kT / q}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

Image from: Ghannam, R. et al. (2019) Artificial intelligence for photovoltaic systems. (doi:10.1007/978-981-13-6151-7_6)

SPICE Solar Cell Model

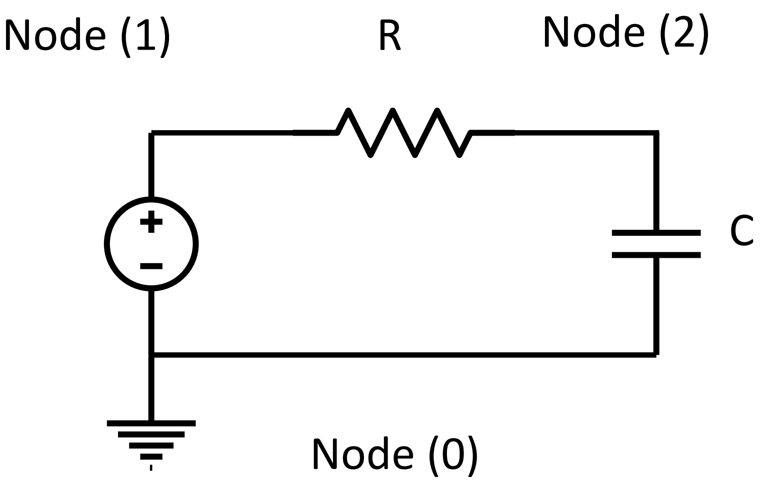


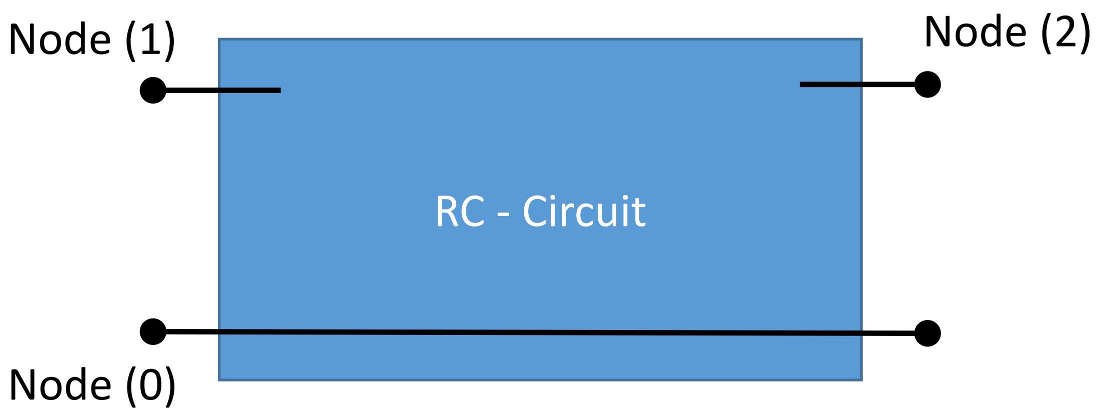
$$I_L = \frac{J_{sc}A}{1000}G$$



G = Irradiance values ($100W/m^2$, $500W/m^2$, …etc)

SPICE Solar Cell Model

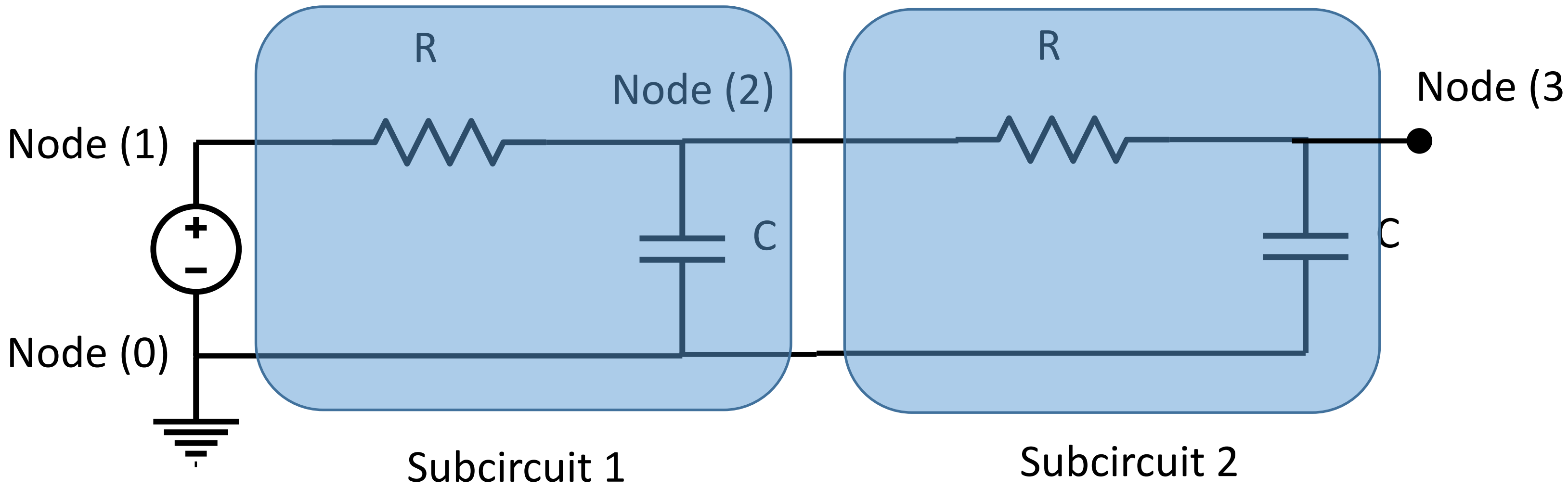




Resistor Syntax :	rxx node_a node_b {value}
Capacitor Syntax :	cxx node_a node_b {value}
Pulse V. Source :	vxx node+ node- pulse (initial_value pulse_value delay risetime falltime pulse_length period)
Transient analysis:	….
Postprocess :	.probe
Plot results :	.plot tran {variable1} {variable2}
End file :	.end

```
*learning.cir
r1 1 2 1K; resistor between node (1) and node (2) value 1 KOhm
c1 2 0 1n; capacitor between node (2) and node (0) value 1 nF
vin 1 0 pulse (0 5 0 1 u 1 u 10 u 20 u); voltage source between node (1) and node (0)
.tran 0 40 u
.probe
.plot tran v(1) v(2)
.end
```

SPICE Solar Cell Model



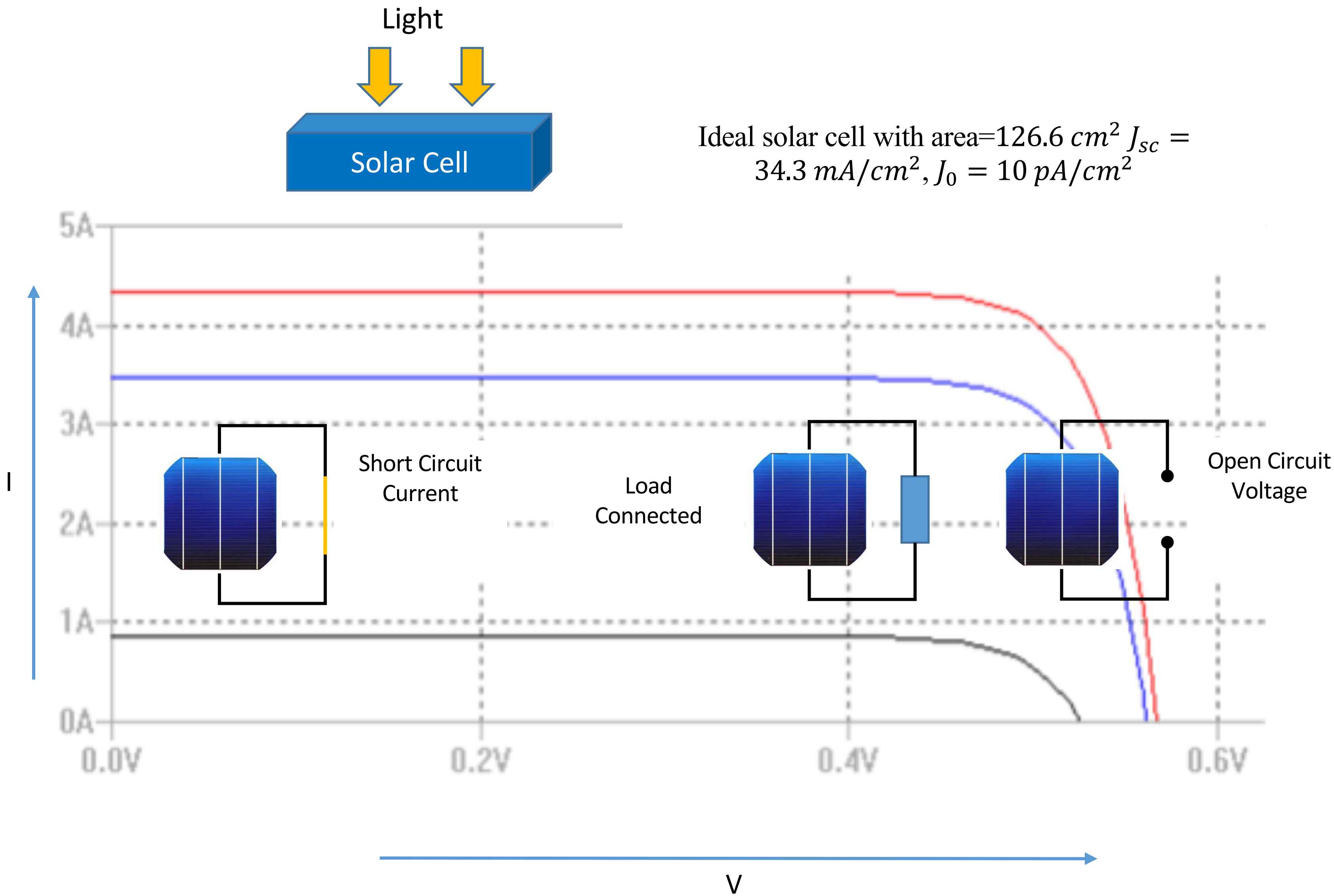

```
* rc.lib
.subckt rc 12 11 10 params: r=1 c=1
r1 11 12 {r}
c1 12 10 {c}
.ends rc
```

```
* learning_subckt.cir
.include rc.lib
xrc1 2 1 0 rc params: r=1k c=1n
xrc2 3 2 0 rc params: r=10k c=10 n

vin 1 0 pulse (0 5 0 1 u 1 u 10 u 20 u)
.tran 0.1 u 40 u
.probe
.plot tran v(1) v(2) v(3)
.end
```

Effect of Illumination

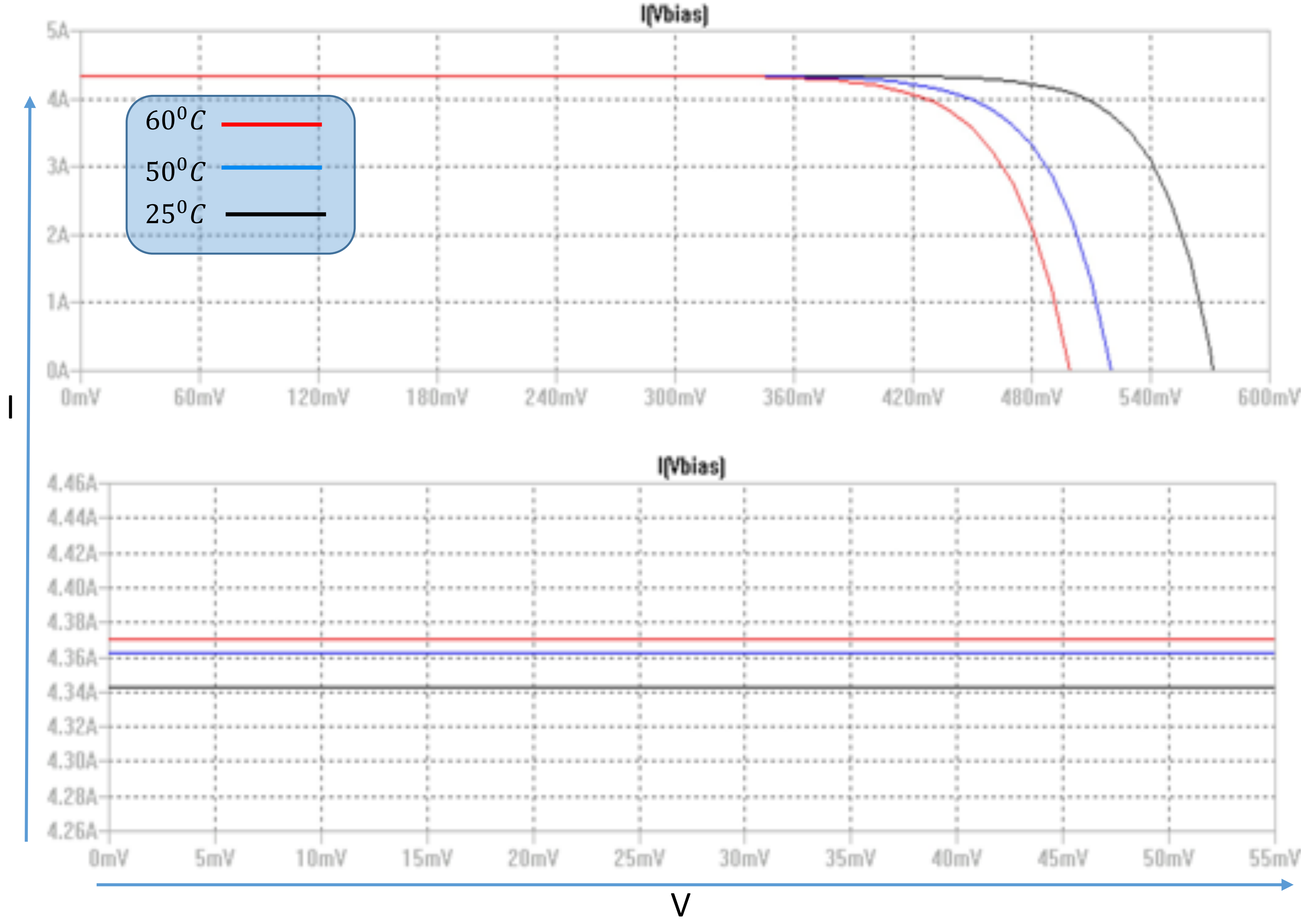
Ideal solar cell with area=126.6 cm^2 $J_{sc} = 34.3\ mA/cm^2, J_0 = 10\ pA/cm^2$



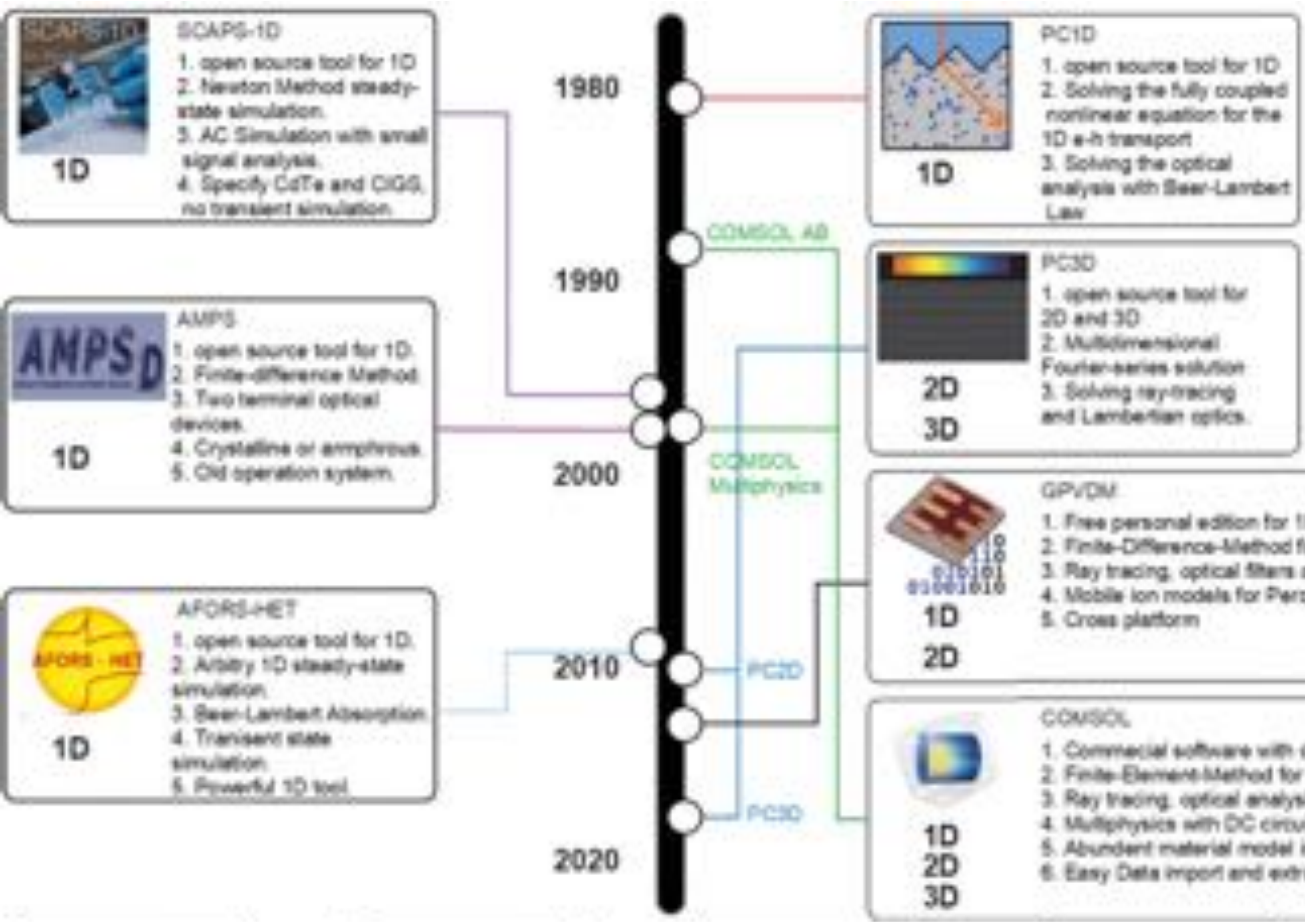
Effect of Temperature

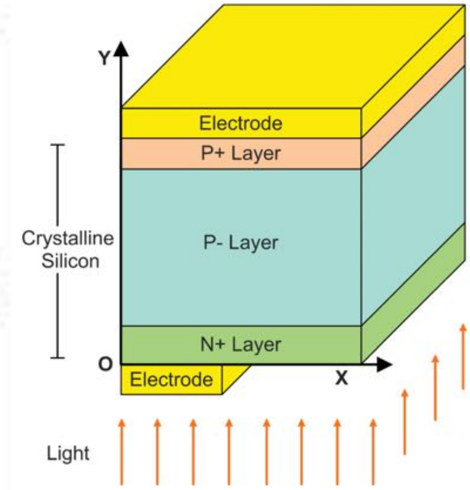
$R_s = 1\mu\Omega$,
$R_{sh} = 10k\Omega$.
Temperature varied from 25^0C (black line), to 60^0C (red line).

As temperature increases the open circuit voltage decreases since the band gap of the intrinsic semiconductor shrinks.

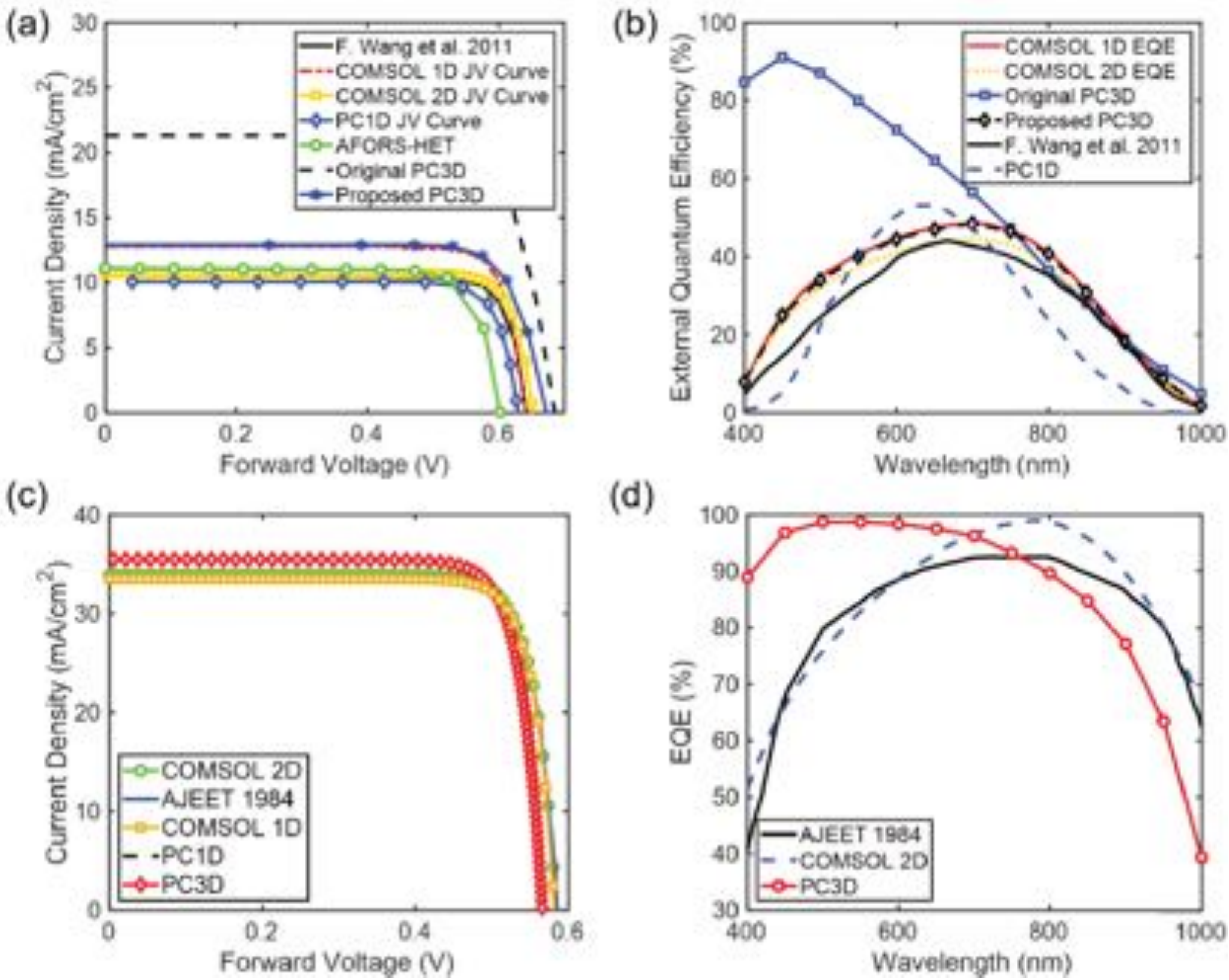


PV Device Modelling





PV Device Modelling



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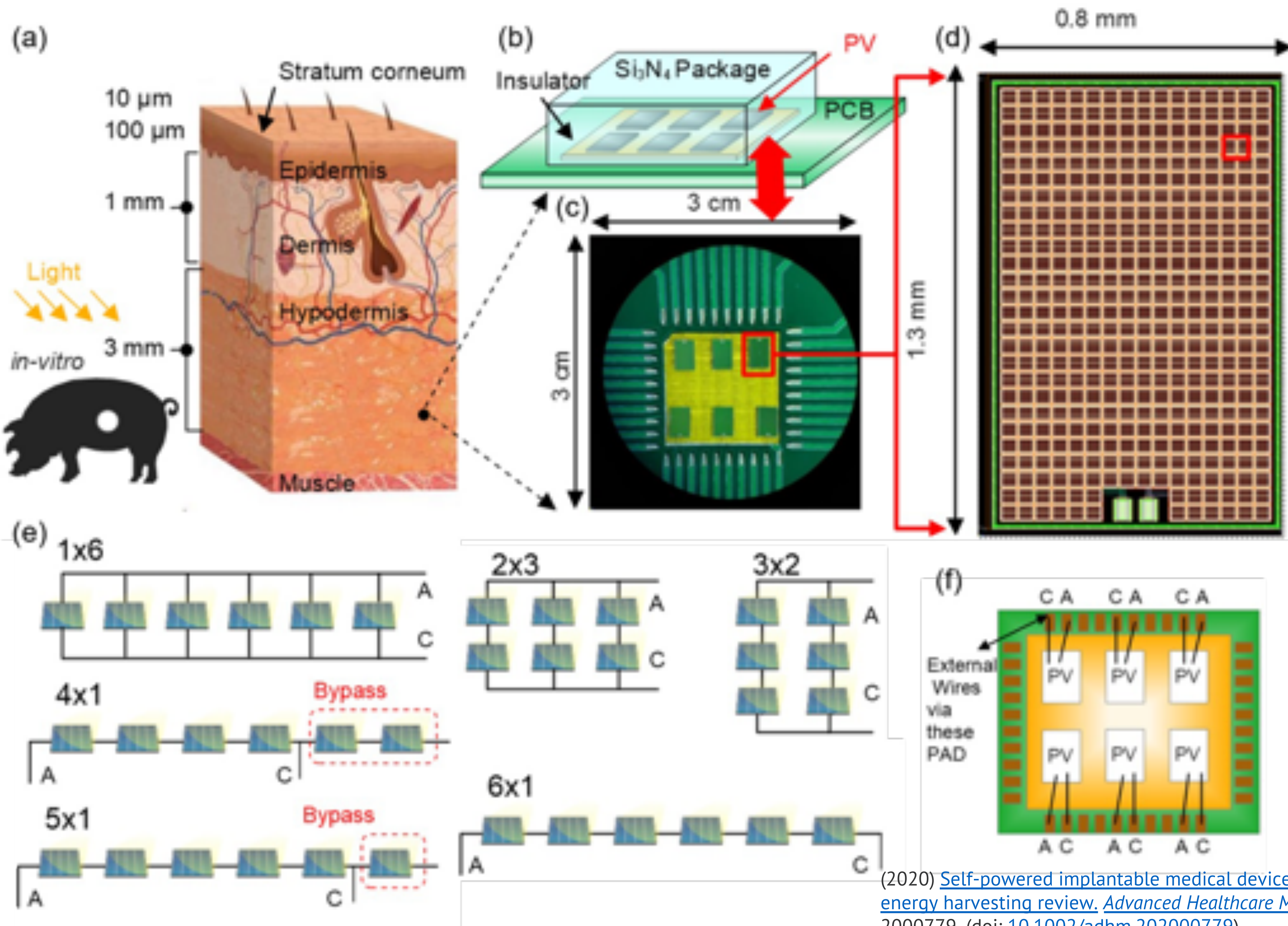
PV Device Modelling



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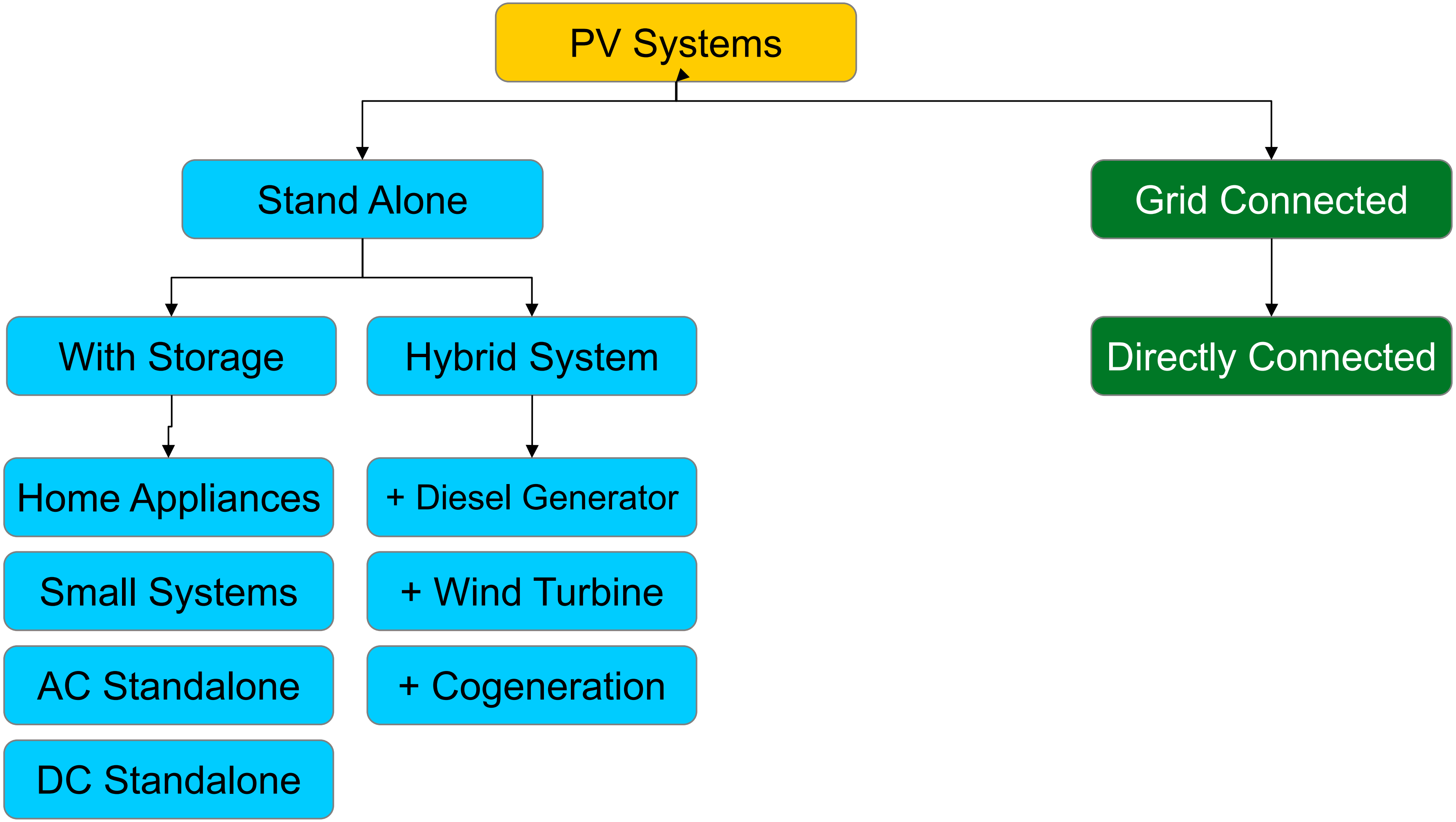
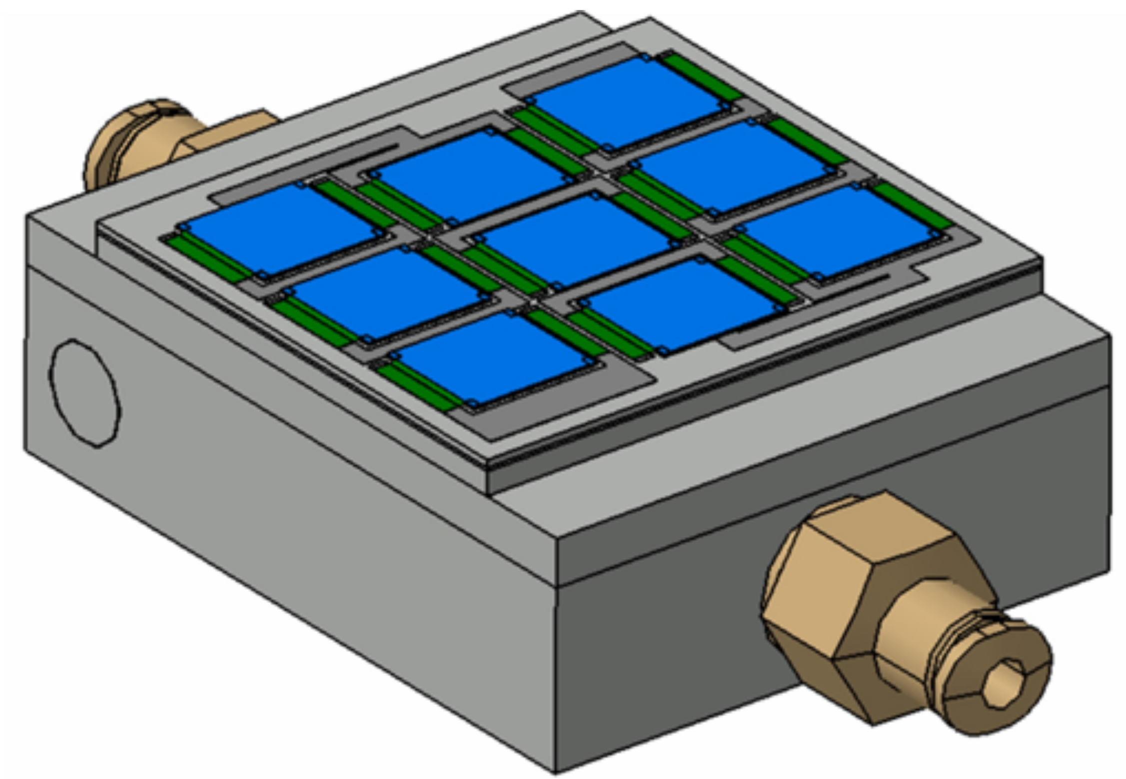
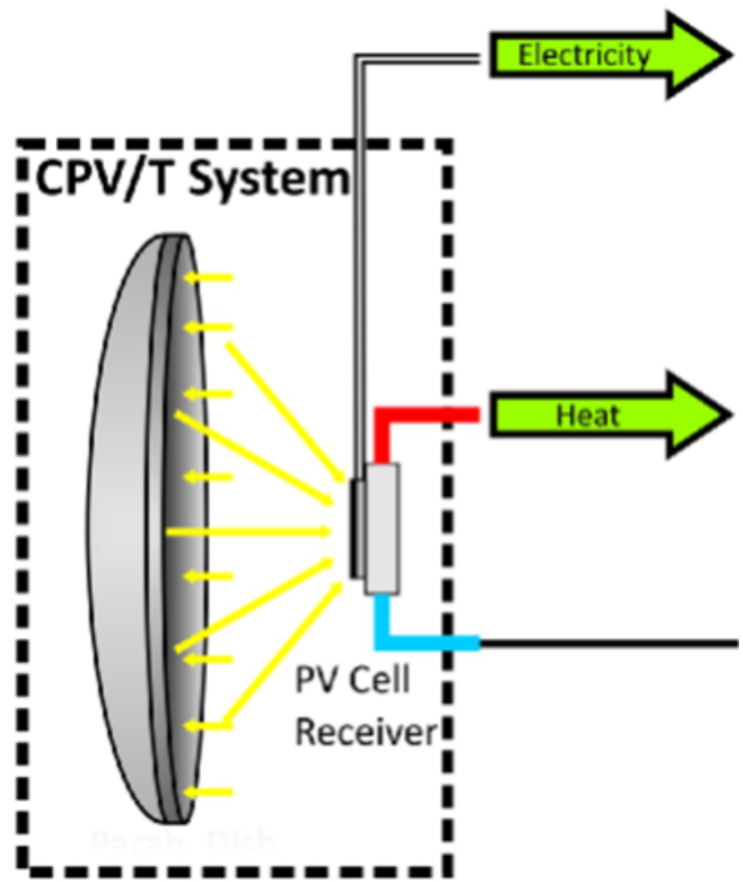
(2022) On-chip photovoltaic cell for energy-autonomous implantable devices, Under Review IEEE TED.

PV System Types



Concentrated PV Systems





Energy from Batteries

Battery State of Charge (SOC)

The fraction of battery capacity that is available from the battery.

Depth of Discharge (DOD)

The Depth of Discharge (DOD) of a battery determines the fraction of power that has been withdrawn from the battery.

SOC	DOD
100%	0%
75%	25%
50%	50%
25%	75%
0%	100%

The notation to specify battery capacity is written as **Cx**, where **x** is the time in hours that it takes to discharge the battery. For example, **C10 = xxx** means that the battery capacity is xxx when the battery is discharged in 10 hours.

Inverters

A solar inverter, or PV inverter, converts the variable direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid or used by a local, off-grid electrical network.

String

Inverters that are wired and connected in series.

Micro

Small inverter for converting DC power from individual panels

Central

For large power plant applications that are >100 kW in size.

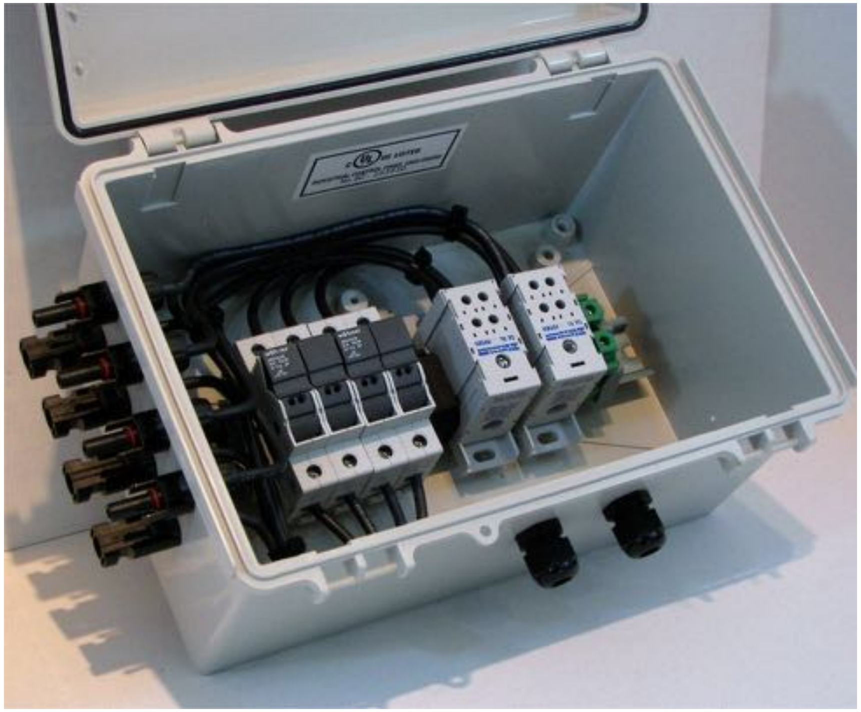
Charge Controllers

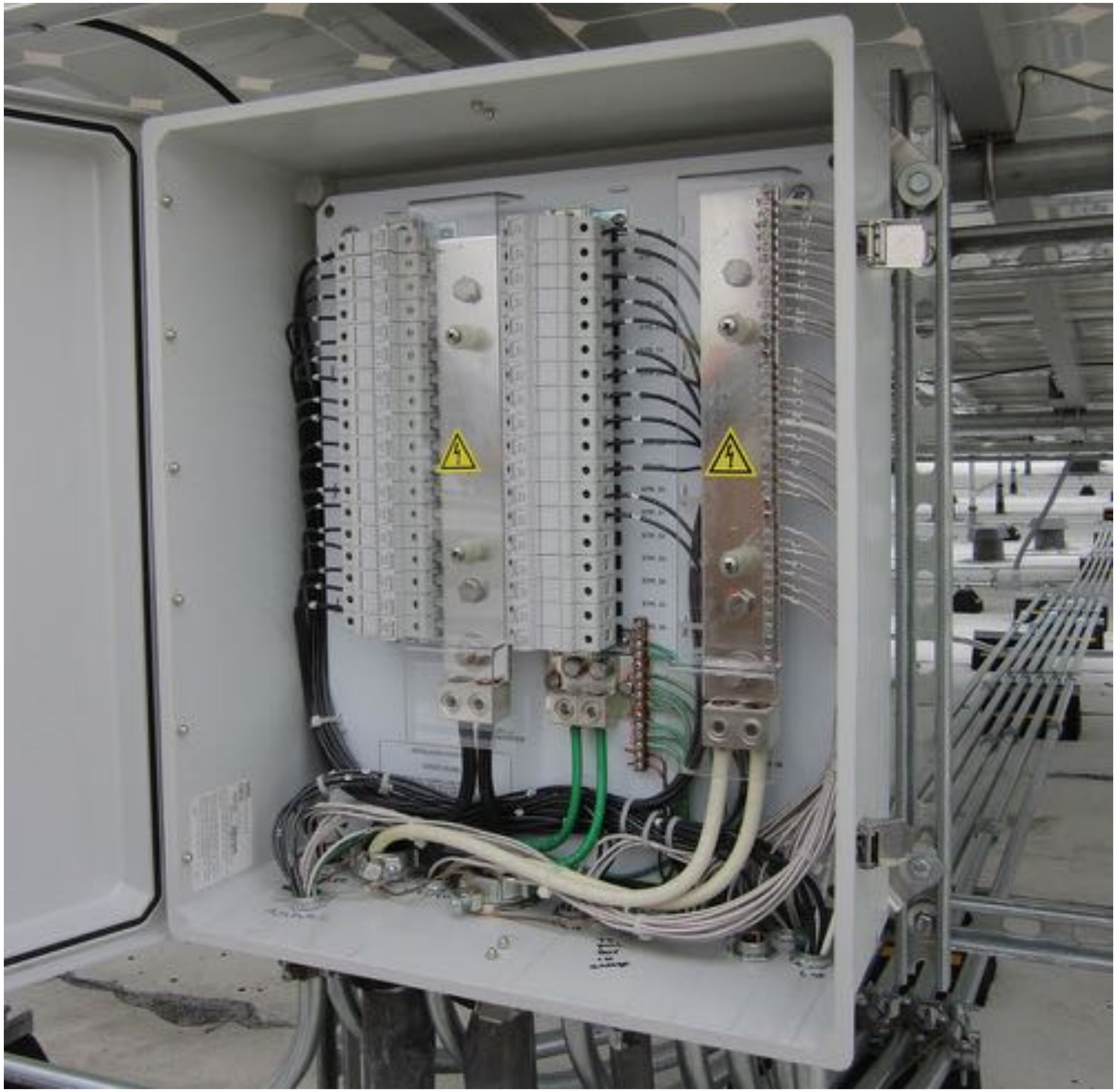
University of Glasgow

A charger controller, charger regulator or battery regulator limits the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and may protect against overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk. It may also prevent completely draining ("deep discharging") a battery, or perform controlled discharges, depending on the battery technology, to protect battery life.

Maximum power point tracking (MPPT) charge controllers aim to achieve the maximum possible power from the PV array. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency. It is the purpose of the MPPT system to sample the output of the cells and determine a resistance (load) to obtain maximum power for any given environmental condition.

Combiner Boxes





Combiner boxes are an integral part of many PV installations, serving as the "meeting place" where the wiring from array series strings come together in parallel connections.

PV System Design

The first step in designing a solar PV system is to find out the total power and energy consumption of all loads:

The daily energy use will be:

<Number of appliances × Power consumption × operating per day >

Example: A house has the following electrical appliance usage:
One 18 Watt fluorescent lamp with electronic ballast used 4 hours per day. Two 60 Watt fan used for 2 hours per day. One 75 Watt refrigerator that runs 24 hours per day with compressor run 12 hours and off 12 hours.

Total appliance use = (1x18 W x 4 hr) + (2x60 W x 2 hr) + (1x75 W x 24 x 0.5 hr)

= 1,212 Wh/day

PV System Sizing

The required PV module power is given as:

$$P_{PV} = \frac{Load \; * hr}{\eta_{system} * S_{pk-hr}}$$

S_{pk-hr} is the pk sun hours*

$$\eta_{system} = \eta_{cable} \times \eta_{inv} \times \eta_{reg} \times \eta_{batt}$$

The number of panels required to provide this power is:

$$N = \frac{P_{PV}}{Panel_{pk}} = \frac{P_{PV}}{\eta_{PV}.A_{PV}.G_t}$$

η_{pv} is the instantaneous PV generator efficiency, A_{PV} is the area of a single module used in a system (m^2), G_t is the global irradiance incident on the titled plane (W/m^2) and N is the number of modules.

Battery System Sizing

1. First calculate the daily energy use or load in the system: E_{load}

2. Then calculate E_{Tbat}

$$E_{Tbat} = N_{aut} * \frac{E_{load}}{DOD}$$

with N_{aut} the number of days of autonomy and DOD_{max} the maximum depth-of-discharge (DOD) of the batteries

3. Divide by system voltage to obtain Ahr_{Tbat}

4. Then divide by battery capacity to obtain N_{bat} in parallel

5. Number of batteries in series obtained from system voltage

What if we could design PV systems…

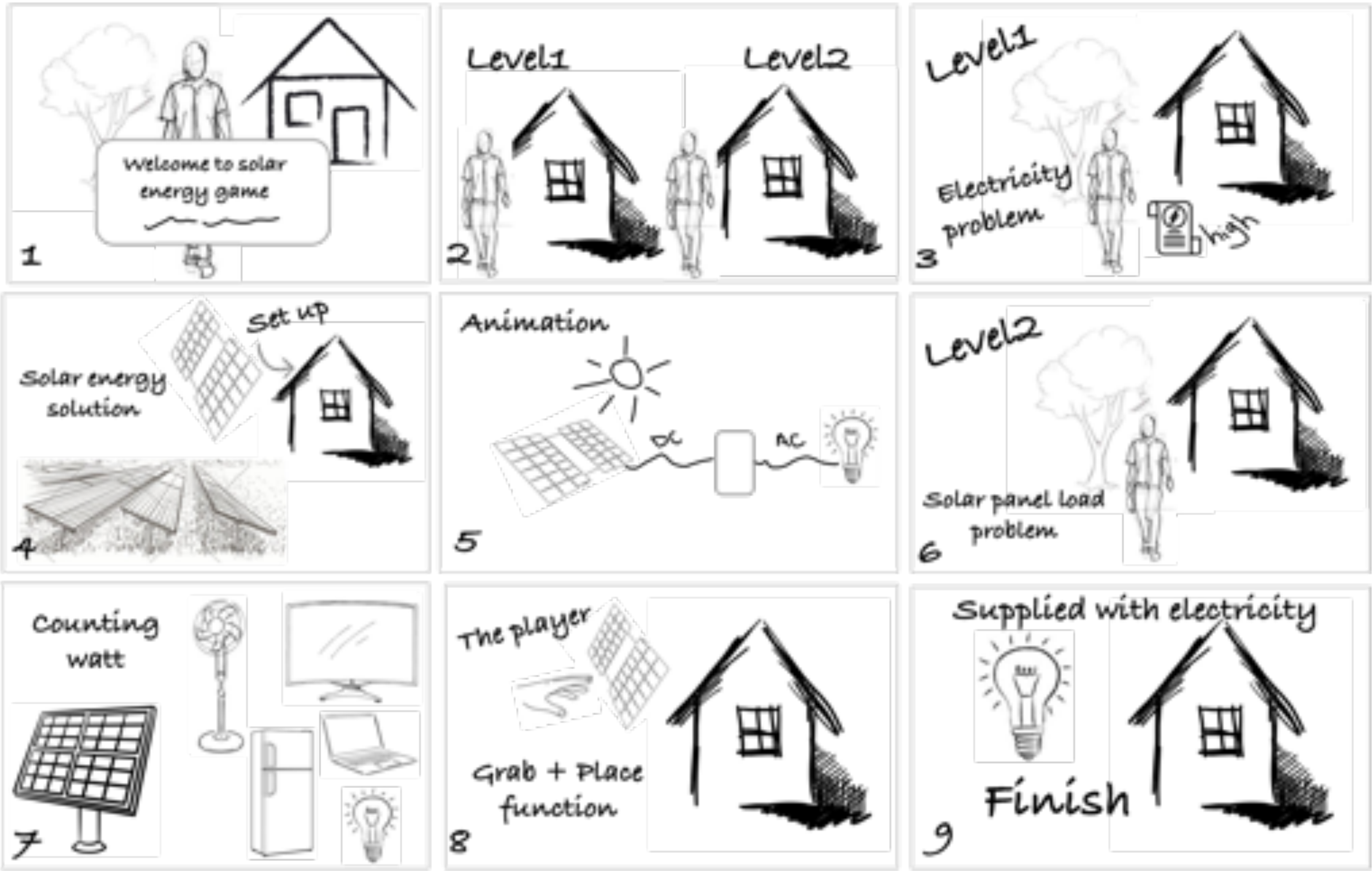
…. differently?


GARAGE

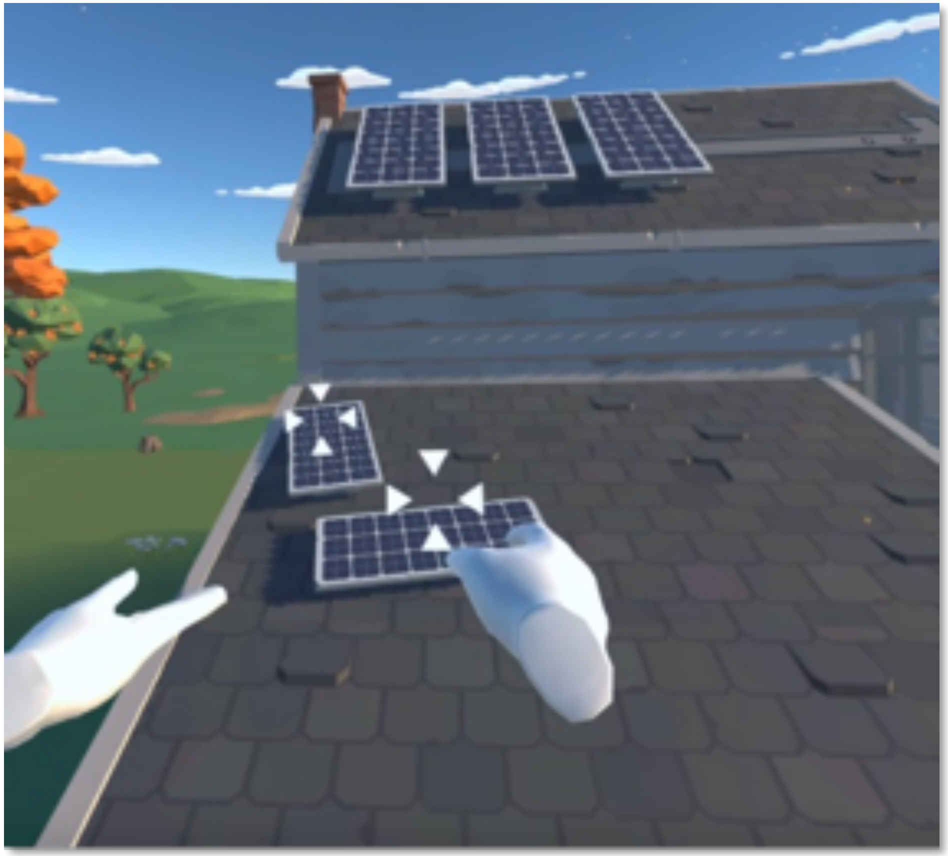
Background

Why Extended Reality for Climate Change?

Experiment

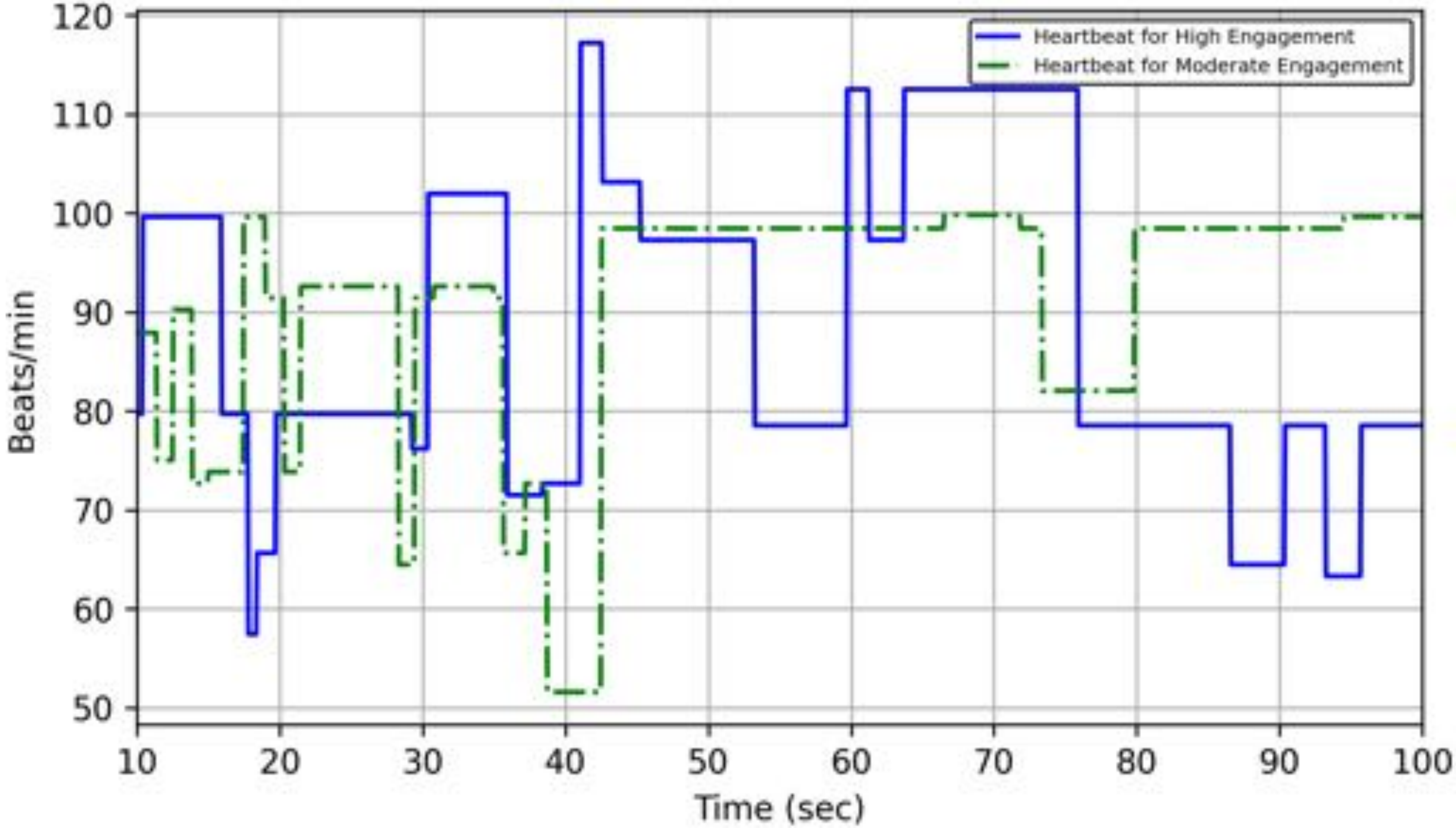

Welcome to solar energy game
1
Level1
Level2
2
Level1
Electricity problem
high
3
Solar energy solution
Set up
4
Animation
DC
AC
5
Level2
Solar panel load problem
6
Counting watt
7
The player
Grab + Place function
8
Supplied with electricity
Finish
9

Results



Results + Experiments

Results



Heartbeat for High Engagement
Heartbeat for Moderate Engagement
Beats/min
Time (sec)
120
110
100
90
80
70
60
50
10
20
30
40
50
60
70
80
90
100

AR/VR/XR Work

Current Work



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Thank you!

References

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3. Abdellatif, S., Kirah, K., Ghannam, R., Khalil, A.S.G. and Anis, W., 2018, February. Comprehensive study of various light trapping techniques used for sandwiched thin film solar cell structures. In *Physics, simulation, and photonic engineering of photovoltaic devices VII* (Vol. 10527, p. 1052715). International Society for Optics and Photonics.

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