PV sizing & PV markets

Dr Konstantinos Ninikas
kninikas@uth.gr

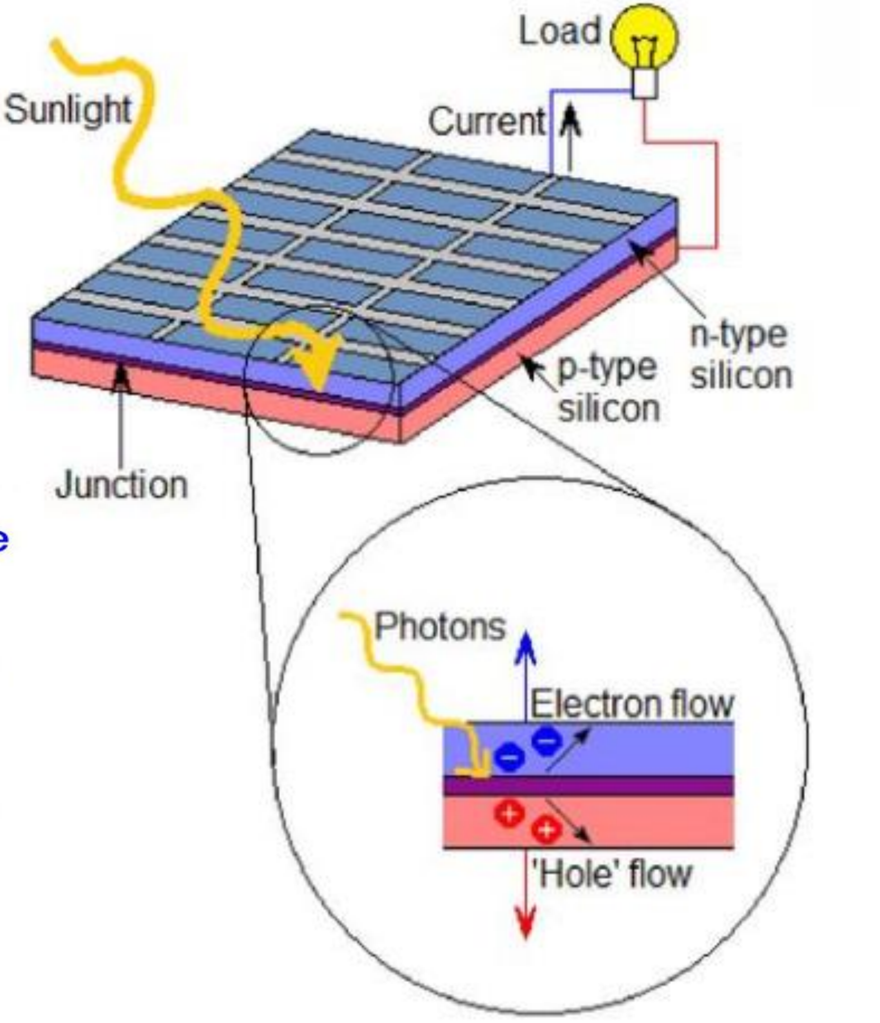
Solar Photovoltaic PV

- PV cells are made from layers of semi-conducting material, usually silicon.
- When light shines on the cell it creates an electric field across the layers.
- The stronger the sunshine, the more electricity is produced.
- Groups of cells are mounted together in panels or modules that can be mounted on your roof.

Solar Photovoltaic PV

The solar PV cell operation is based on the ability of specifically engineered semiconductors to convert the absorbed energy from sunlight d.c. (direct current) electricity

In the conversion process, the incident energy of the sun's light creates electrically charged, free electrons in the solar cell, which are then separated by the engineered semiconductor's (solar cell's) internal structure to produce electrical current which is collected to an external electrical load.



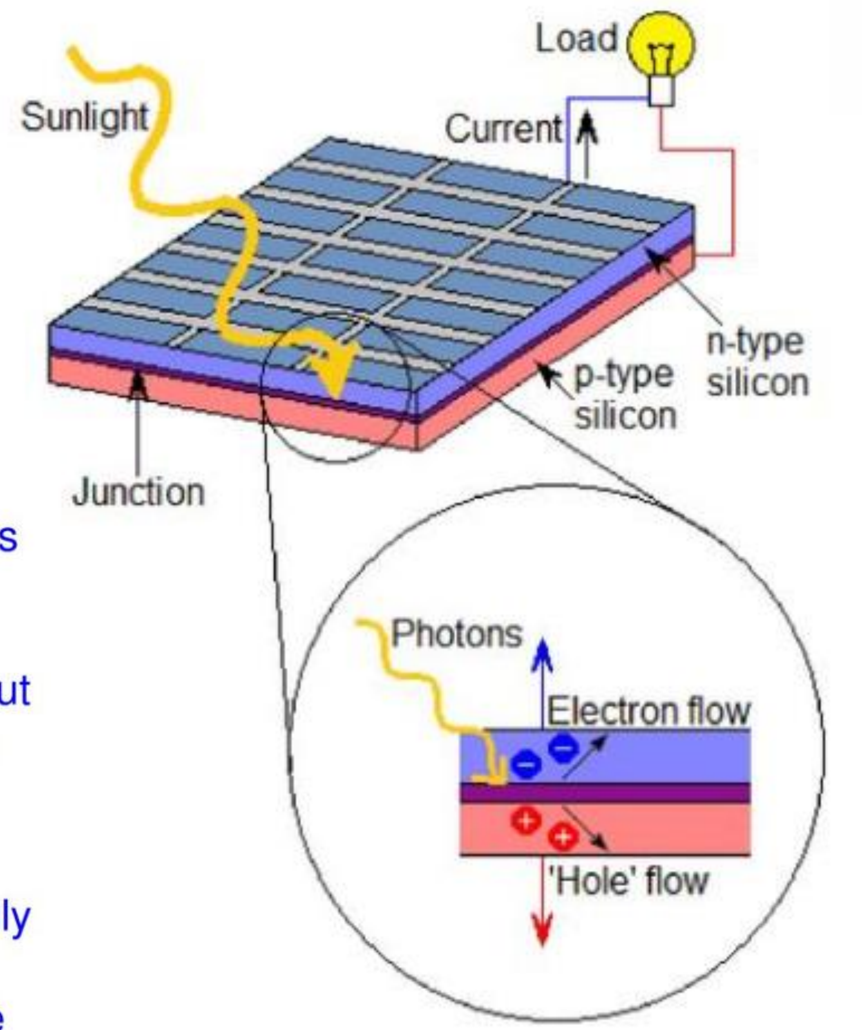
Solar Photovoltaic PV

Solar inverters, also called grid-tied inverters, convert the direct current (d.c.) electricity produced by your solar PV panels to alternating current (a.c.) electricity that can be used in the home and exported back to the grid.

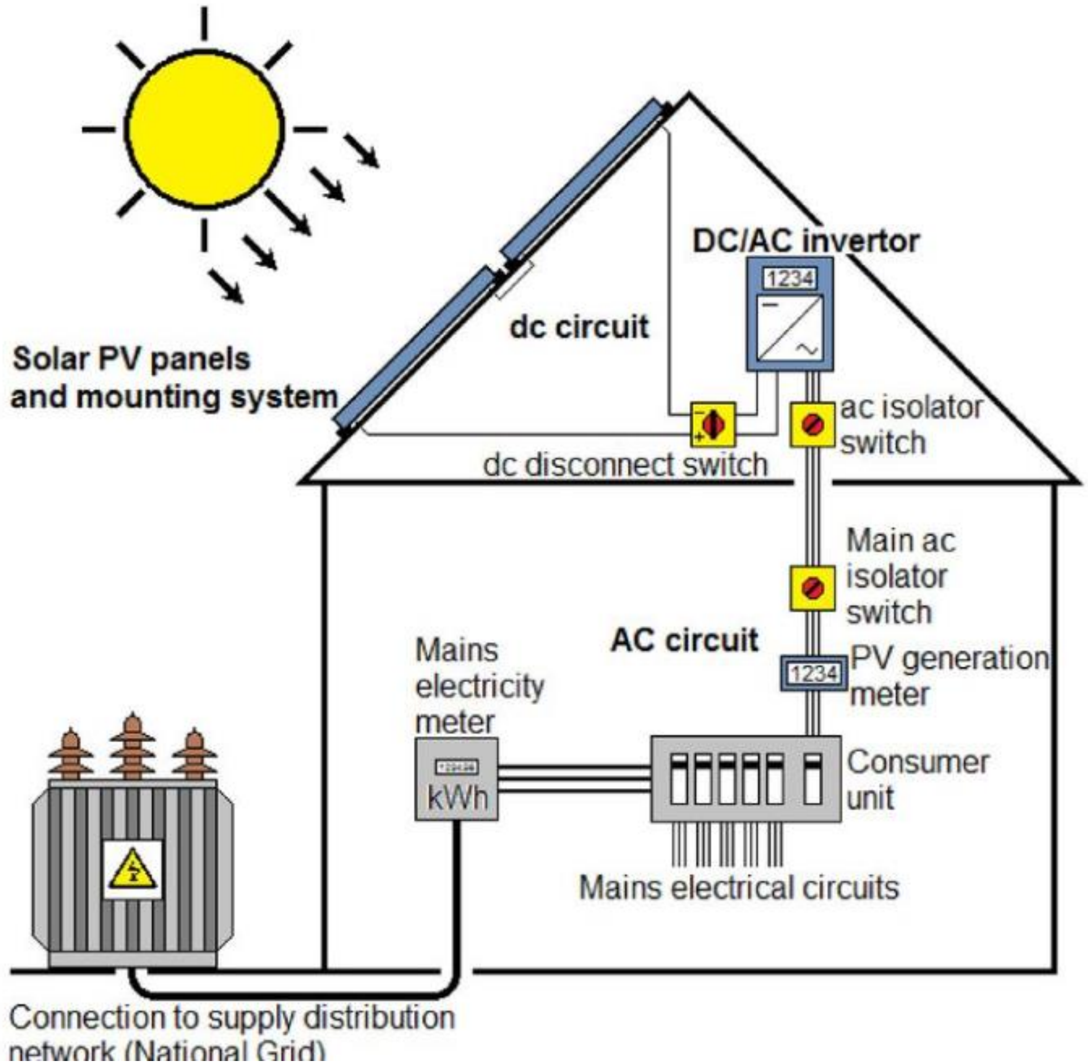
Solar invertors also:

- ensure compliance with regulations about feeding electricity into the grid, for example by immediately disconnecting if there is a power cut
- maximise electricity production by constantly varying its resistance (load).

Solar inverters are very efficient, usually 93–96% depending on the make and model - never 100% because they use some of the input d.c. power to run, generally around 10-25W.



Solar Photovoltaic PV



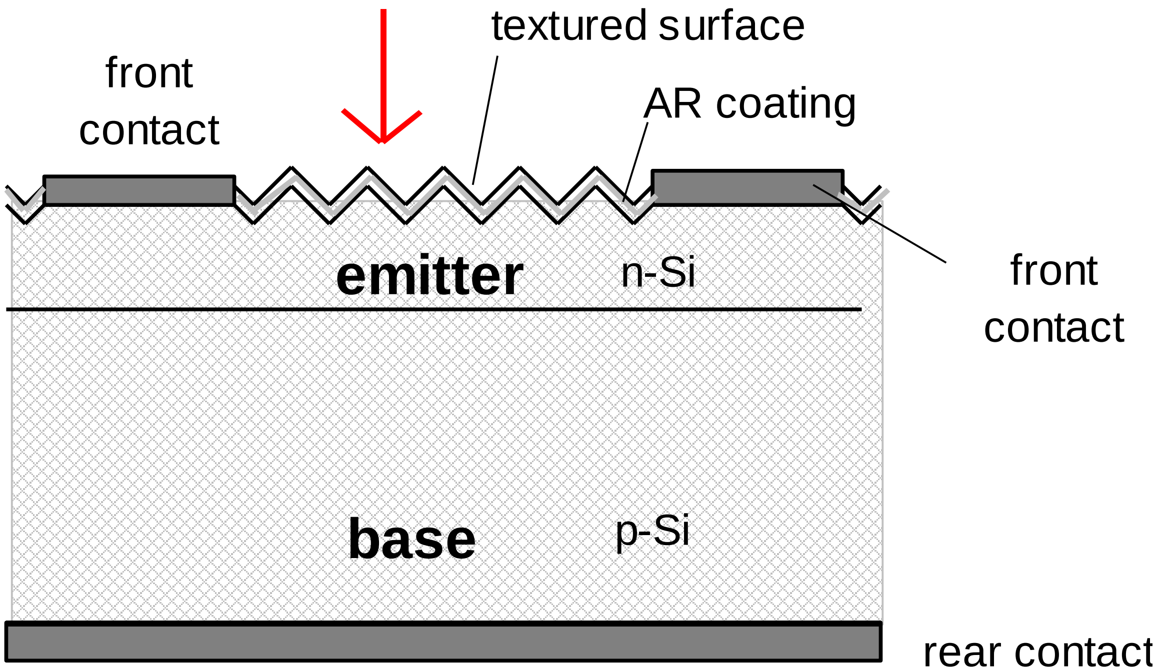
Forms of silicon PV

Monocrystaline

- One of the two most used form of Silicon PV
- To produce monocrystalline silicon a crystal of silicon is grown from highly pure molten silicon.
- These PV cells have typical efficiencies of 17-19% and are the most efficient type of the three types of silicon PV cell.
- Best commercial module currently is sitting at 22.6% (Sunpower Maxeon 3)
- However, they require more time and energy to produce than polycrystalline silicon PV cells and are therefore slightly more expensive.
- Smooth textures and thick. Very rigid, need to be mounted on a frame
- All PV panels suffer from Light induced degradation (LID) which is the annual power loss. Mono crystalline can exhibit a loss of 0.25% per year – the smallest of silicon PV)
- Over a typical 25 life span that is around a 10% loss compared to the original stated capacity.

How is monocrystalline PV is actually made?

- First step is the silicon wafer production. This is done by the Czochralski process.
- https://www.youtube.com/watch?v=AMgQ1-HdElM
- Once the wafer is produced, it is doped, electrical circuitry is screen printed and an antireflective coating is added.
- More can be seen here https://www.youtube.com/watch?v=IAufbqbUS6k

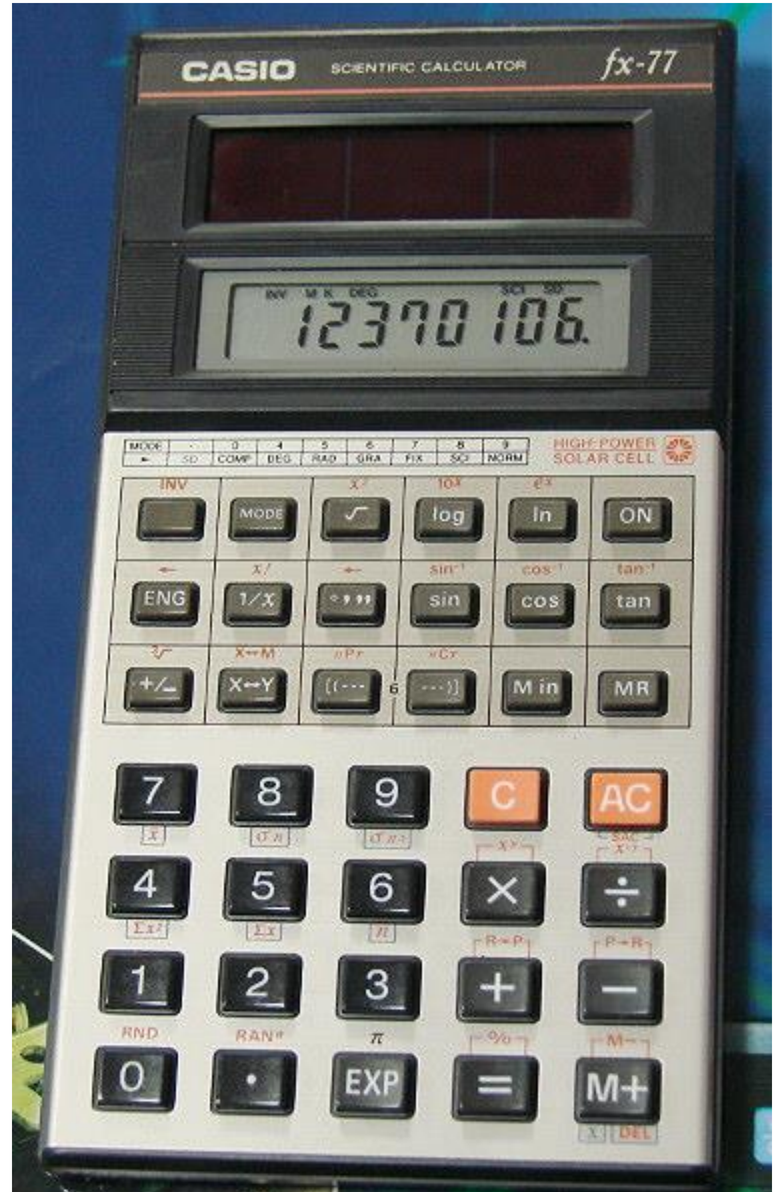


Polycrystaline

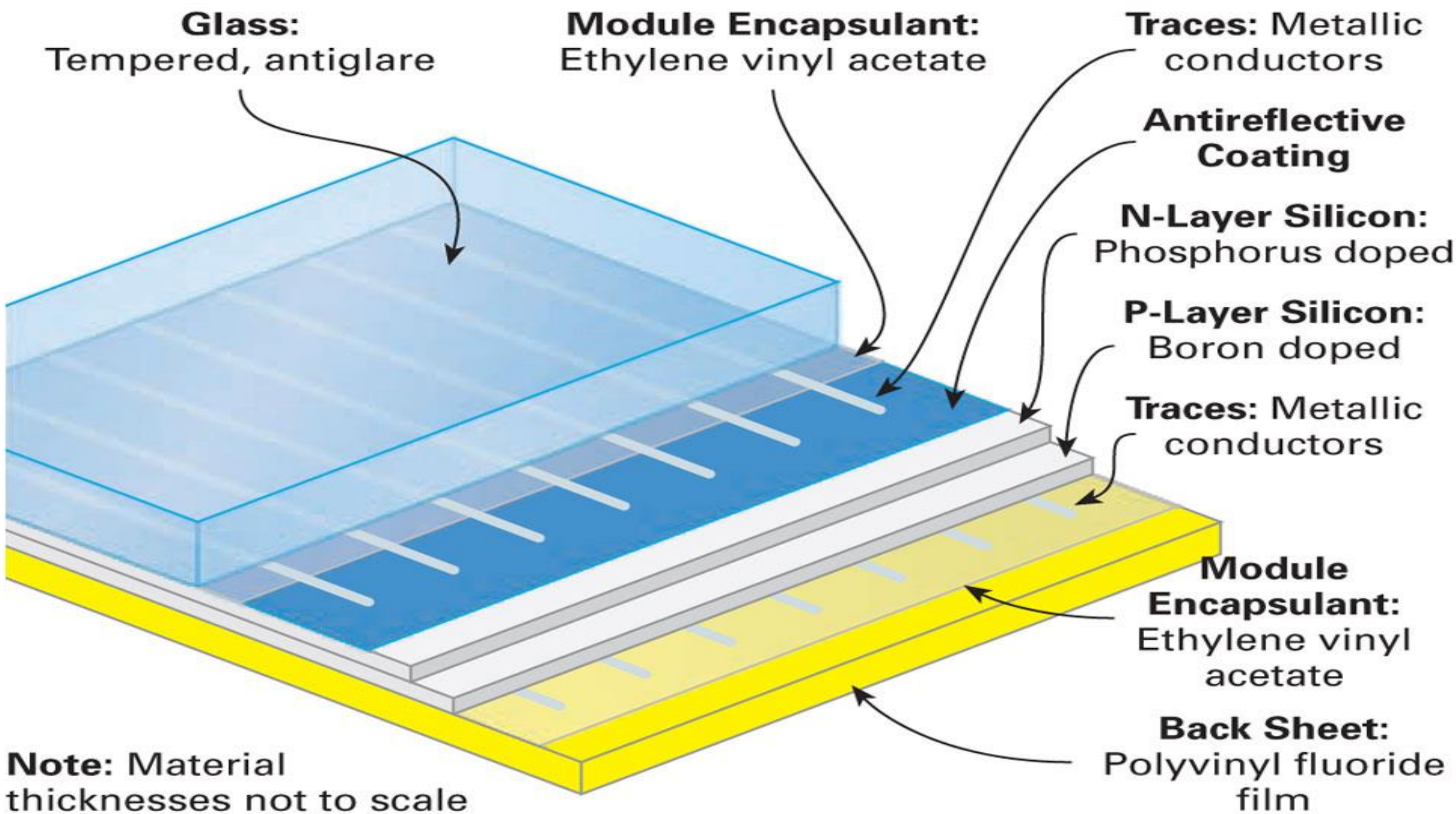
- Polycrystalline silicon is also produced from a molten and highly pure molten silicon, but using a casting process.
- The typical blue appearance is due to the application of an anti-reflective layer. The thickness of this layer determines the colour- blue has the best optical qualities.
- Indicative Efficiencies of 16-17% , less efficient but less expensive that monocrystaline
- Polycrystalline (or Multicrystaline)cells are effectively a slice cut from a block of silicon, consisting of a large number of crystals.


Amorphous Silicon PV

- Amorphous silicon is non-crystalline silicon
- The layer of semi-conductor material is only 0.5-2.0µm thick
- film of amorphous silicon is deposited as a gas on a surface such as glass.
- Efficiency between 6-8%
- Due to the amorphous nature of the thin layer, it is flexible
- One characteristic of amorphous solar cells is that their power output reduces over time eventually becoming stable
- Usually dark and glossy appearence
- 20% better performance on hot environments and up to 12% better performance in low and diffuse light conditions when compared equally rated crystalline modules.


CASIO
SCIENTIFIC CALCULATOR
fx-77
12370106.
HIGH-POWER SOLAR CELL
MODE
ln
log
ON
ENG
1/x
sin
cos
tan
X↔Y
M in
MR
7
8
9
C
AC
4
5
6
×
÷
1
2
3
+
−
0
•
EXP
=
M+

PV Module Anatomy

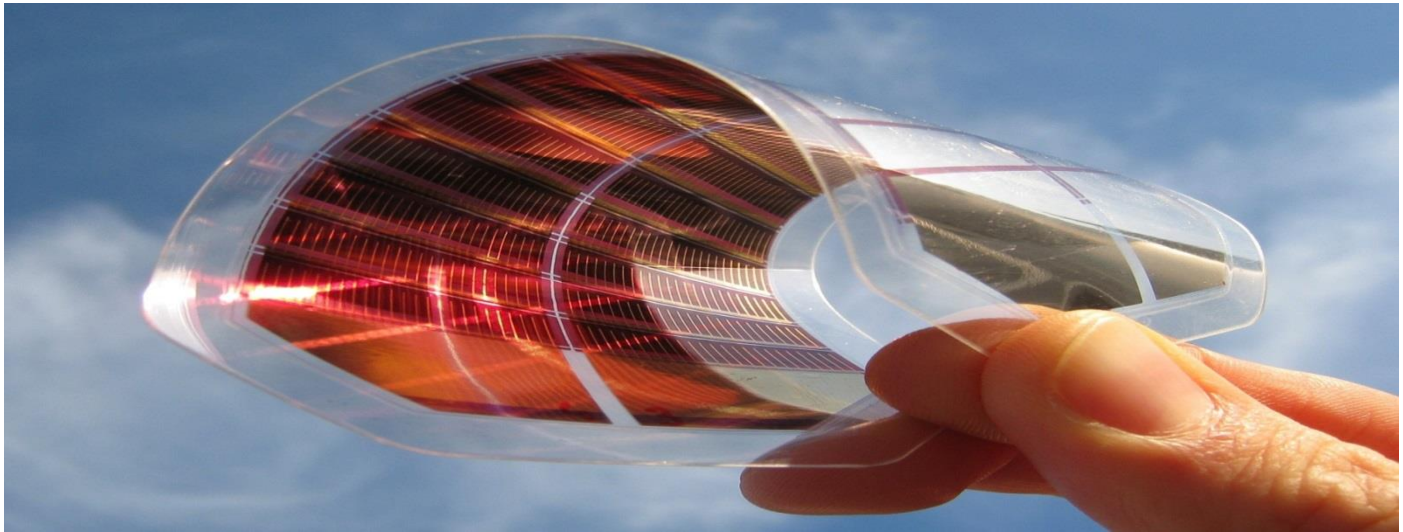


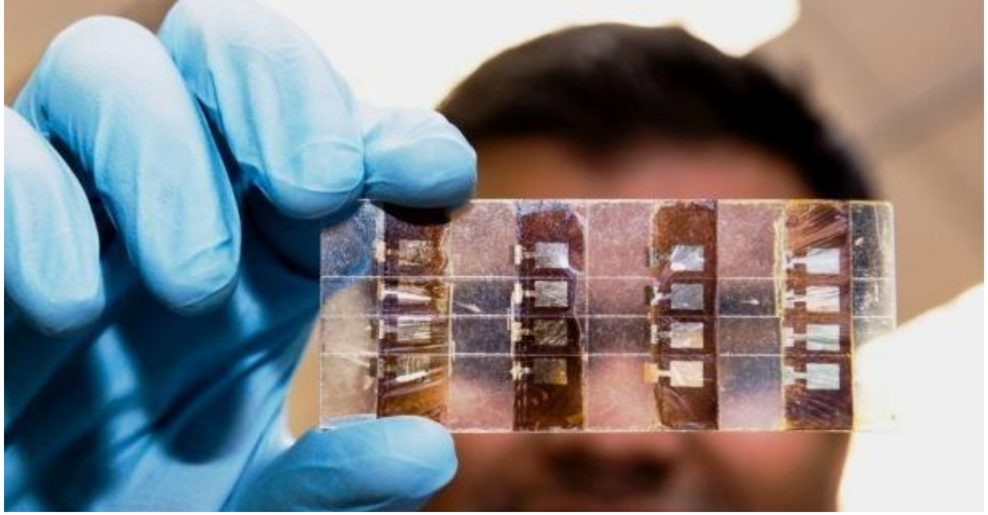
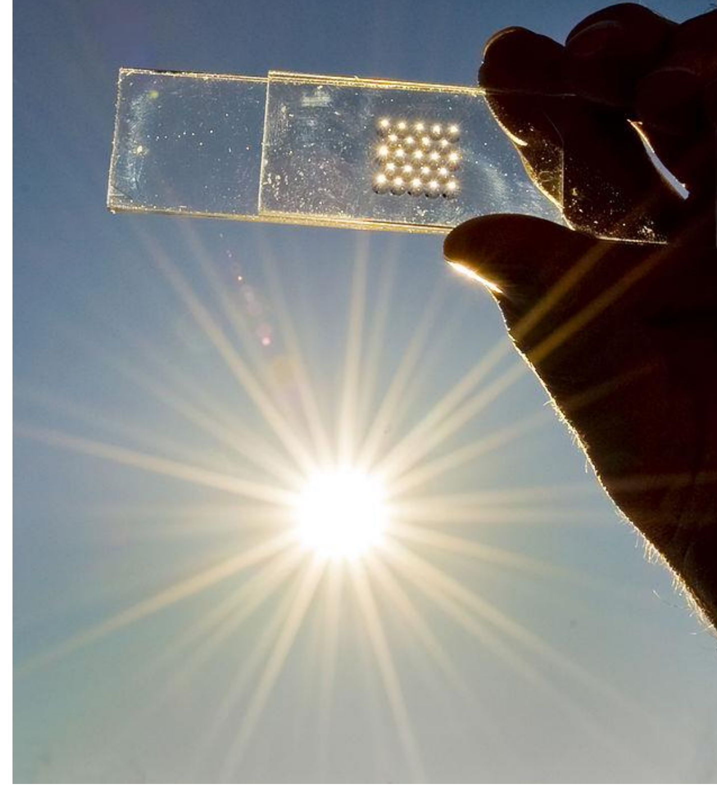
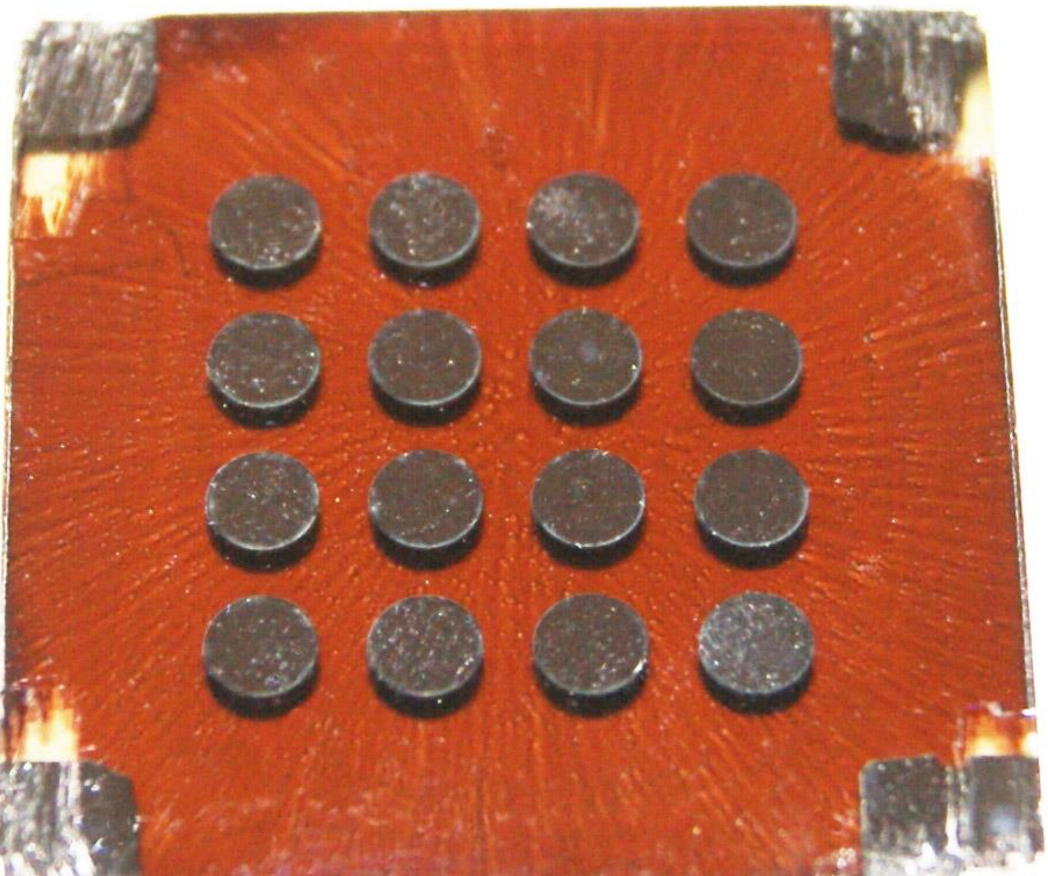
Hybrid PV:

- Hybrid photovoltaic cells are classified as PV cells that use two different types of PV technology or a combination of PV and solar thermal technologies
- The Hybrid PV cell shown here is made by Sanyo and comprises a monocrystalline PV cell covered by an ultra-thin Amorphous silicon PV layer. Higher efficiencies (more than 18%) but a higher cost.

A mention of Emerging technologies – third generation cells

- Organic solar cell made with organic electronics.
- Polymer solar cell
- Quantum dot solar cell.
- Dye-sensitized solar cell, also known as the Grätzel cell, semi transparent, roll printed
- Copper zinc tin sulfide solar cell (CZTS)
- Perovskite solar cells , made from Perovskite*, a crystal form of $CaTiO_3$
- Promising but lower efficiencies currently.




- Dye sensitised cells: low cost, thin film. Absorption occurs in dye molecules at a porous structure of TiO_2 in an electrolyte
- Lower efficiencies than typical thin film but at a lower cost
- Electrolyte has temperature stability problems potentially freezing at low temperatures. It also containts volatile organic compounds (VOC’s) than need to be sealed

- Organic solar cells and polymer solar cells: Thin film technology, first ones from conducting polymers such as polyphenylene vinylene (PPV) and p-type copper phthalocyanine and n-type bisbenzimidazo[2,1-a:2',1'-a']anthra[2,1,9-def:6,5,10-d'e'f']diisoquinoline-10,21-dione (that’s a mouthful
- Main characteristic is that the analogous p-n junction isn’t layered, but the donor and acceptor area is mixed together in an amorphous structure with different regions
- Can be printed, fairly cheap but very low efficiencies

- Perovskite solar cells: Made from $CaTiO_3$ (Calcium titanate) and lead or tin halide based materials- cheap to make.
- Fast advancing technology almost quadrupled their efficiency in 7 years (from 3.6% to 21%). Remember:
- NO commercial modules yet.
- Not very stable
- Promising for tandem (hybrid) cells

- You also get multi junction cells: Using various semiconductors that absorb light at different frequencies
- And of course any combination of the above

PV installations – how to (1/2)

- Ideally you want the PV to be facing the sun vertically at all given times.
- The sun moves from the east to the west everyday (azimuth angle)
- The sun changes its elevation (also known as altitude) constantly throughout the day reaching a maximum around noon
- So your best case scenario is a movable PV in two axis. One from east to west and one that follows the sun’s elevation
- A simplified version would be a single axis tracker that either tracks elevation or east to west
- An even more simplified version would have you manually adjust some times per year.
- To “add insult to injury” usually radiation is measured on a horizontal plane and this should be converted to an inclined one

PV installations – how to (2/2) – use software

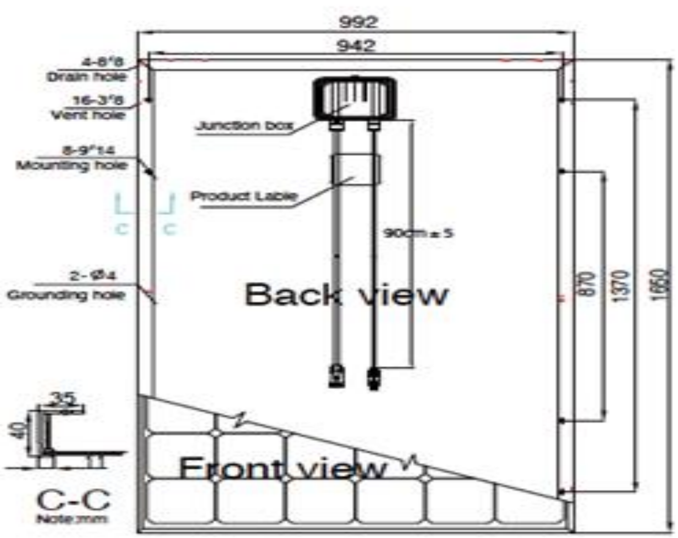
- Radiation has two components (see previous classes) direct and diffuse
- Each of the two components should be calculated for your inclination
- Your inclined direct radiation is given by $G_{d,i}$ =$G_{d,h*}$cos(h-α)/sinh where a is the inclination of your module and h is the elevation of the sun.
- Your inclined diffuse radiation is given by G_{dif},i=$G_{dif,h}$*(1+cosa)/2
- Don’t forget about reflected radiation… (involves geometry of surrounding area and albedo)
- It appears that the process is somewhat complicated.
- Free software exists that tracks the sun. A good example is http://www.suncalc.org
- Cheat and use the global solar atlas https://globalsolaratlas.info/ (play with azimuth and inclination)

Rules of thumb for fixed PV installations aka workaround when no tracker option exists

- For maximum efficiency throughout the year for a fixed installation, PV panels are facing south (for the north hemisphere and vice versa for the southern)
- For latitudes below 25^o , your optimum angle is latitude*0.87
- For latitudes between 25^o and 50^o your optimum angle is latitude*0.87+3.1
- For latitudes above 50^o (Glasgow has a latitude of 55^o) use the same angle as the latitude
- For maximum energy before midday, face them east
- For maximum energy after midday, face them west
- Your energy is always $E=H*A*\eta$ where H is your insolation (energy per surface) at the angle of your panel, A is your area and η your efficiency.
- Your power is always $E=I*A*\eta$ where I is your irradiance (power per surface)

Typical commercial PV

Characteristics	ZDNY-240C60	ZDNY-245C60	ZDNY-250C60	ZDNY-255C60	ZDNY-260C60
Max.Power(Pmax)	240Wp	245Wp	250Wp	255Wp	260Wp
Optimum Operating Voltage(Vm)	30.34V	30.84V	31.17V	31.17V	31.20V
Optimum Operating Current(Im)	7.92A	7.95A	8.03A	8.19A	8.34A
Open-circuit Voltage(Voc)	37.76V	37.80V	37.85V	37.97V	38.82V
Short-circuit Current(Isc)	8.35A	8.38A	8.40A	8.58A	8.71A
Cell Efficiency	16.7%	17.1%	17.4%	17.8%	18.10%



Solar Cell	Mono-crystalline 156*156mm
Output Tolerance(Pmax)	0 ~ +3%
Number of cells	60 cells in series
Module Dimension	1650*992*40mm
Weight	19.5kg
Max.System Voltage	1000V(TUV)/600V(UL)
Max.Series Fuse Rating	15A
Output Cable	PV 4mm2
Cable Length	90cm±5
Number of bypass diodes	6
Temperature cycling range	(-40 ~ 85˚C)
NOCT	47˚C ±2˚C
Temperature coefficients of Isc	+(0.053±0.01)%/K
Temperature coefficients of Voc	-(0.35±0.001)%/K
Temperature coefficients of Pmax	-(0.40±0.05)%/K
Load Capacity	285 pcs/20'GP
	756 pcs/40'HQ

- Some clarification between (peak) “sun hour” and “sunlight hours”
- **Sunlight hours** show you the amount of time per day you have sunlight
- A **sun hour** is an unconventional energy unit equal to 1 kWh/m^2 (maximum possible insolation and also part of STC).
- Simply put shows total insolation in an area with regard to the maximum possible insolation . You receive a total of 3 kWh/m^2 over a whole day? That would be the same as receiving the maximum for 3 hours.
- Becomes useful(ish) when trying to calculate peak current.
- An ok approach is to say that you’ll get your peak current for the same amount of time as your (peak) sun hours.

PV sizing example

A site experiences on average 3.5 kWh/m^2 (3.5 peak sun hours) per day per year on the optimum angle, with an average temperature of our modules being 10 C^o (freezing)*. A house on that site has the following demand:

10x 18W lamps 4 hr per day (2A, 9V)
200 W refrig at 12hr per day (4A, 50V)
100 W TV at 3hr per day (5A, 20V)
100 W heater 3 hr per day (10A, 10V)

Design a suitable PV layout using the PV modules with the following characteristics. 240 Wp, 30.34 Vmpp, 7.92 Amp, efficiency 16.7%. Temperature corrections are Isc 0.053%K and Voc 0.35%K

Maximum Power Point Voltage (Vmpp). The Vmpp is the voltage when the power output is the greatest

Open-circuit voltage (Voc). The maximum voltage that the solar panel can produce with no load on it

*finding module temperature from ambient is difficult but check out https://www.sciencedirect.com/science/article/pii/S096014810500073X , https://www.hindawi.com/journals/ijp/2013/192854/ and https://core.ac.uk/download/pdf/82098574.pdf if you have an interest in that.

Linear approximations are difficult and most are based on steady state – lots of papers on the field gives results +/-3% of the simulated value (Muzathik, 2014)

$$T_{module}\left({}^{o}C\right) = 0.943 \times T_{ambient} + 0.0195 \times Irradiance - 1.528 \times WindSpeed + 0.3529$$

First question. How much electricity can we get from our modules?

The module area is 1650mm by 992 mm giving us a total area of 1.64m^2

Our **available** energy from the PV is **ALWAYS** E=A*n*H where A is the area of the module, n is the efficiency and H is the total insolation on **TILTED** panels.

That is NOT the energy we get though, since there are losses* in our inverter, in our cables etc. The sum of these losses is taken into account in order to calculate the performance ratio (PR). A good PR could be over 90% whereas a bad one could drop down to 60%.

The energy we will eventually get is our available energy multiplied by the PR. For this case let's assume a PR of 90%.
Thus our energy will be 1.64*0.167*3,500*0.9=862.72 Wh.

*These losses are part of the BOS and not of the PV module itself. Don't blame PV manufacturers

A Solar PV Balance-of-System (BOS) refers to the components and equipment that move DC energy produced by solar panels through the conversion system which in turn produces AC electricity. Most often, BOS refers to all components of a PV system other than the modules.

Second thing we need to do is to calculate our total load.

For this example or our loads are DC loads. If AC loads were present, we would multiply these AC loads by the inverter efficiency to convert them to DC loads.

Total mean daily load is 10x18x4+200x12+100x3+100x3= 720+2400+300+300= **3720 Wh/day**

Nominal DC voltage = Voltage of our biggest load = **50 V**

Demand in Ah/day =daily load demand/Nominal voltage = 3720/50 = **74.4 Ah/day**

Our PV system has to be able to provide 3,720 kWh/day with a voltage of 50V at 74.4 Ah/day

From the previous page, our PV system gives us 862.72 Wh per module.

How many modules do we need? 3,720/826.87 = 4.31 so we need 5 modules.

NO! We are not done yet.

Sizing the PV array

Remember that all PV modules are rated against STC. Our module temperature is 10 C^{o} and the temperature in STC is 25 C^{o} . We have a temperature difference of 15 C^{o}

With the current there is going to be a difference of 0.053%*15= 0.795% and with the Voltage 0.35*15=5.25%.

Since we have a lower temperature than STC the current is going to decrease while the voltage will increase.

So at the maximum power point we are going to have

I=7.92*(100-0.795)%=7.92*99.205%=**7.86 Amps**
V=30.34*(100+5.25)%=30.34*105.25%=**31.93 V**

Standard Test Conditions (STC) and are the industry standard for the conditions under which a solar panel are tested

Sizing the PV array

We need a nominal DC voltage of 50 V and the max we can get from a single module is 32.02 V.
So **50/31.93= 1.57** modules connected in series. So the minimum number of modules in series is **2**.

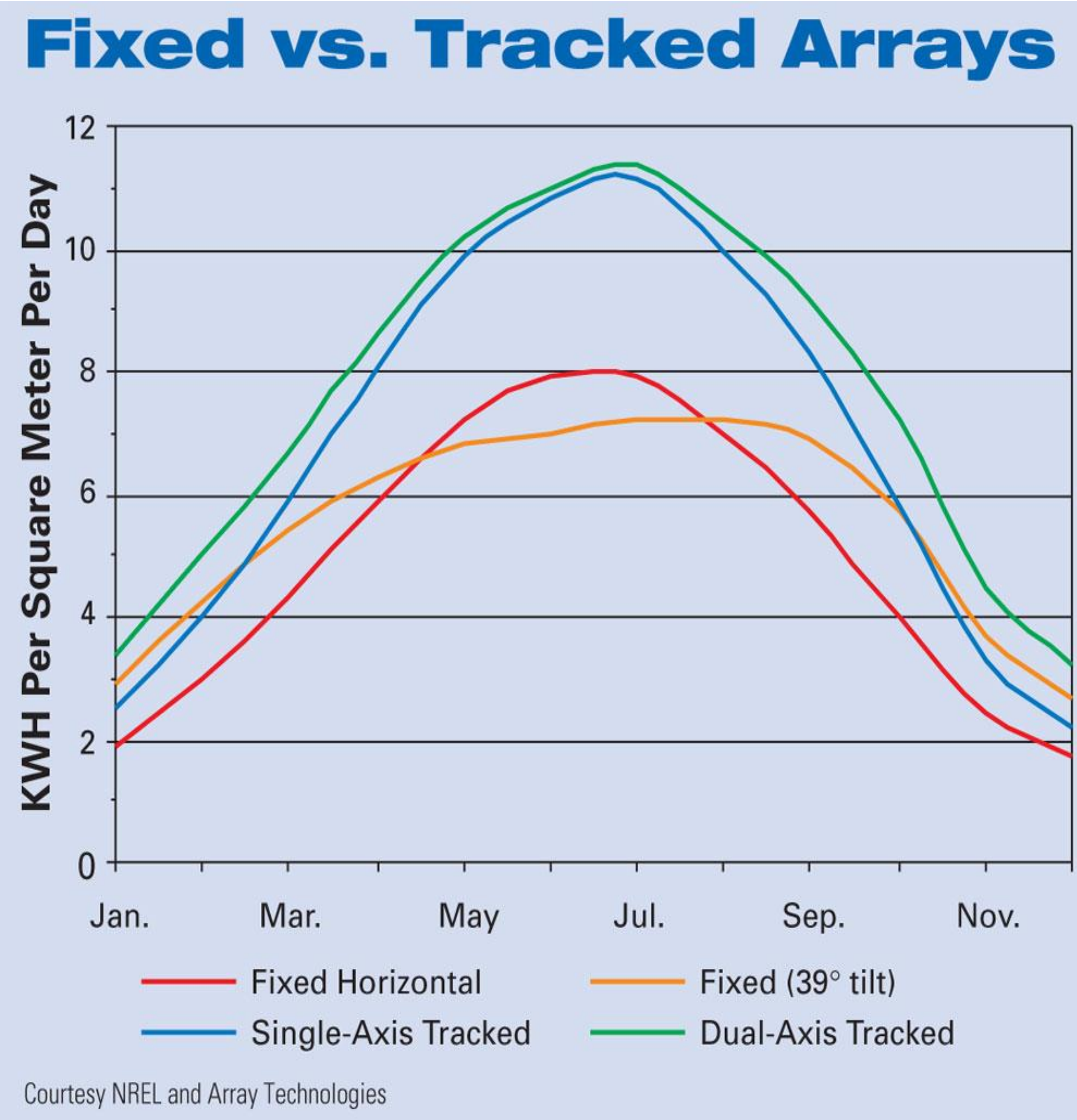
Remember that in a series connection, the current stays the same while the Voltage adds up

Module peak current is 7.86 A and we have that for is for 3.5 hours per day. So 7.86*3.5= 27.51 Ah max per day.

Multiply by 95% to accomodate for module mismatch and cable and diode losses we get a mean daily output of 27.51*95%=**26.13** Ah max per day.

Our mean daily load current is 74.4 Ah/day and the maximum we can get from the module is 26.13, so we need **74.4/26.13=2.84** modules. So the minimum number of modules in parallel will be **3**

Remember that in a parallel connection the Voltage stays the same, while the current adds up.
In total we will need **6** modules then (2x3). Done, you have successfully sized your first PV system



- Power source for the axis tracker
- Increased complexity of the system
- Increased costs of maintenance
- More chances that something goes wrong
- Needs more space
- Not suitable for roofs
- Need accurate predictions for elevation
- Needs monitoring
- Depending where you are, up to 40% more energy can be captured from a dual axis system

Balance of systems (BOS)

Electrical components

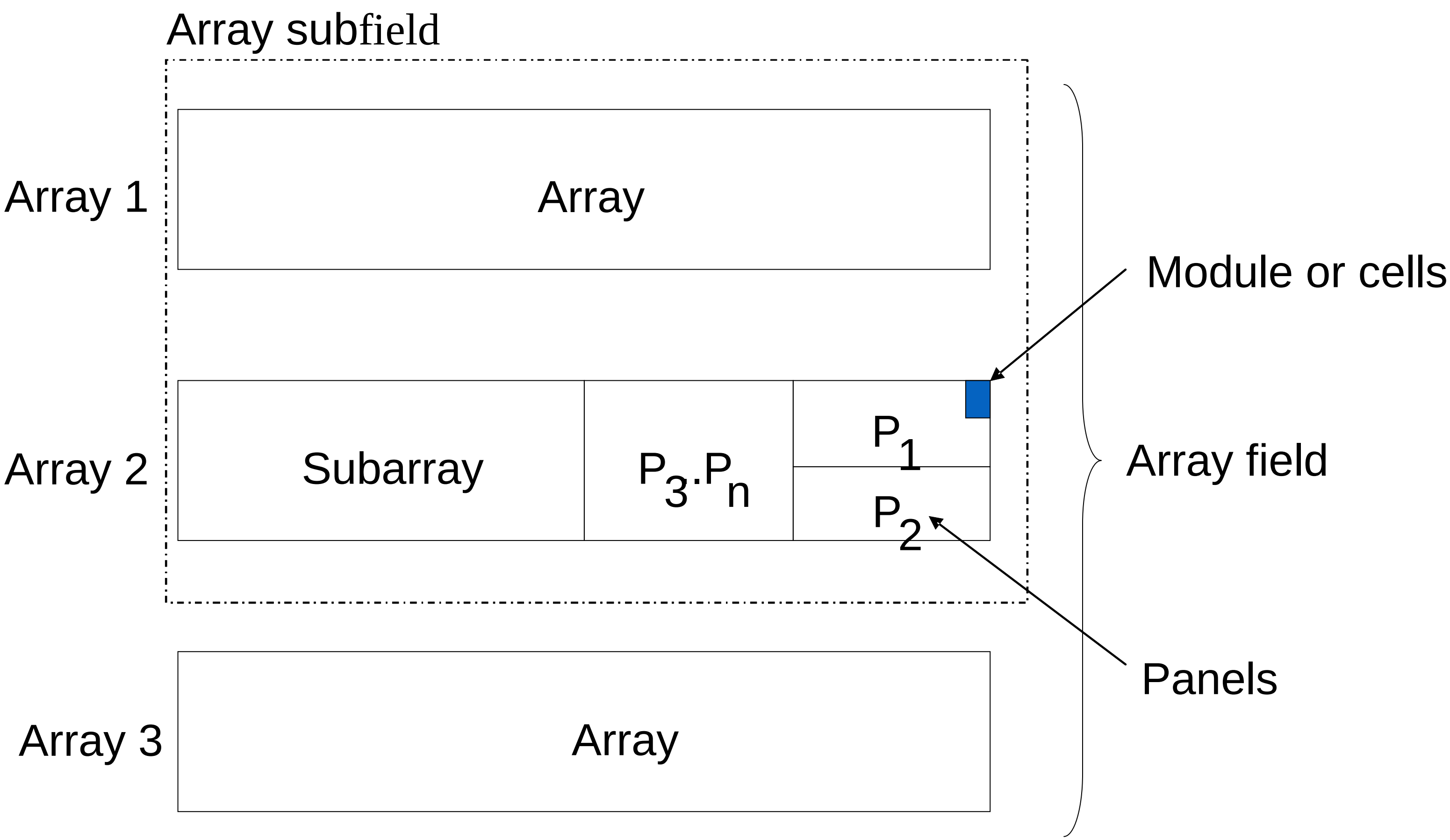
- Cables
- Fuses
- Earthing
- Lightning Protection
- Battery
- Charge Regulation
- Low Voltage Disconnect
- Inverters (remember that PV produces DC electricity)
- Trackers
- Sensors

Mechanical components

- Frame
- Screws, fittings etc

In 2008 67% of the cost was the PV modules, in 2015 68% is the BOS according to industry averages

PV array terminology



Two kinds of systems

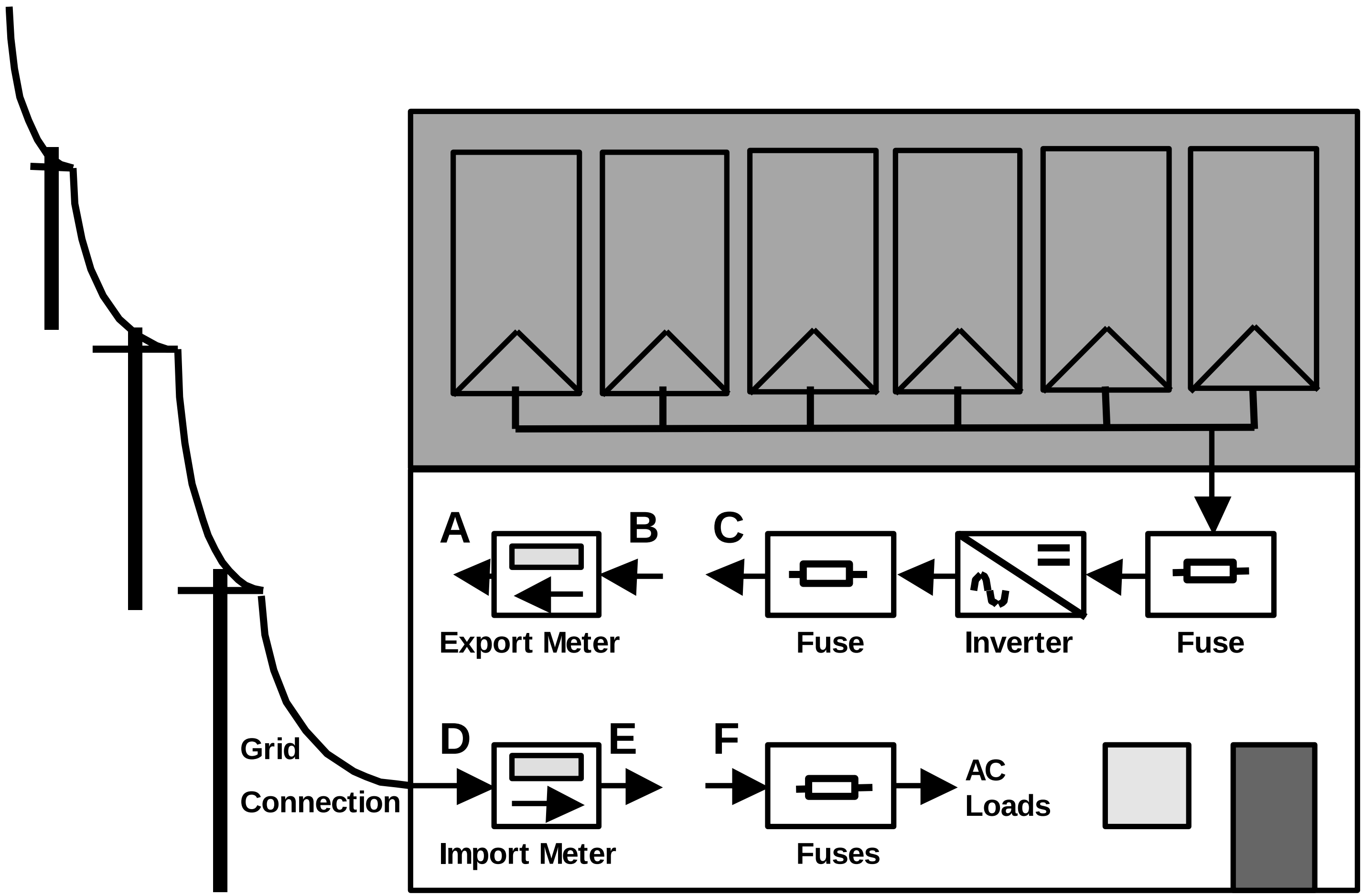
Stand alone

- PV only
- PV with storage/backup
- Hybrid System

Grid connected

- generally subsidy driven
- connection scheme depends on subsidy scheme
- Energy produced by the PV is fed to the grid
- The price that the energy is sold is higher than the price to buy energy from the Grid

Possible Schemes



4 possible scenarios for grid connection

1)PV power directly to house
2)PV power + mains power directly to house
3)PV power to batteries and the rest to the grid
4)Ideal scenario. PV directly to the house and excess to the grid(rare)

Advantages of Solar photovoltaic (PV)

- Benefit from the Governments feed-in tariff.
- The feed-in tariff is guaranteed by the Government for 20 years.
- Panels designed for European countries generate power even on cloudy days.
- Clean energy means carbon emissions can be reduced.
- Producing your own power protects against rising energy prices.
- Once installed requires very little maintenance.

Disadvantages of Solar photovoltaic (PV)

- A large area of unshaded south, south-west or south-east facing roof is required to maximise payback. Smaller systems can be installed but payback will be longer.
- Panels degrade over time by approximately 20% over 25 years; this however is taken into account in most reputable suppliers calculations.
- It may be beneficial to replace the inverter after 10 years to optimise power generation, although this is not essential.

Reliability is key

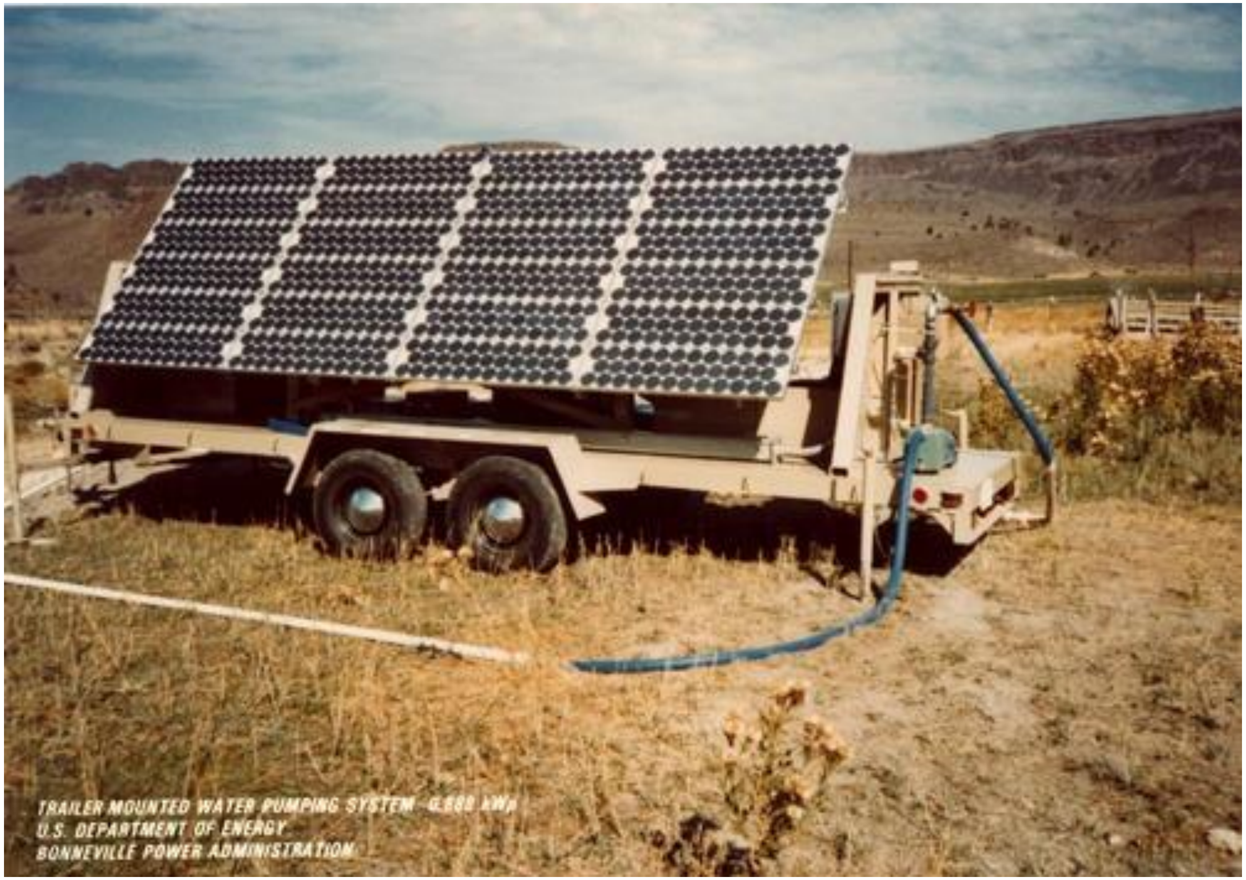
Telecommunications

Navigational Aids

Social Applications
Village Electrification

Social Applications
Vaccine Refrigeration

Social Applications
Irrigation



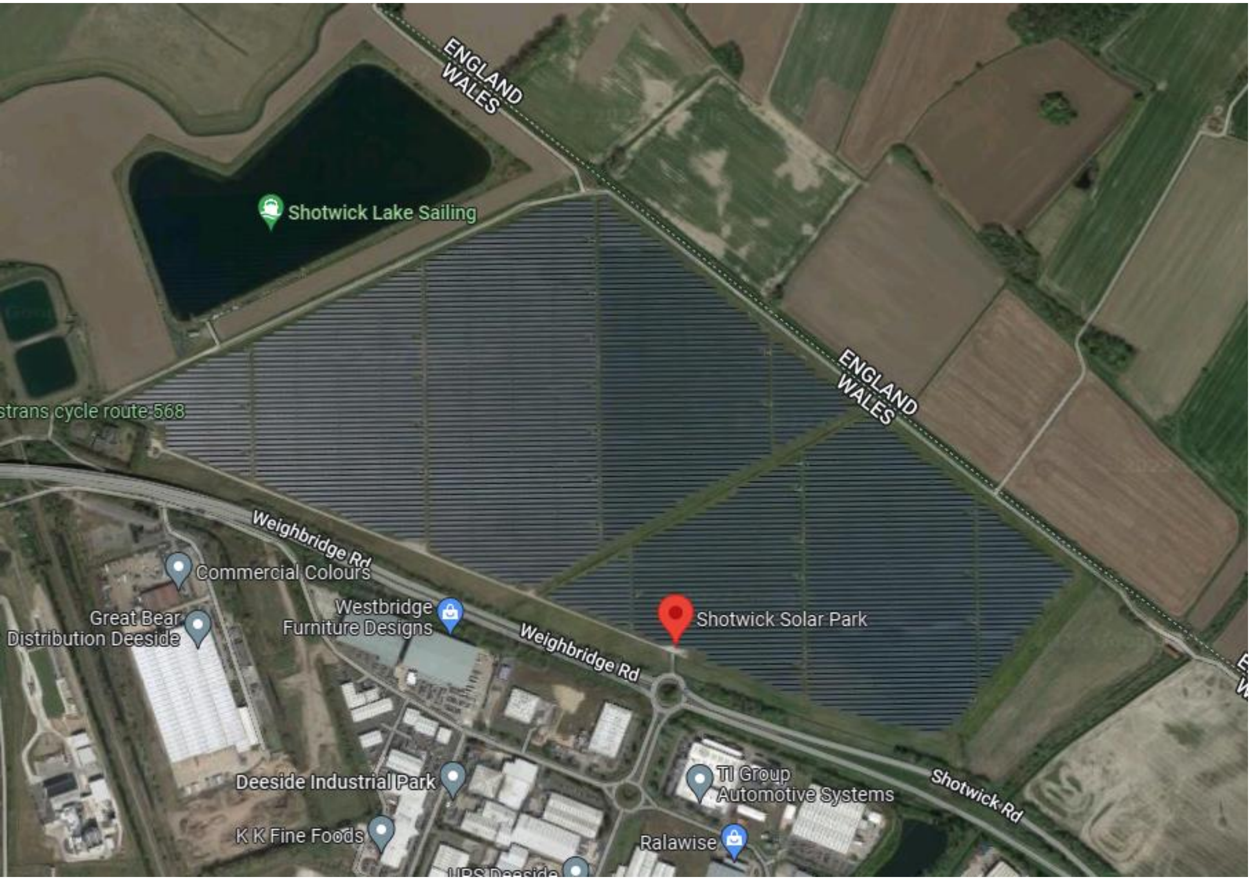
Consumer Applications

- Pocket calculators
- Garden pumps
- Garden lighting
- Phone chargers

Different uses of PV

BIPV True building integration

Uk largest solar farm



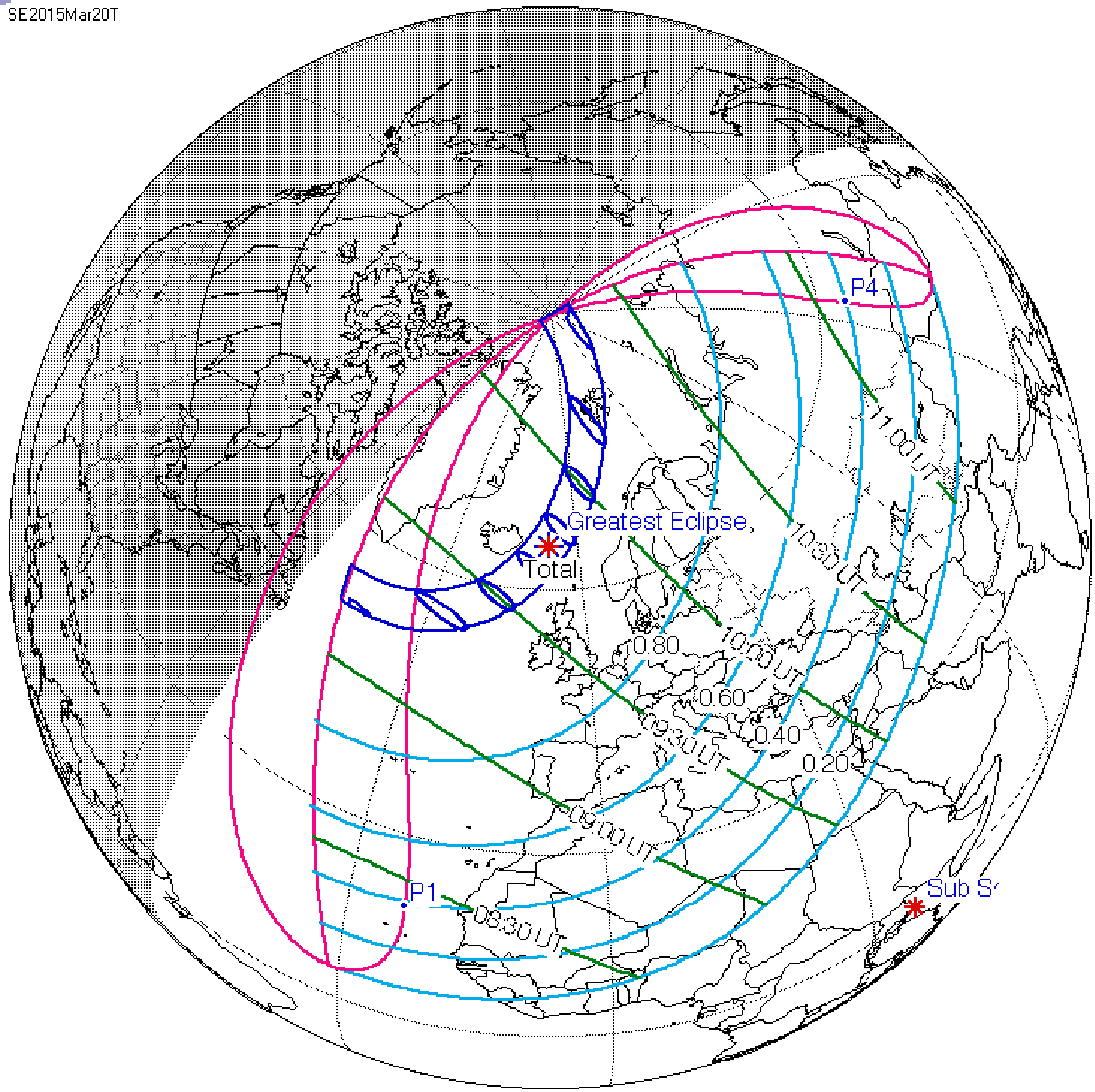
The Shotwick Solar farm in Wales with a power rating of 72.2 MW.

Taking up an area of 1.01 km^2

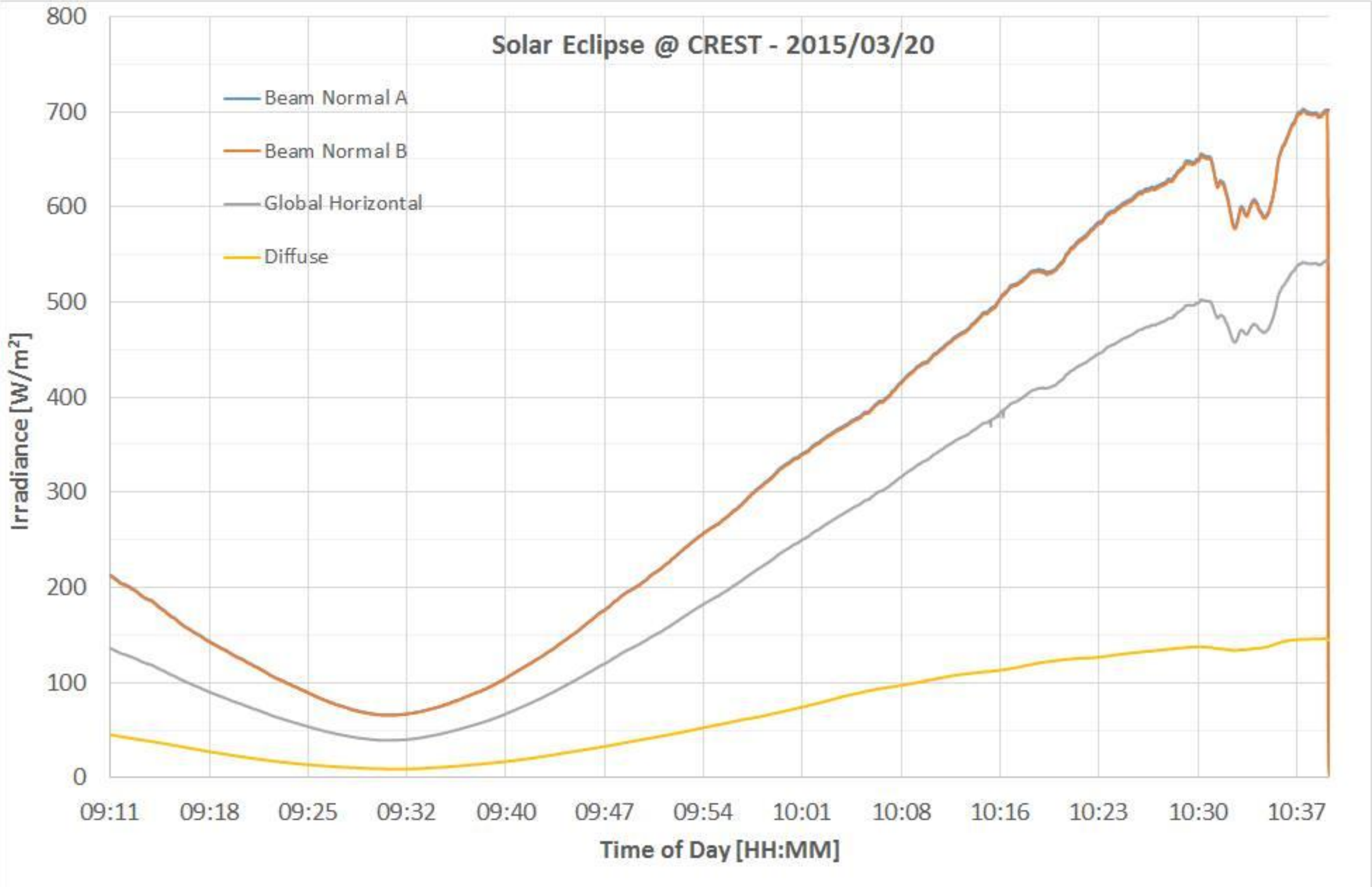
World's largest operational solar farm

Went into operation in March 2020, rated at 2,245 MW in Bhadla, India.

Area is 5,700 hectares or 57 km^2



Remember the eclipse in March 2015?


Solar Eclipse @ CREST - 2015/03/20
Beam Normal A
Beam Normal B
Global Horizontal
Diffuse
800
700
600
500
400
300
200
100
0
Irradiance [W/m²]
09:11
09:18
09:25
09:32
09:40
09:47
09:54
10:01
10:08
10:16
10:23
10:30
10:37
Time of Day [HH:MM]

- Germany lost 13GW of output
- Power gradient was −400 MW/minute and +700 MW/minute.
- Temperature decreased by 3 °C
- Wind power may have decreased as winds are reduced by 0.7 m/s

Solar roadways

https://www.youtube.com/watch?v=qITA3rnpgzU&t=307s

So….a “few” problems I can think of

- In terms of PV, they have no ideal orientation
- The tempered toughened glass has a lower transmissivity thus less energy available to the panels
- They will be shaded by the cars
- But they are replacing tarmac which is a good thing….right?

Funding stuff

- $100.000 initial funding USDOT. Contained no solar cells, or glass
- Awarded “Most promising Renewable energy” etc
- $50.000 community award
- $750.000 USDOT
- $2.200.591 Indiegogo campaign
- $60.000 Indiegogo In demand.
- $750.000 USDOT.
- Average cost for PV in the USA is $2.87-$3.85 per W.

Data taken from
https://enlighten.enphaseenergy.com/pv/public_systems/V3vh1173801/overview

Solar f.....g roadways

- 14 m^2 and 39 panels in total for the demo,
- Reached a peak of 1.30 kWh in a single day – best day ever, with a maximum output of 0.18 kW
- Global solar info shows 4.4 kWh/m^2 (on average-you would expect more in the summer)
- So you would expect 61.6 kWh for that area per day
- Efficiency of..2.1%
- Oh…and it's a road as well eh?
- In Idaho (59.26% Trump voters in 2016, 63.80% in 2020)..Science lovers

- Uses LED’s, 56 of them per panel. Typical small LED is 2-5W but they can go higher. So 0.112 kW to 0.28 kW for the LED per PANEL
- And it’s heated!
- But the heaters and LED’s are powered by the grid…… Very roughly though 1 kg of fluffy snow needs 100 kWh of energy in order to become water.
- With a snowfall of 1 cm over the panels, you have 140 lt of snow, or 14 kg of the fluffiest snow ever. So we need only 1400 kWh in order to melt the snow
- And the cost to cover all the roads is..56 trillion USD.
- (GDP of USA is 18 trillion USD)

What about this?

Solar flower
https://www.youtube.com/watch?v=mQARjr0721E

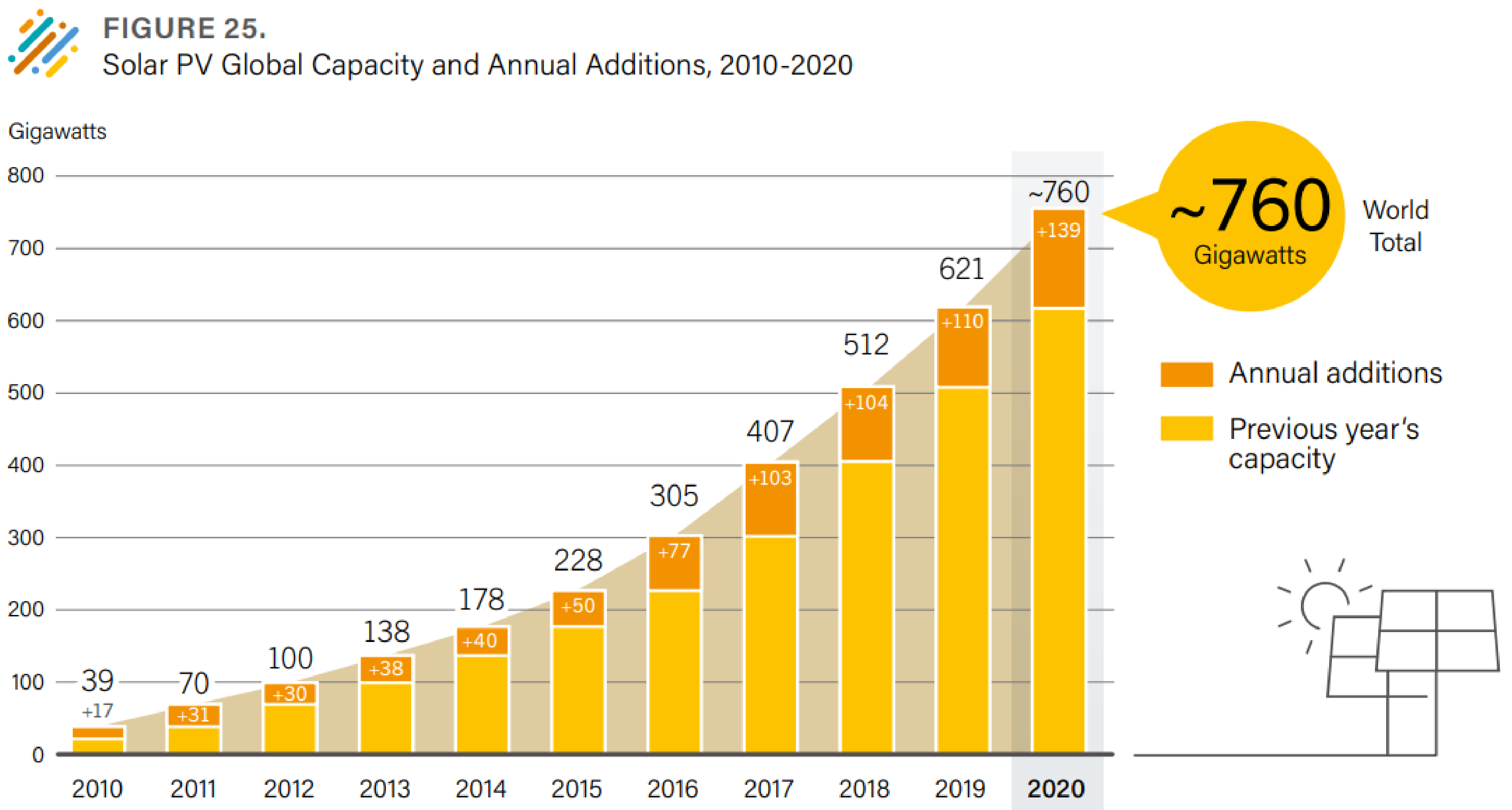
A dual axis system at best can give you a 40% advantage compared to a static one at the best angle*.

Roughly 60-70% of the petal area is covered by PV.

If a static panel has a yield of Estat then the flower would have (at best) a yield of Estat*1.4*0.7=0.98Estat.

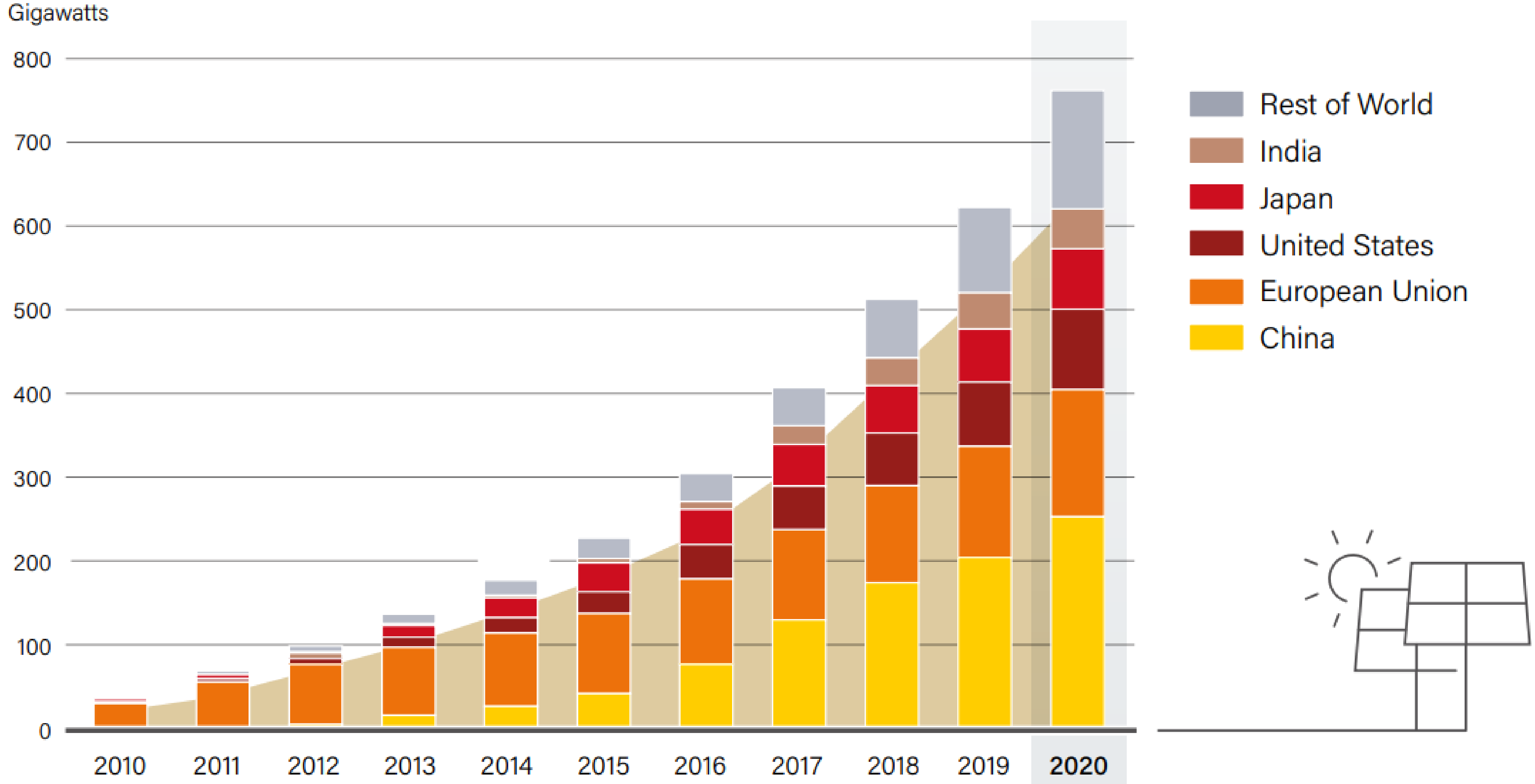
Plus it is using energy to track the sun..
What about heavily intermittent weather?
Manufacturers give warranty of 25 years for the PV but 5 years for the system.

Total installed capacity

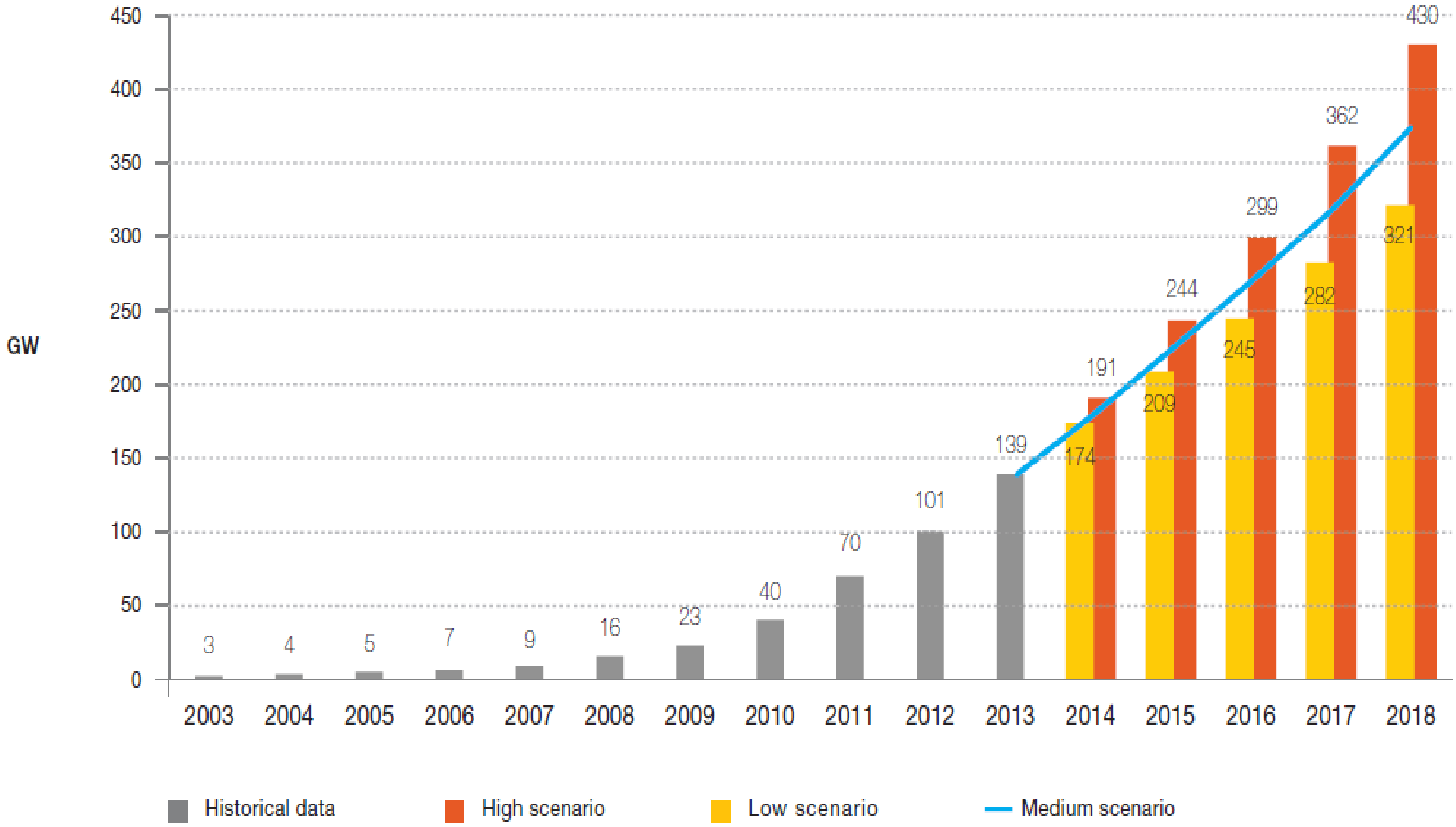


From REN21

FIGURE 26.
Solar PV Global Capacity, by Country and Region, 2010-2020

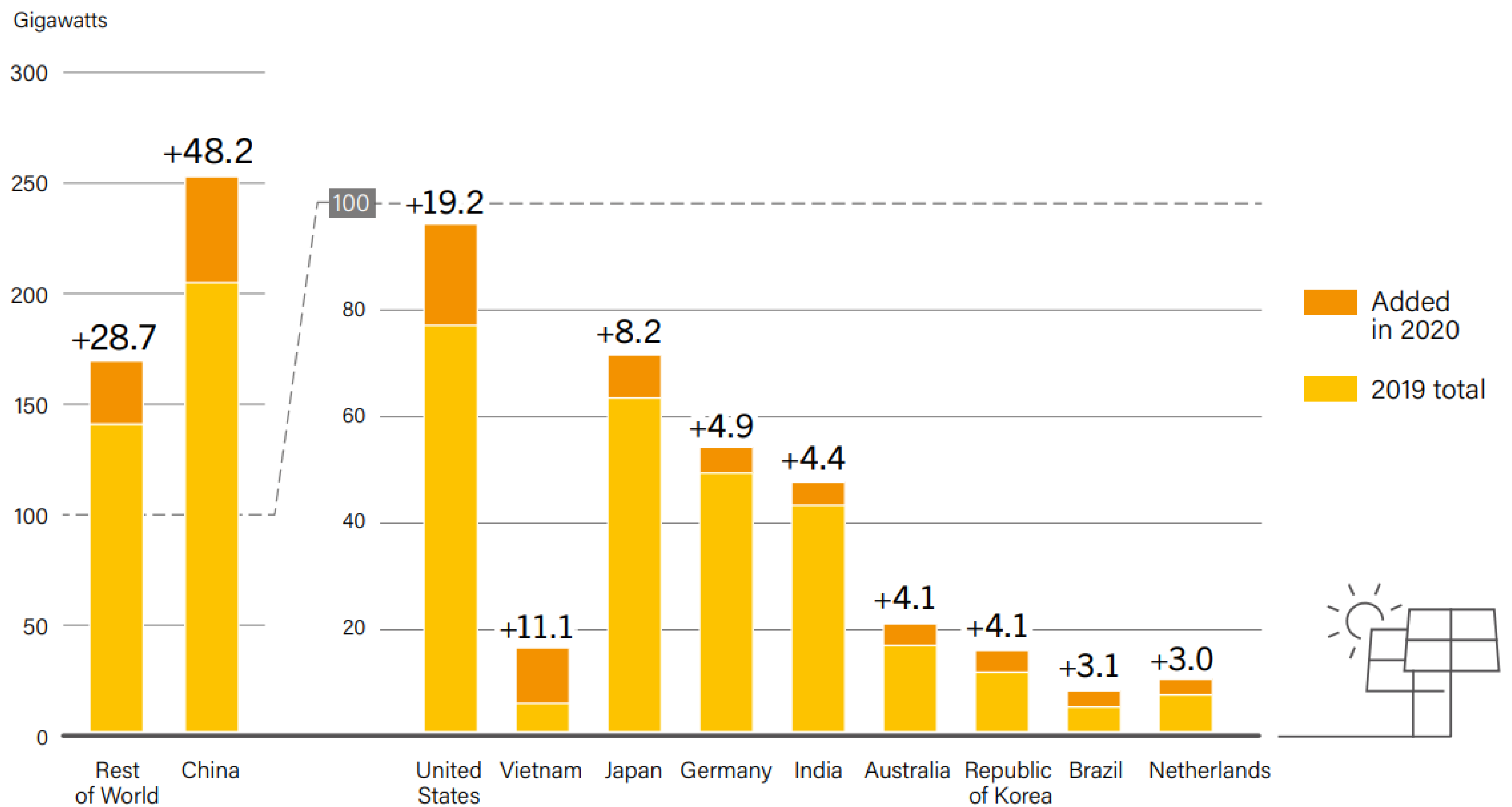


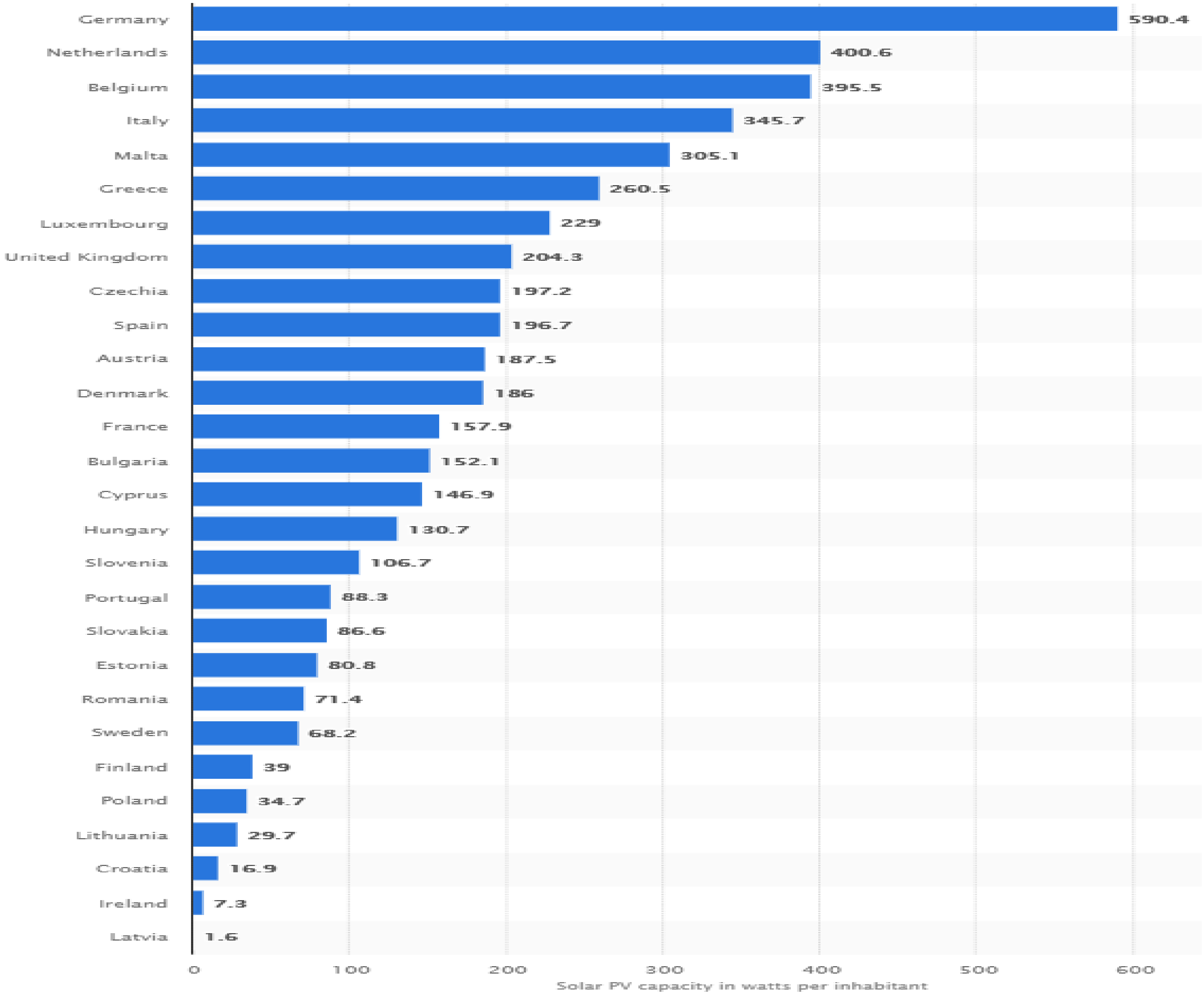
Global projections from 3 years ago



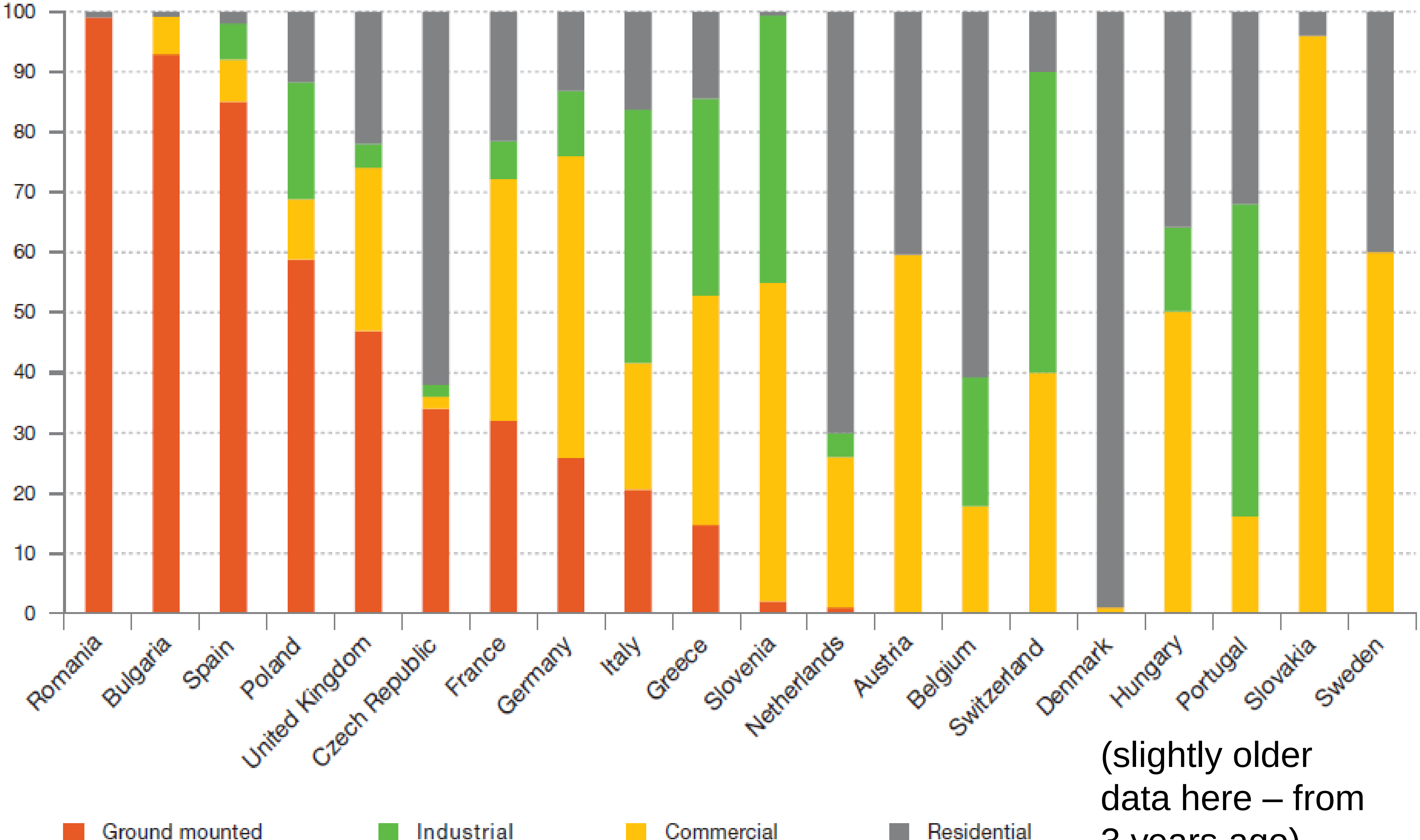
Surpassing the high scenario, yay!

Top 10 countries in the world




Germany
Netherlands
Belgium
Italy
Malta
Greece
Luxembourg
United Kingdom
Czechia
Spain
Austria
Denmark
France
Bulgaria
Cyprus
Hungary
Slovenia
Portugal
Slovakia
Estonia
Romania
Sweden
Finland
Poland
Lithuania
Croatia
Ireland
Latvia
590.4
400.6
395.5
345.7
305.1
260.5
229
204.3
197.2
196.7
187.5
186
157.9
152.1
146.9
130.7
106.7
88.3
86.6
80.8
71.4
68.2
39
34.7
29.7
16.9
7.3
1.6
0
100
200
300
400
500
600
Solar PV capacity in watts per inhabitant

Market distribution according to type for Europe



(slightly older data here – from 3 years ago)