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**INSTYTUT METALURGII I INŻYNIERII MATERIAŁOWEJ**
**im. Aleksandra Krupkowskiego**
**Polskiej Akademii Nauk**

# Photovoltaic systems – theory and practice

## Part 1

**Marek Lipiński**

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*Projekt nr WND-POWR.03.02.00-00-IO43/16*
*Międzynarodowe interdyscyplinarne studia doktoranckie z zakresu nauk o materiałach z wykładowym językiem angielskim*
*Program Operacyjny Wiedza Edukacja Rozwój 2014-2020, Działanie 3.2 Studia doktoranckie*

# Cours description

## 1. Introduction to photovoltaics

*Basic information about the solar energy and photovoltaic Energy conversion*

## 2. Technology of solar cells

*The industrial technology of silicon solar cells and thin films solar cells will be presented*

## 3. Emerging photovoltaics

*Emerging materials and devices including dye-sensitized solar cell, organic solar cell, perovskite solar cell and quantum dot solar cell*

## 4. Photovoltaic systems

*Technology, applications, economics of photovoltaic systems*

# INSTITUTE OF METALURGY AND MATERIALS SCIENCE
# POLISH ACADEMY OF SCEINCES


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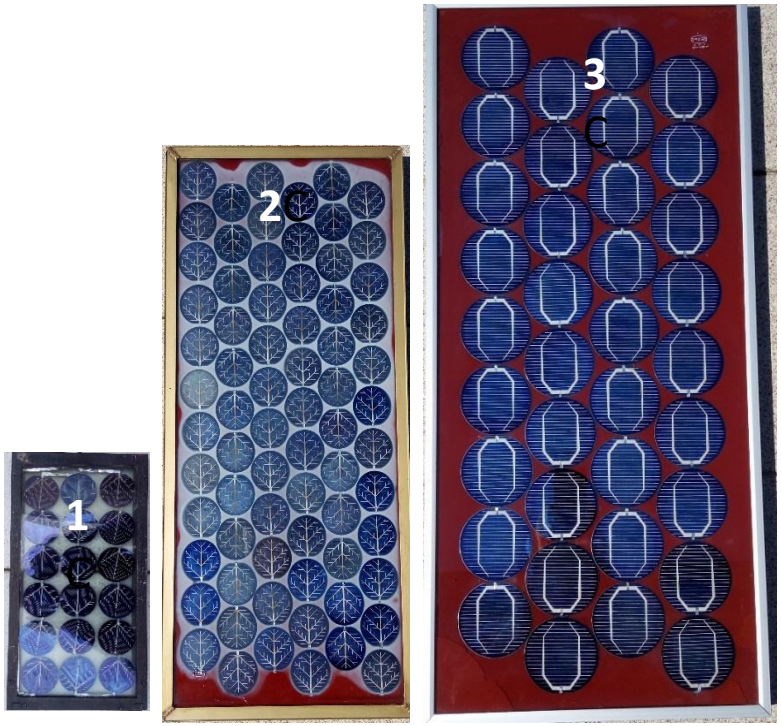
*http://www.imim.pl/departments/department-of-multilayer-materials*

# *Photovoltaic Laboratory of IMMS PAS*

**Over 40 years of experience in solar cells:**

- ✓ The first silicon solar cell in Poland (1977)
- ✓ A unique laboratory in Poland that makes silicon crystalline solar cells and modules




**Historical PV** modules made from monocrystalline Cz-Si (1977-1985).

# *Photovoltaic Laboratory of IMMS PAS*

**Main research areas:**

- ✓ Technological processes of silicon crystalline solar cells and perovskite solar cells.
- ✓ Technological processes of PV modules.
- ✓ Characterization of solar cells and PV modules

**Research Projects**

- ✓ Ministry of Science and Higher Education
- ✓ National Science Centre
- ✓ National Centre for Research and Development
- ✓ Structural Funds

*http://www.imim.pl/departments/department-of-multilayer-materials*

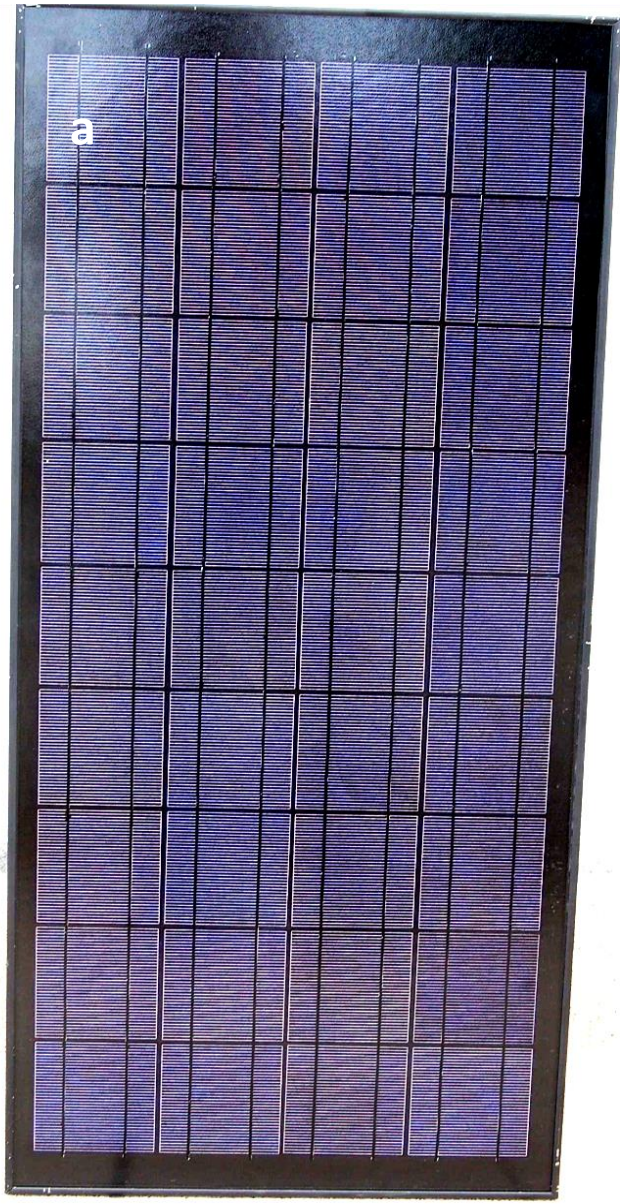
# *Photovoltaic Laboratory of IMMS PAS*

- *Special photovoltaic systems for the use in Polish Military Forces,. Development project No. 0021/R/T00/2009/08*, 2009-2011.
- *PV-In-line processing of n+/p and p/p+ junction systems for cheap photovoltaic module production (Inline)*, Polish-Norwegian Research Programme, No. POL-NOR/199380/89/2014, 2014-2016
- *Isothermal and refrigeration photovoltaic car body* (WOLTER), GEKON Programe - Generator of Ecological Concepts, 2015-2017
- *Innovative flexible photovoltaic cover -EPF*, GEKON Programe - Generator of Ecological Concepts, 2016-2018
- *Development of technology for manufacturing of functional materials for applicationin non-silicon photovoltaic cells*, TECHMATSTRATEG II, 2/409122/3/NCBR/2019, 2019 – 2021
- *Development of technology for manufacturing of functional materials for applicationin non-silicon photovoltaic cells*, TECHMATSTRATEG II, 2/409122/3/NCBR/2019, 2019 - 2021

# *Photovoltaic Laboratory of IMMS PAS*

- *Development of technology for the production of copper component and pastes used in themanufacture of silicon cells electrical contacts*, POIR.01.01.01-1598/15-00 (2016-2018)
- *Self-cleaning, PV panels on the flexible subgrade integrated with the acousticscreen and the smart monitoring system,* POIR.04.01-00-001/17 as part of the BRIK project (2018 - 2021)
- *Investigation of influence of metal and semiconductor nanoparticles onopto-electronic properties of composite materials*, OPUS project No.2012/05/B/ST8/00087, 2012-2016
- *Selection and detailed analysis of the directional surface texturization ofcrystalline, photovoltaic silicon in order to improve the optoelectronic properties*. PRELUDIUM project No. 2013/09/N/ST8/04165, 2014-201
- The effect of the process parameters of the metal nanoparticles photochemicaldeposition on titanium dioxide on plasmonic properties of obtained nanostructures., PRELUDIUM project No. 2014/13/N/ST8/00858, 2015-2017
- *Preparation and characterization of new materials for perovskite solar cells*, OPUS project, project No. 2018/31 /B/ ST8/03294, 2019-2022.

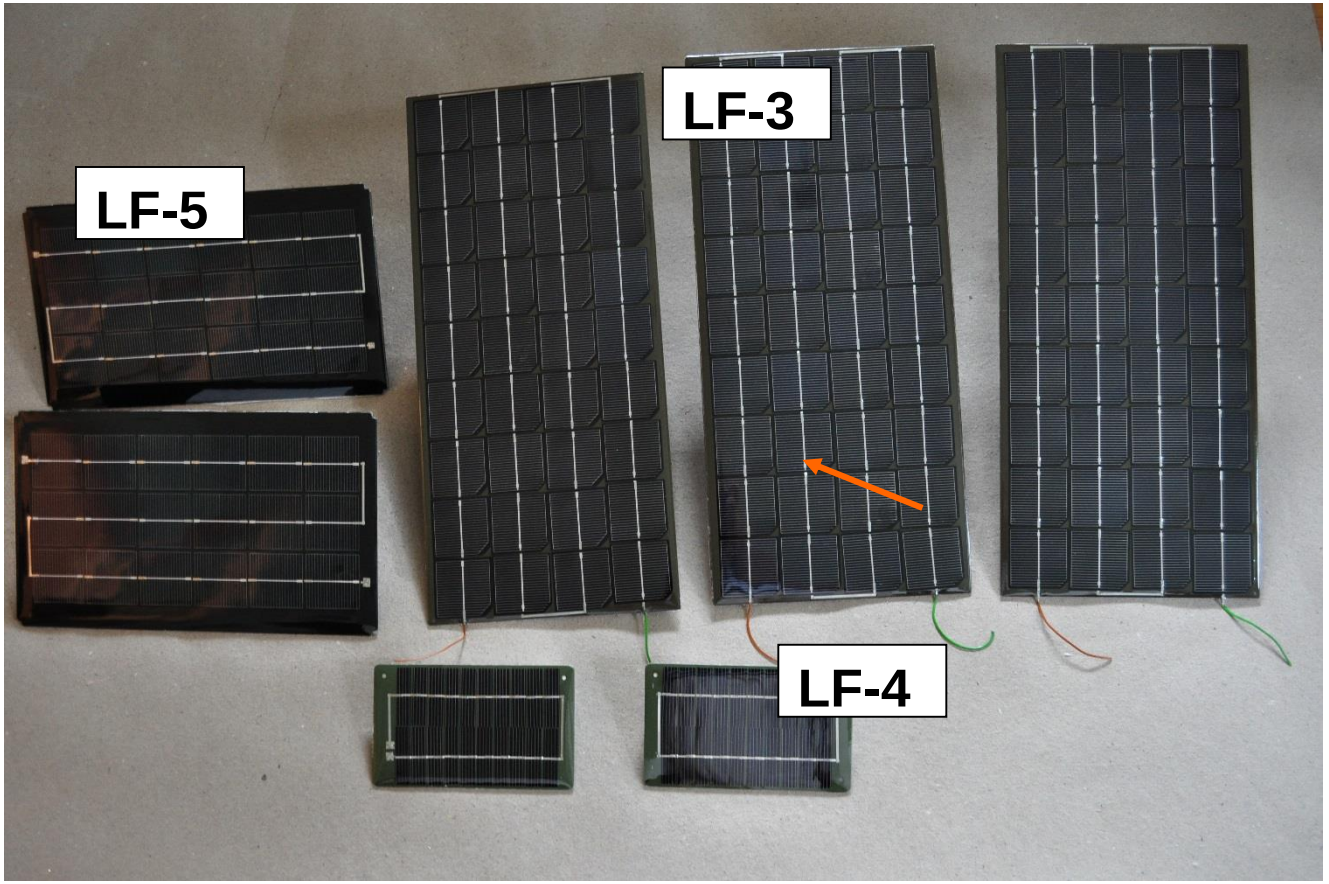
# Photovoltaic Laboratory of IMMS PAS





The module consists of 36 cells 10 cmx 10 cm, power of about 50 Wp (a) and a mini module manufactured for educational purposes with a power of 4.5 Wp (b)

# Photovoltaic Laboratory of IMMS PAS




Sets of various types of LF type solar modules. The LF-3 modules were prepared for use in the tracking camera PV system, the LF-5 modules to power the system for a single soldier, and the LF-4 modules to supply combat agents.

# Photovoltaic Laboratory of IMMS PAS

*Mobile water treatment filter powered by a PV module made at IMIM PAN, honored with the prestigious Defender Award at the 20th International Defense Industry Exhibition Kielce 2012 (a) transportable field solar plant system (b) at the International Defense Industry Exhibition in Kielce 2012.*

# Photovoltaic Laboratory of IMMS PAS

*Solar car body on an isothermal box semitrailer, body concept (left), ready working prototype mounted on the body (right).*

# ENERGY SOURCES

1. **Fossil fuels** : coal, oil, natural gas
2. **Clean Energy**: solar, wind, geothermal, hydropower, biomass/biofuels, tides, ocean thermal energy and nuclear

**Renewable resources** (= Clean Energy without nuclear**)**

Renewable resources also produce clean energy, meaning less pollution and greenhouse gas emissions, which contribute to climate change.

*https://www.energy.gov/science-innovation/energy-sources*

# ENERGY SOURCES

| Fossil sources | Total Energy Resoucese [years] |
|---|---|
| coal | 158 |
| oil | 41 |
| gas | 63 |
| Uranium(*) | 300 |

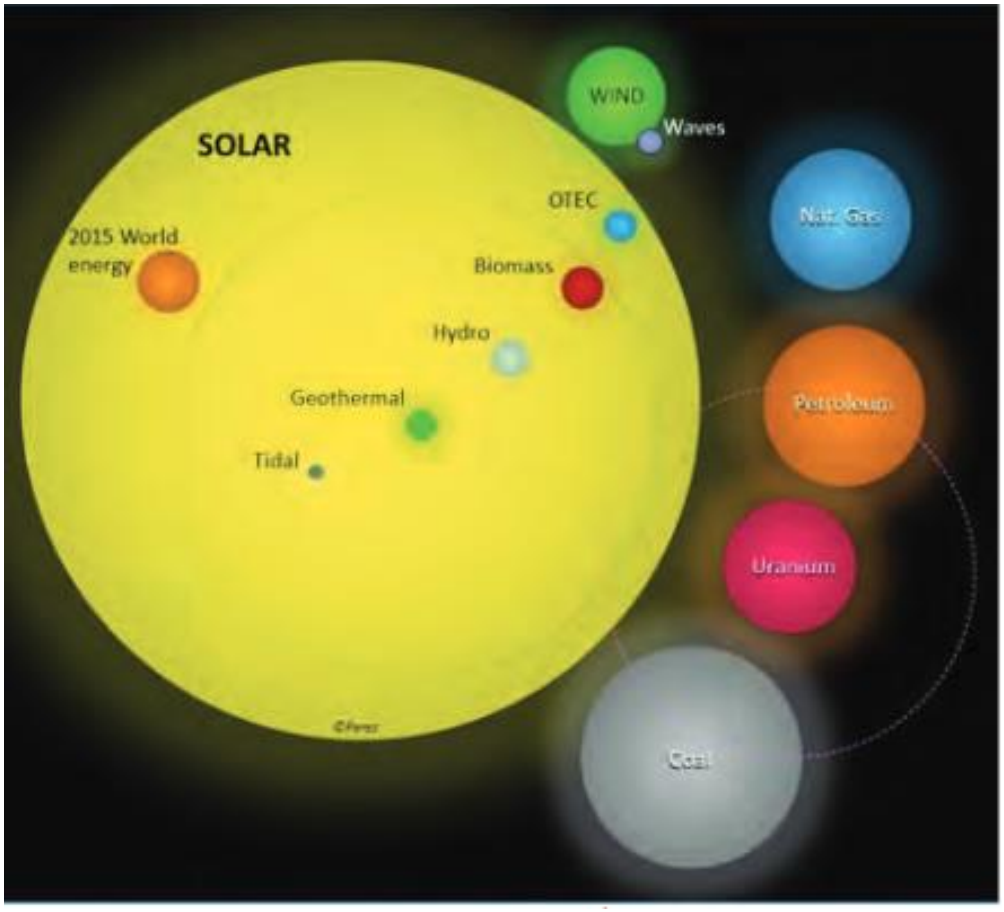
ŚWIATOWE ZASOBY SUROWCÓW ENERGETYCZNYCH – WNIOSKI DLA POLSKI (WORLD RESOURCES OF ENERGY RAW MATERIALS - APPLICATIONS FOR POLAND), E. Mokrzycki, R. Ney, J. Siemek („Rynek Energii" – nr 6/2008)

(*) https://www.forbes.pl/wiadomosci/swiatowe-zasoby-uranu-wystarcza-na-200-300-lat/czdhn9g

# Photovoltaic Laboratory of IMMS PAS

**Solar is abundant resource**. See the chart below:

| World Energy | |
|---|---|
| **2015 Use** | **18.5 TWy/y** |
| **RENEWABLE** | **[TWy/y]** |
| Solar | 23 000 |
| Wind | 75-130 |
| Waves | 0.2-2 |
| OTEC | 3-11 |
| Biomass | 2-6 |
| Hydro | 3-4 |
| Geothermal | 0.2-3 |
| Tidal | 0.3 |
| | |
| **FINITE** | **TWy** |
| Nat. Gas | 220 |
| Petroleum | 335 |
| Coal | 830 |
| Uranium | 185 |




2015 estimated finite and renewable planetary energy reserves (Terawatt-years). Total recoverable reserves are shown for the finite resources. Yearly potential is shown for the renewables

R. Perez and M. Perez, 6 November 2015 shc solar update *„A Fundamental Look At Energy Reserves For the Plane”*, 2009

IN OUR CLIMATE:

1367 W/m²

100 %

ABSORBE CLOUDS

15 %

ABSORB ATMOSPERE

3 %

REFLECT THE CLOUDS

11 %

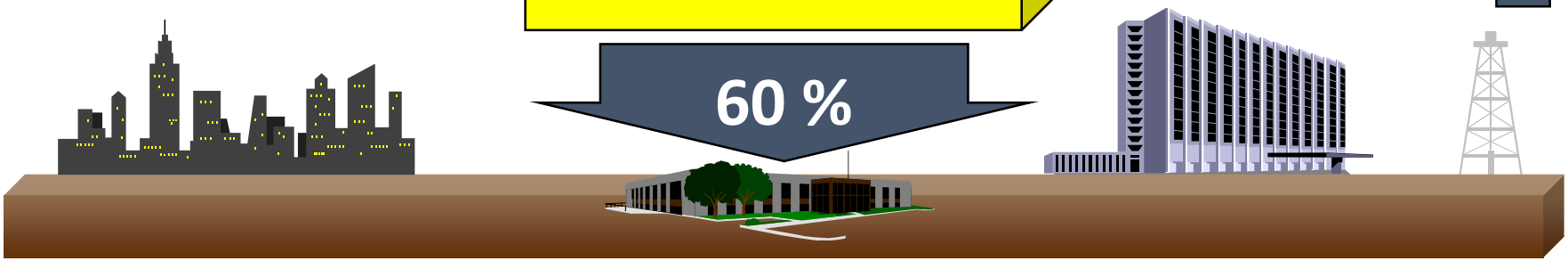
REFLECT THE ATMOSPHERE

6 %

REFLECT THE EARTH

5 %

60 %



~ 1000 W/m²

***The intensity of solar radiation*** expressed in watts per square meter (W/ $m^2$) is the density of radiation power falling within one second on a surface perpendicular to the direction of radiation.

The highest radiation intensity was recorded on Kasprowy Wierch - around **1200 W/$m^2$** and in the coastal belt - around **1050 W/$m^2$**.

The most common values of solar radiation range from **600-800** W/$m^2$.

- **Photovoltaic cells**, which convert sunlight into electricity.

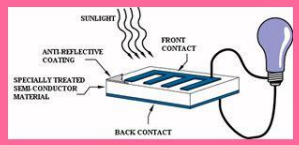
- **Solar thermal technology**, where heat from the sun is used to make hot water or steam.

- **Passive solar heating**, which can be as simple as letting the sun shine **through** windows to heat the inside of a building

## Methods of Using Solar Energy

**Photovoltaic cells**

- Consists of semi-conductors
- As light hits the surface, energy is produced




**Solar Thermal Electricity**

- A mirror is used to reflect the sunlight to a central receiver
- A fluid is circulated that drives a generator
- The generator produces electricity

**Solar Thermal Heater**

- Solar panels on roof absorbs sunlight
- Sunlight is converted into energy that heats the house

**Solar thermal technologies** capture the **heat** energy from the sun and use it for **heating** and/or the production of electricity. This is different from photovoltaic **solar** panels, which directly convert the sun's radiation to electricity.

# This is not PV !!

## Concentrated Solar Power (CSP)

https://sunsol.pl/blog/radosne-wiesci-w-czasach-zarazy-rekordowa-produkcja-energii-w-hiszpanii-z-pv/

## Solar Thermal Collector

# Photovoltaic systems

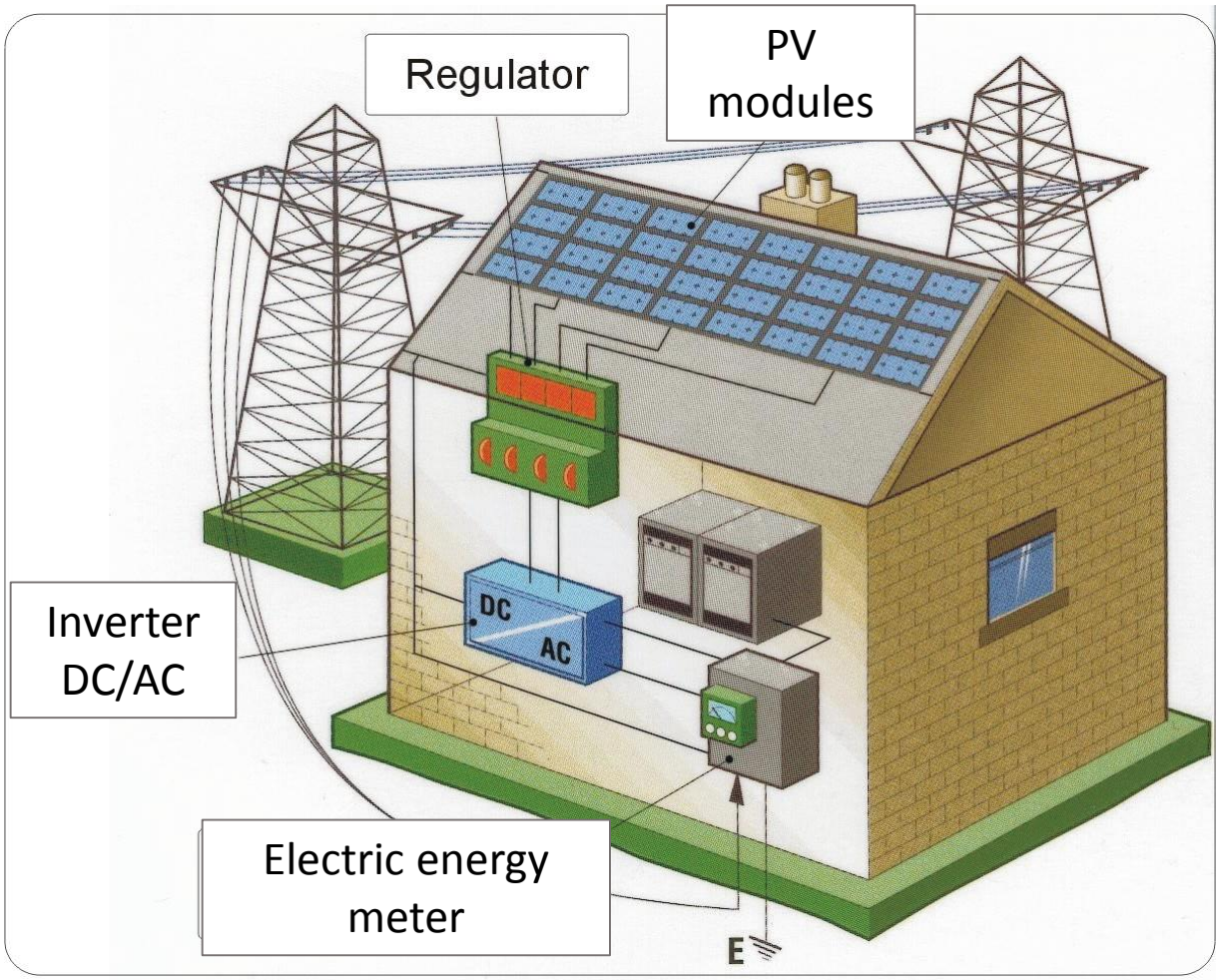
A **photovoltaic system:** power system which convert solar energy directly to electricity.

It consists of an arrangement of several components,
- Solar modules (panels) or PV modules
- Inverter to convert the output from direct to alternating current
- Other electrical accessories as well as cabling, ..
- Optionally: solar tracking, battery.

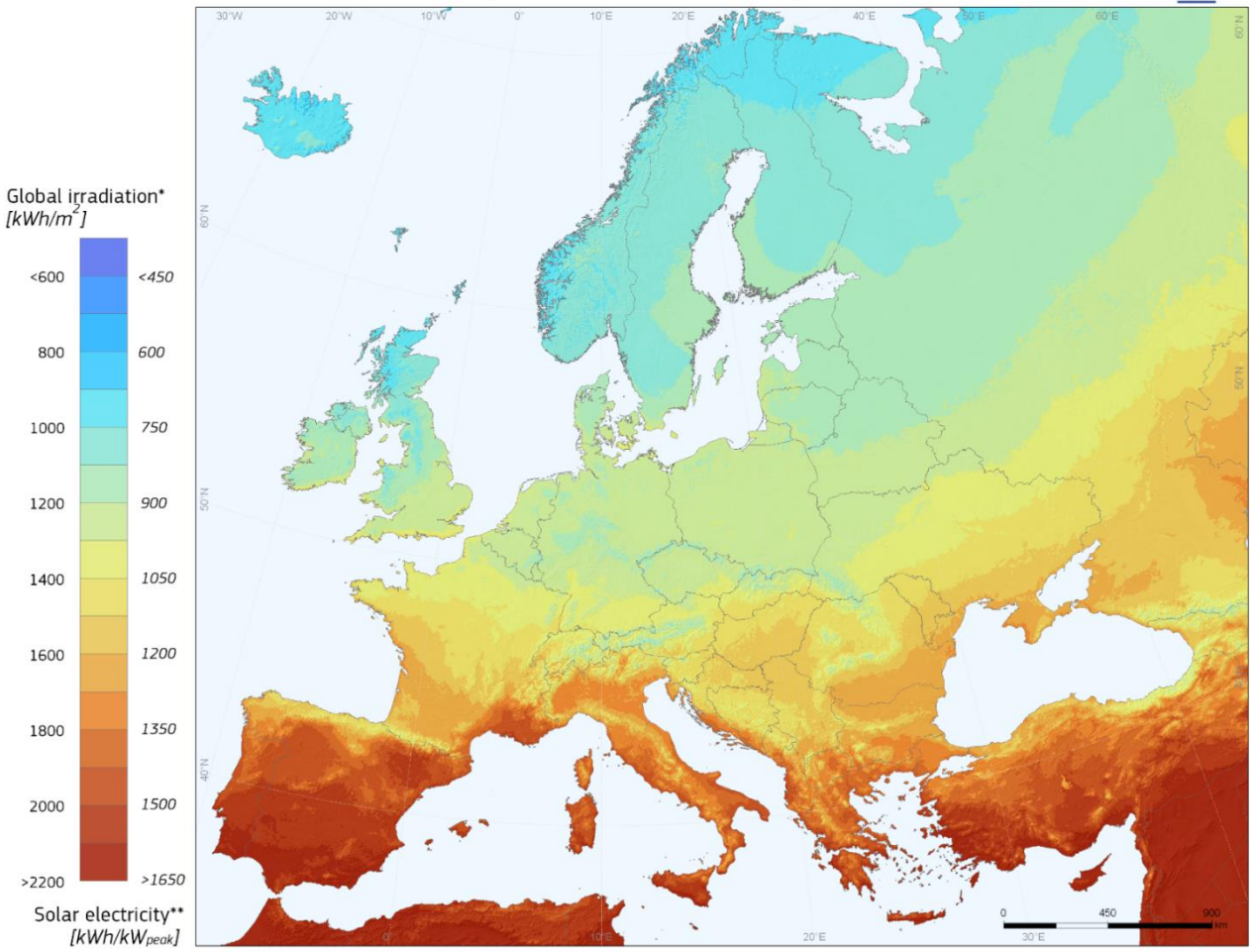
A **photovoltaic system** = solar array the ensemble of solar panels and so called balance of system (BOS).

PV systems convert light directly into electricity, they are not to be confused with other solar technologies, such as **Concentrated Solar Power** or **Solar Thermal** used for heating.

# Photovoltaic systems



# Photovoltaic Solar Electricity Potential in European Countries




* Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

***Yearly sum of solar electricity generated by optimally-inclined 1kWp system with a performance ratio of 0.75*



PVGIS http://re.jrc.ec.europa.eu/pvgis/

Authors: Thomas Huld, Irene Pinedo-Pascua
EC · Joint Research Centre
In collaboration with: CM SAF, *www.cmsaf.eu*

## Global irradiation and solar electricity potential

Horizontally mounted photovoltaic modules

**POLAND / POLSKA**


https://re.jrc.ec.europa.eu/pvg_download/map_index.html#!

CM SAF

Joint Research Centre

Authors: Thomas Huld, Irene Pinedo-Pascua
European Commission - Joint Research Centre
Institute for Energy and Transport, Renewable Energy Unit
PVGIS http://re.jrc.ec.europa.eu/pvgis/

# Global irradiation and solar electricity potential

## Optimally-inclined photovoltaic modules

## POLAND / POLSKA


Yearly sum of global irradiation
[kWh/m$^2$]

>1100 1200 >1300

>825 900 >975

*Yearly sum of solar electricity generated by 1kW$_p$ system with performance ratio 0.75*
*[kWh/kW$_{peak}$]*

Urban area

Water body

*Projection:* Lambert Azimutal Equal Area, WGS84, lat 52° lon 10°
*Source of ancillary data:* CORINE Land Cover
DTM SRTM-30
GISCO database
Geonames
Natural Earth

https://re.jrc.ec.europa.eu/pvg_download/map_index.html#!

CM SAF Climate Monitoring

Joint Research Centre

*Authors:* Thomas Huld, Irene Pinedo-Pascua
European Commission • Joint Research Centre
Institute for Energy and Transport, Renewable Energy Unit
PVGIS http://re.jrc.ec.europa.eu/pvgis/

# Advantages and disadvantages of photovoltaics

# Advantages of photovoltaics

- ✓ There are no pollution of the environment during work
- ✓ Made from silicon (a very common element)
- ✓ Allow the construction of systems from mW to MW
- ✓ They are light that you can cover different surfaces without special constructions
- ✓ Photovoltaics is one of the cheapest sources of green Energy.

# Advantages of photovoltaics

- ✓ Do not contain toxic liquids and gases
- ✓ There are no movable parts no noise, durability
- ✓ Fast response to load
- ✓ Can work in limited different conditions

# Disadvantages of photovoltaics

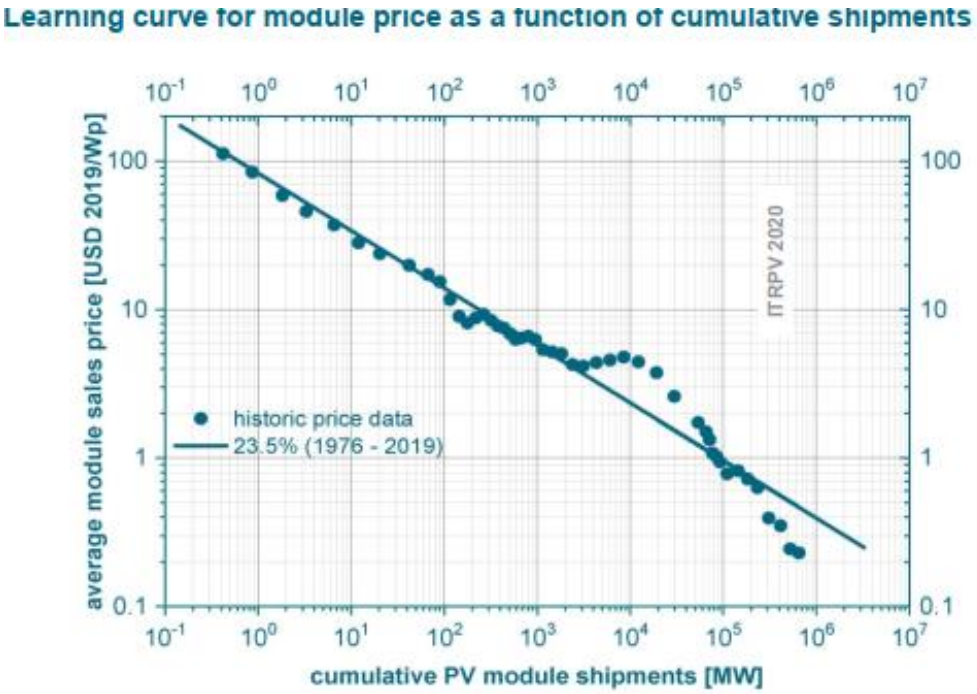
✓ Unstable amount of energy supplied
- energy storage: electricity network as an energy storage,..

✓ Low density of solar energy - the necessity to use large areas

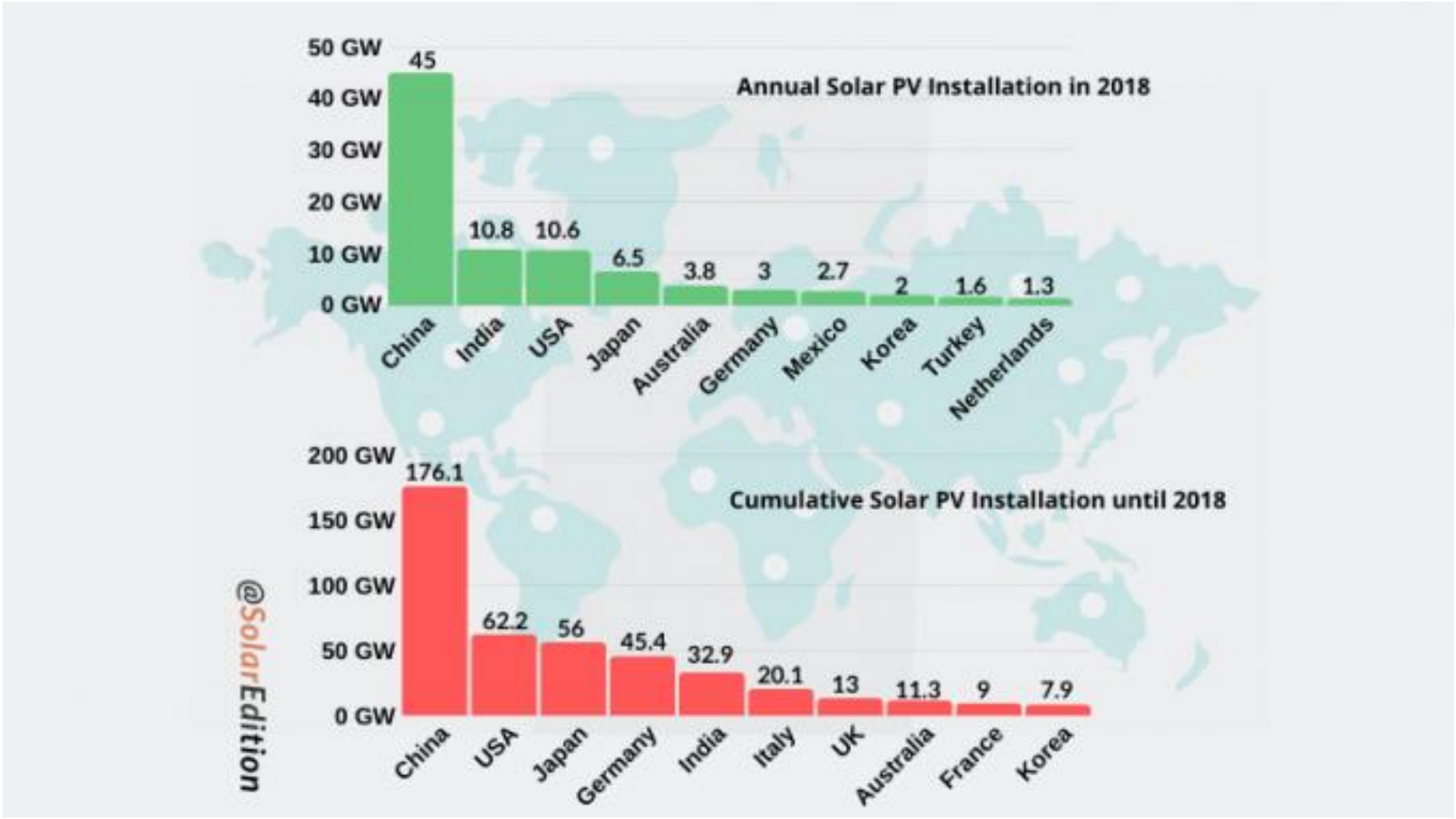
**For micro PV system:**

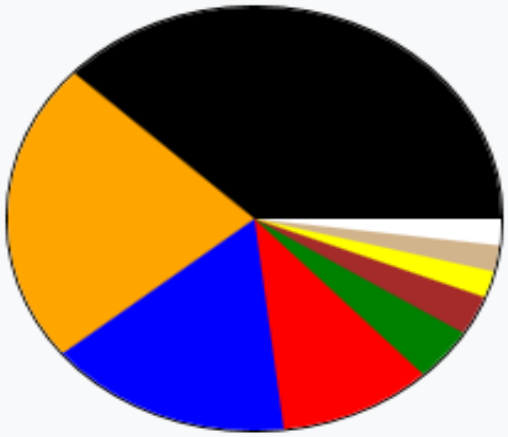
- Roofs,
- Walls,
- **For large PV system:**
- Areas devastated by industry (opencast mines), landfills,
- Roads and railways – acustic sreens
- Lakes, seas, oceans

# Swanson law




Swanson law - empirical law resulting from observation regarding the price trend of solar photovoltaic cells, according to which every doubling of the solar industry production capacity causes a decrease in the price of solar cells by 20%


Annual Solar PV Installation in 2018
50 GW
40 GW
30 GW
20 GW
10 GW
0 GW
China 45
India 10.8
USA 10.6
Japan 6.5
Australia 3.8
Germany 3
Mexico 2.7
Korea 2
Turkey 1.6
Netherlands 1.3
Cumulative Solar PV Installation until 2018
200 GW
150 GW
100 GW
50 GW
0 GW
China 176.1
USA 62.2
Japan 56
Germany 45.4
India 32.9
Italy 20.1
UK 13
Australia 11.3
France 9
Korea 7.9
@SolarEdition



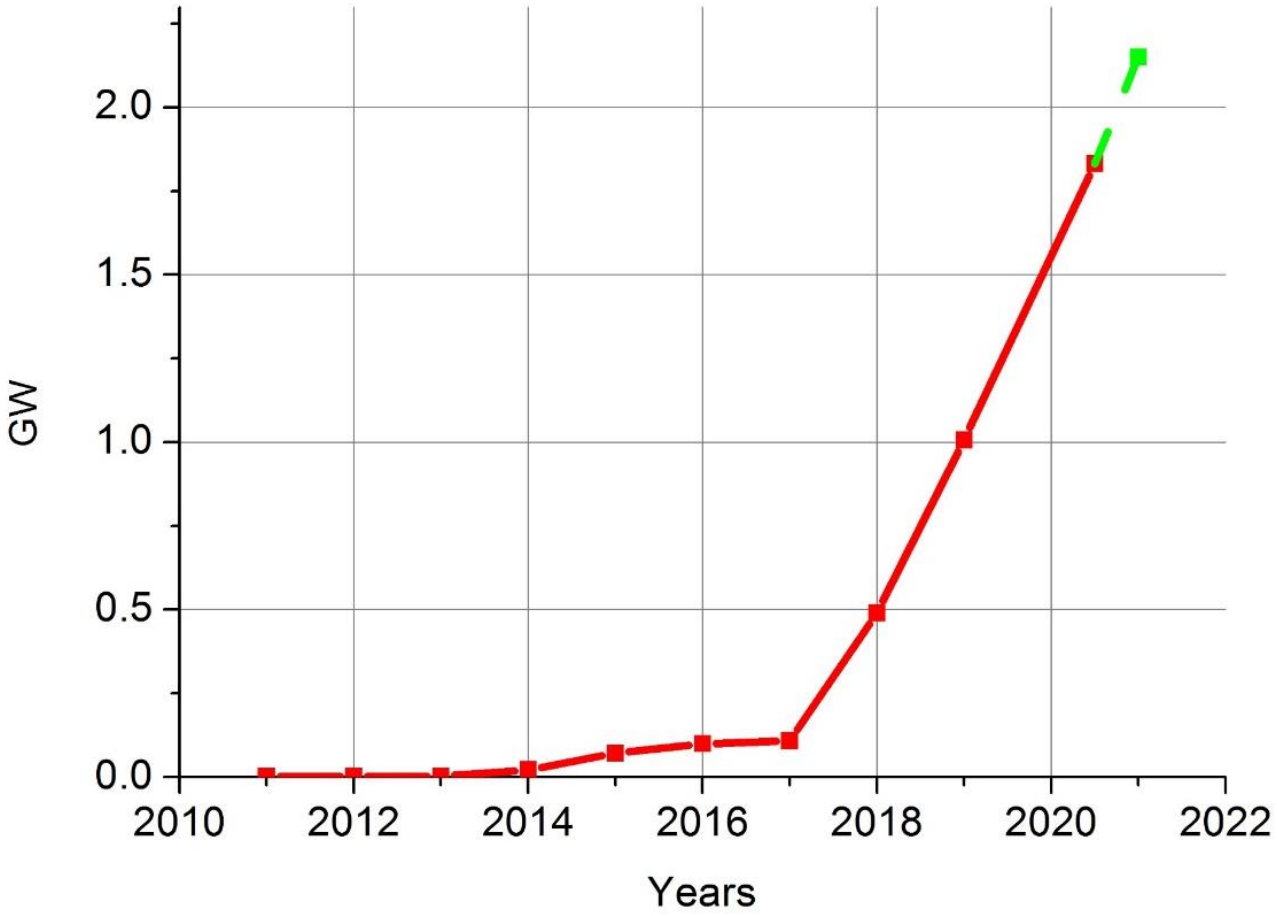
World electricity generation by source in 2017. Total generation was 26 PWh.[1]

- Coal (38%)
- Natural gas (23%)
- Hydro (16%)
- Nuclear (10%)
- Wind (4%)
- Oil (3%)
- Solar (2%)
- Biofuels (2%)
- Other (2%)

Photovoltaics (PV) is rapidly-growing with global capacity increasing from 177 GW at the end of 2014 to 385 GW in 2017.

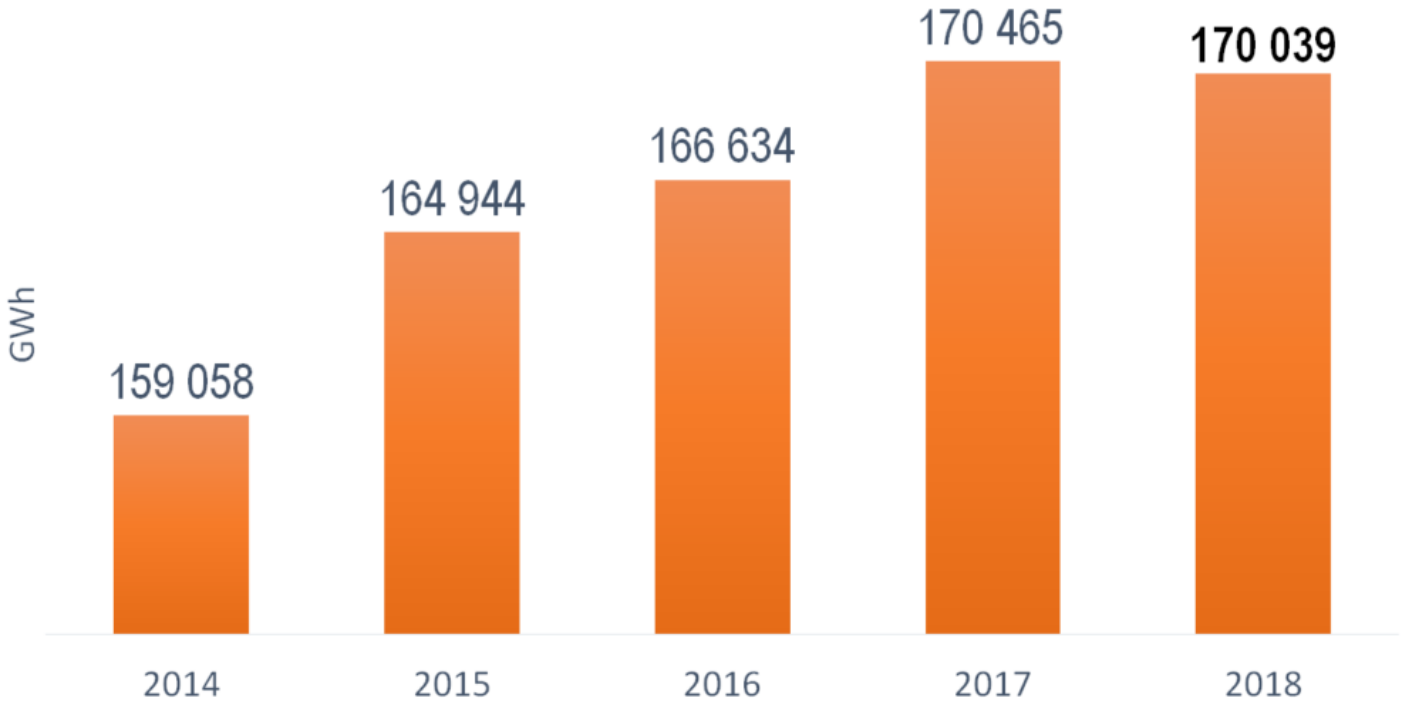
https://en.wikipedia.org/wiki/Renewable_energy

# Cumulated capacities of PV systems in Poland



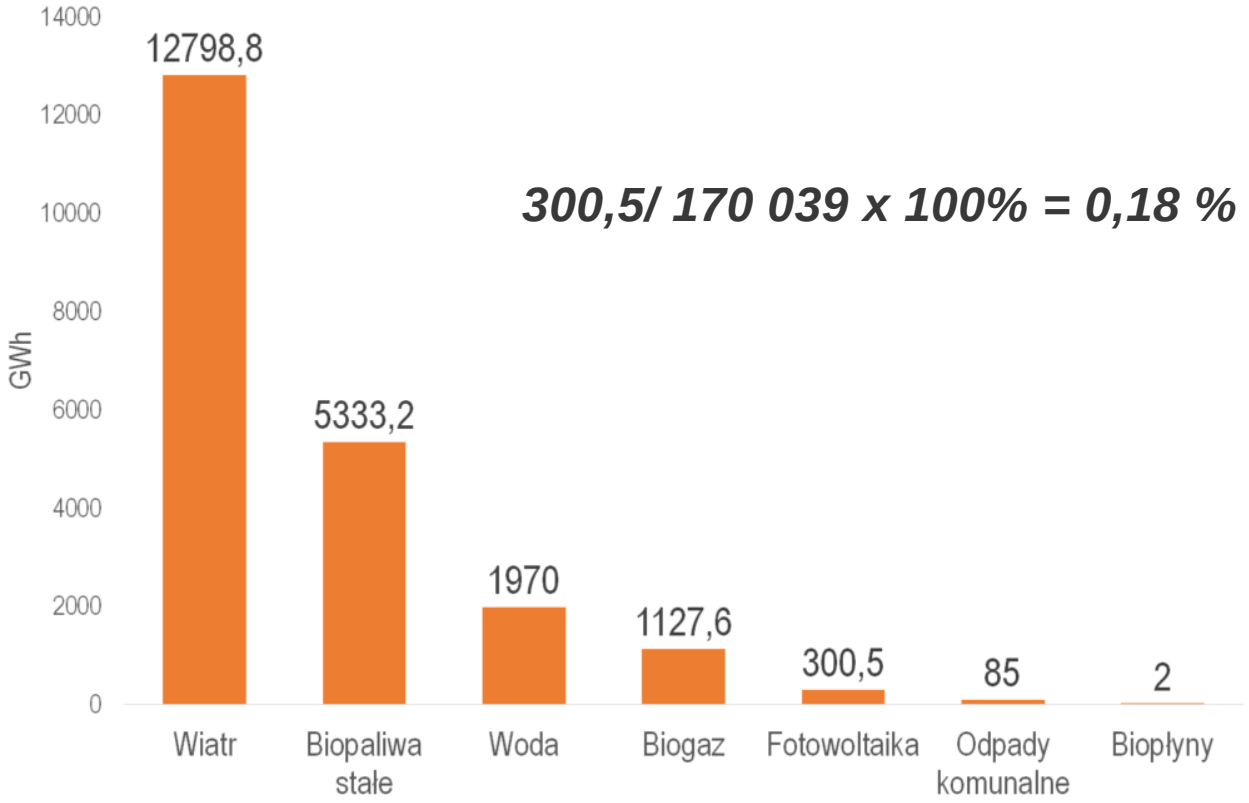

Source: URE (**Urząd Regulacji Energetyki**)

# *Electricity production in Poland*




*Electricity production in Poland in 2018 amounted to 170 039 GWh. Hard coal was the most important fuel for electricity generation in 2018 (47.8%).*

# Production of electricity from renewable sources in Poland in 2018




***300,5/ 170 039 x 100% = 0,18 %***

https://globenergia.pl/fotowoltaika-w-polsce-to-juz-490-mw-rekordowy-rok-2018-mamy-dane-z-rynku/

## What Are Peak Sun-Hours?

Peak sun-hours refers specifically to how much solar energy is available in an area during a typical day.
A peak sun-hour, specifically, is an hour during which the intensity of sunlight is 1,000 watts per square meter.

**peak sun-hours"** are not the same as "**hours of daylight**."

## How to Calculate Your Peak Sun-Hours?

The easiest way is visit NASA' s website http://eosweb.larc.nasa.gov/cgi-bin/sse/retscreen.cgi?email=rets@nrcan.gc.ca
Then input Latitude and Longitude data of your location, click "Submit" button to get result.

Electricity production in Poland in 2018 amounted to ***170 039 GWh***.

**The sum of all PV installations ≈ 2 GW**

**Total HOZ insolation : 930-1160 kWh/m²*year ,**

**average insolation: 1000 kWh/m²*year**

**Global horizontal irradiance (GHI) (on a sunny summer day at noon) ≈ 1 kW/m²**

**The nominal power of module for STC** (irradiance 1kW/m2, T=25°C, AM1.5)

1000 kWh/m²/1 kW/m² **= 1000 h in year**

2 GW x 1000 h x 0.75 = **1500 GWh** ***(Performance ratio = 0.75)***

**1500/170039 x 100% = 0.9 %**

To meet Poland's energy needs, you need approx. 111 times more power, i.e. approx. **222 GW.**

One module: 2m² - 370 W 1m² - 185 W

***S*** = 222 GW/185 W [m²] =1.2 Gm² = **1 200 km²** (35 km x 35 km)

A more realistic estimate of the area needed to meet energy needs in Poland:

**3.77 MW – 7.7 ha = 0.077 km$^2$ (PV power plant in Czernikowo)**

The number of power plants (3.77 MW) that would cover the demand in Poland:

222 GW/3.77 MW = 222 000/3.77 = **60 000 power plant**
60 000 x 0.077 = **4 620 km$^2$ (68 km x 68 km)**

## In Germany:

- In 2018, Germany accounted for about 9% (45.9 GWp) of the cumulative PV capacity installed worldwide (**515 GWp**) with about 1.6 million PV systems installed in Germany.
- In 2018 the newly installed capacity in Germany was about 2.81 GWp; in 2017 it was 1.66 GWp.
- PV covered **8.7% of Germany's net electricity demand in 2018**. **Renewable sources delivered about 43% of the total net power consumption in 2018 in Germany.**
- In 2018 about 28 Mio. t CO2 equivalent GHG emissions have been avoided due to 46 TWh electrical energy generated by PV in Germany.
- PV system performance has strongly improved. Before 2000 the typical Performance Ratio was about 70%, while today it is in the range of 80% to 90%.

**According to the IRENA International Renewable Energy Agency, at the end of 2019, there were 583.5 GW of functioning solar installations worldwide! In 2019 alone, 98 GW of new capacity installed in PV increased!**

# APPLICATIONS OF PV SYSTEMS

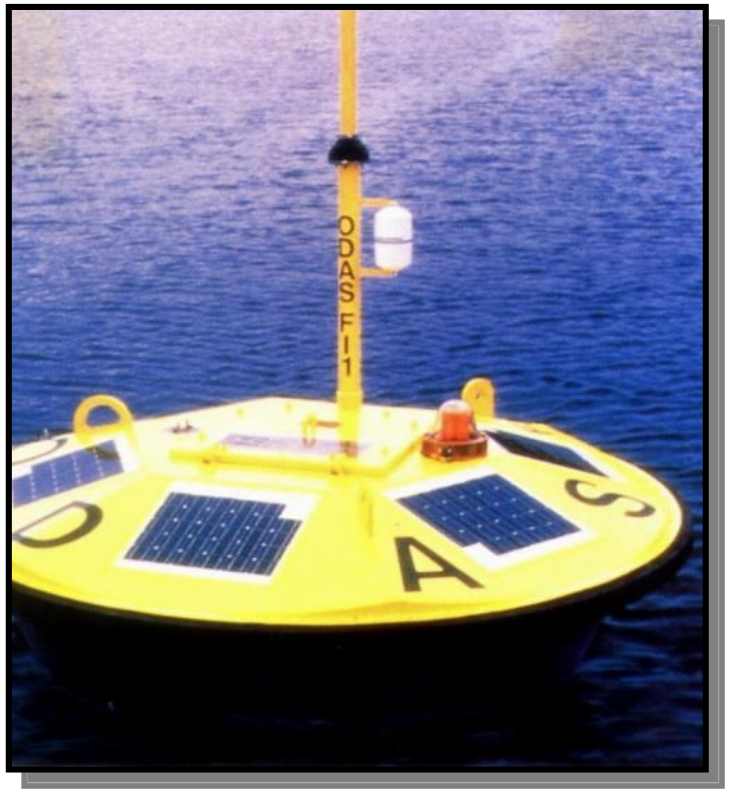
## Autonomous Systems

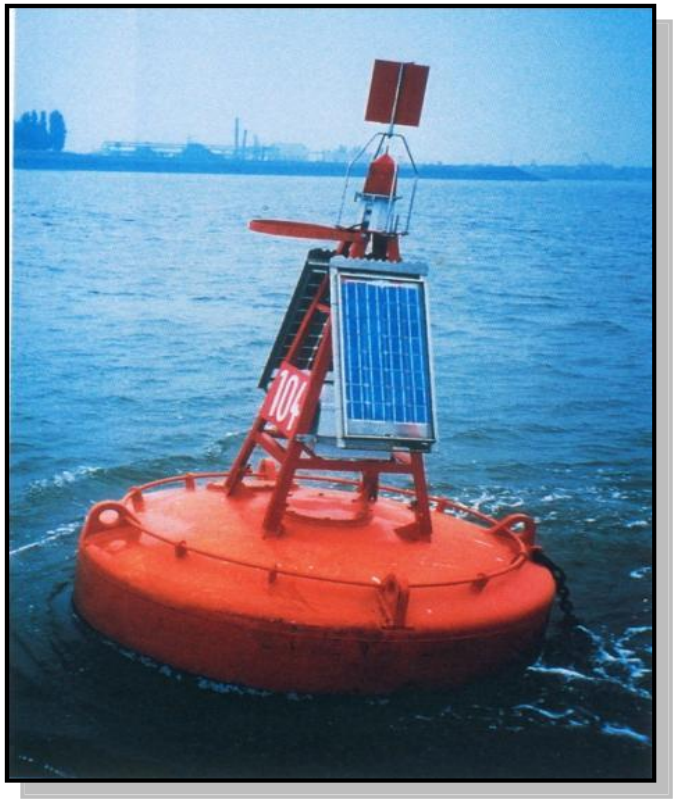
- ✓ IN THE ARMY - power supply for electric field devices
- ✓ IN METEOROLOGY - power supply for isolated meteorological stations.
- ✓ IN HOUSEHOLDS - power supply for household appliances
- ✓ IN MEDICINE - supply of complete field medical outpatient clinics
- ✓ IN TOURISM - autonomous supply systems on caravans, mountain huts.
- ✓ IN NAVIGATION - power supply for sea, inland and air navigation signs,
- ✓ IN AGRICULTURE and FORESTRY - supply of electric pasture and forest protection devices, irrigation and drying devices, fire protection devices.
- ✓ IN TELECOMMUNICATIONS - power supply for radio-telecommunications relay stations, radio stations in remote places, mobile telephony.
- ✓ IN TRANSPORT - power supply of signs on roads and railways, in particular markings of road sections and dangerous tracks being under renovation, marking of airports, etc.

# Examples of applications

# NAVGATION

Supplying marine, inland and air navigation signs, charging batteries on high-seas yachts

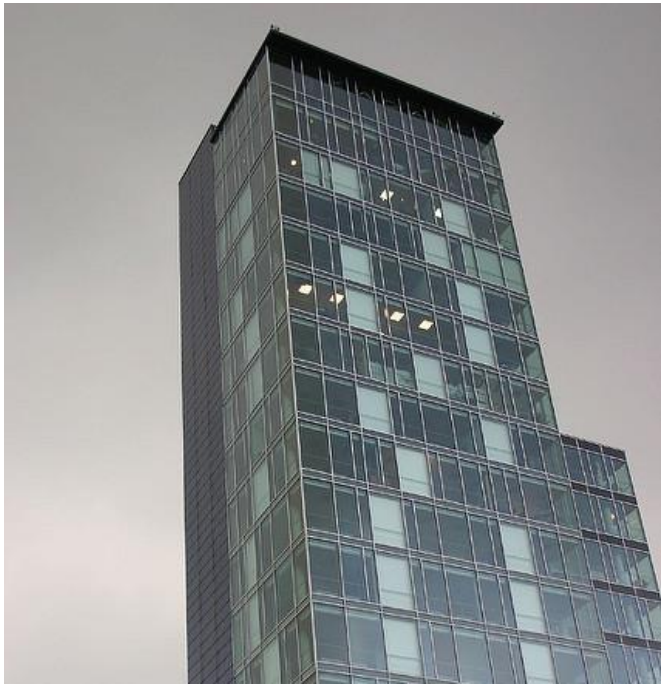


# ARMY


# AGRICULTURAL FARMS

# MODERN ARCHITECTURE - zero energy buildings



Directive 2010/31 / EU, defines the energy performance of buildings erected in the EU after 2020. - Zero energy buildings

Construction Law Art 5 par 2a: In new buildings and existing buildings undergoing reconstruction or undertaking to improve energy efficiency within the meaning of energy efficiency regulations, which are used by public finance sector entities within the meaning of public finance regulations, it is recommended to use energy-using equipment generated in renewable energy sources, as well as technologies aimed at constructing buildings with high energy performance.

# The Sahara: a solar battery for Europe?

http://naukawpolsce.pap.pl/aktualnosci/news%2C30946%2Cturbiny-wiatrowe-i-panele-sloneczne-na-saharze-przyniosa-tam-deszcze-i

# Solar PV plants in large scale

Traffic noise has been recognized by the World Health Organization as an important factor contributing to the pollution of the environment. In addition to causing discomfort, it has significant negative impacts on health in the populations that live near the road infrastructure.

The sounds emerging from the roads are considered among the most annoying. According to studies carried out, the acceptable level of sound coming from the communication channels during the day is approximately L=50-65 dB depending on the type of building in the area. The noise level emitted by the existing communication routes should be limited to this range.

**SOLAR INNOVA GREEN TECHNOLOGY, S.L.**
N.I.F.: ESB-54.627.278
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03660 – NOVELDA (Alicante) SPAIN
Tel./Fax: +34 965075767
E-mail: info@solarinnova.net
Website: www.solarinnova.net


Fundusze Europejskie
Inteligentny Rozwój
Rzeczpospolita Polska
Unia Europejska
Europejski Fundusz Rozwoju Regionalnego
„Magazyn energii adaptujący farmę PV do pracy w inteligentnych sieciach elektroenergetycznych”
Cel projektu: Opracowanie i wybudowanie wraz z instalacją pomiarowo-monitorującą magazynu energii o mocy 500 kVA i pojemności 750 kWh, zlokalizowanego w pobliżu istniejącej elektrowni słonecznej o mocy 500 kW na Górze Żar.
Benefcjent: PGE Energia Odnawialna S.A.
www.mapadotacji.gov.pl

# Floating solar power plants

Offshore solar systems. Oceans cover more than 70% of the earth's surface; they receive a great amount of solar energy. The available solar resource could be exploited to counteract the current generation of electricity using solar PV

Canal top solar systems.

# Floating solar power plants

- Location: Piolenc, France
- Installed capacity: 17 MW
- Status: In operation
- Technology: Floating solar
- $CO_2$ emission reductions per year: 1 096 tons
- Power supply per year: Equivalent to 4733 households
- Cultivated spacies : Arboriculture and market gardening

**O'MEGA1, Piolenc, France, Floating solar, Agrinergie®**

# Solar PV plants in large scale

The largest photovoltaic power plant in Poland has been located in the commune of Czernikowo, in the area of about 7.7 hectares. The farm's installed capacity is 3.77 MW.

# Solar PV plants in large scale


source : https://globenergia.pl/plany-farmy-pv-o-mocy-do-60-mw-w-belchatowie-od-pge/

At the reclaimed municipal landfill site in Końskie completed the construction of a solar farm. Its contractor was MGM Projekt Sp. z o.o. from Katowice, which in an open tender offered a lower amount than the investor's cost estimate, namely PLN 2 398 690 net.

Municipal Economy Enterprise in Końskie saves over PLN 30 thousand a month thanks to the solar power plant operating since the end of June. Almost 500 tons of toxic gases and dust do not enter the atmosphere annually.

Energy produced is sufficient to cover the energy needs of approx. 100 thousand households

Power plant 1MW in Pluskocin

http://www.mgmprojekt.pl/1_13_realizacje.html

# LARGE POWER PLANTS


69.7 MWp - Nikolayevka Solar Park in the Simferopol region of Crimea, Ukraine
Modules: 290,048 (policrystalline) Mounting Type: Ground mounted Land Area: 116 hectares
7% of Crimea's electricity demand.
Read more at: https://satkurier.pl/news/88986/austriacy-buduja-nikolayevka-solar-park-na-krymie.html
Source: Active Solar, http://www.activsolar.com/

# LARGE POWER PLANTS

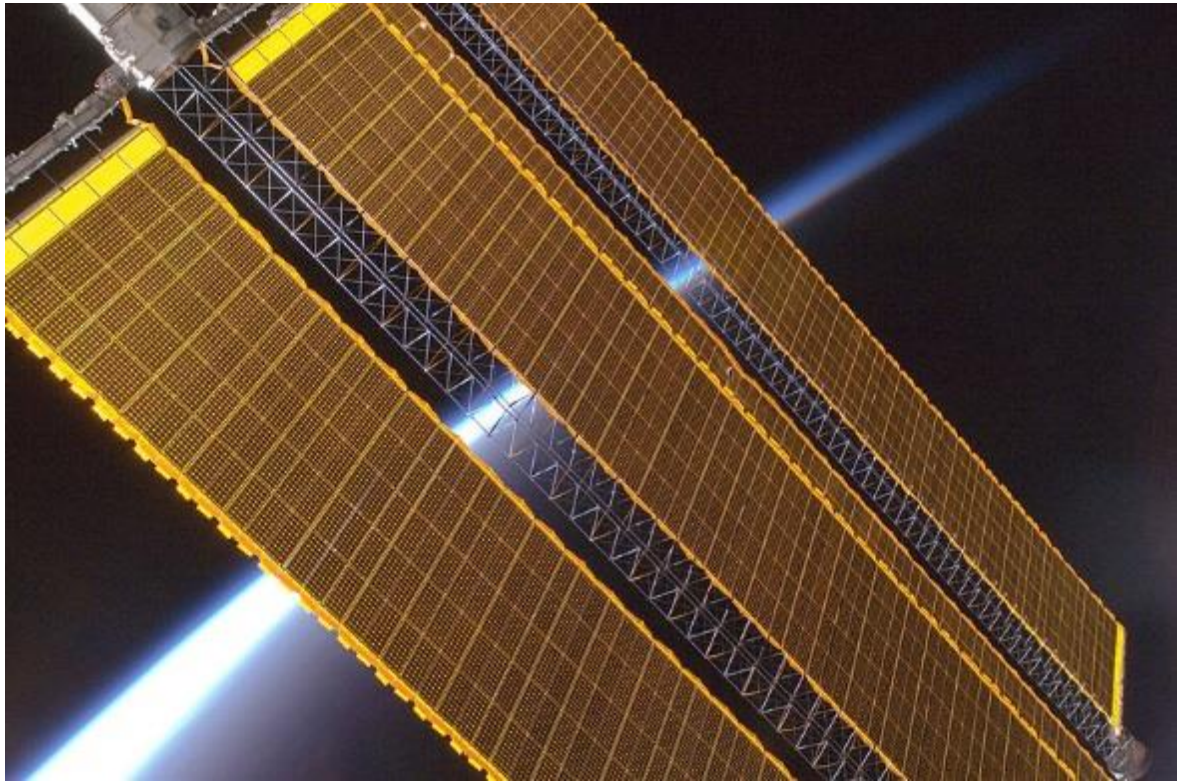
300 MWp - Bordeaux, France
Mounting Type: Ground mounted Land Area: 250 hectares
Price 1 MWh - 105 EURO (price at the nuclear power plant - 55 EURO old treatment plants - 130 EURO new)
470 PLN PKP
Source: NEOEN.fr, Reuters. Koleje Mazowieckie (money.pl 3.12.2018)

# *PV in northern countries*

Solar power in Finland was 3 GWh in 2005.
Because the sun is quite low in the sky at this latitude, vertical PV installations are popular on the sides of buildings. These solar walls also capture light reflected from snow.

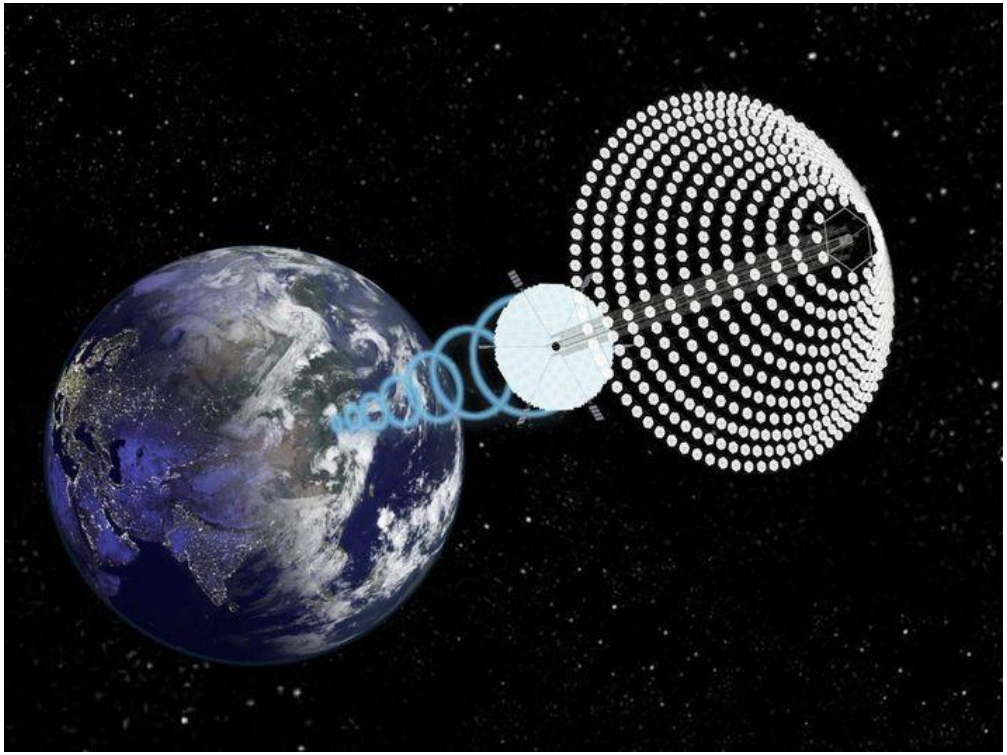
Solar panels extended out from the Apollo Telescope Mount, power solar observatory instruments on the Skylab station, which also had an additional array on the main spacecraft

The solar panels on the SMM satellite provided electrical power. Here it is being captured by an astronaut in a mobile space-suit that runs on chemical battery power.



A solar panel array of the International Space Station (Expedition 17 crew, August 2008)

https://en.wikipedia.org/wiki/Solar_panels_on_spacecraft#/media/File:Earth_horizon_and_International_Space_Station_solar_panel_array_(Expedition_17_crew,_August_2008).jpg



China is planning to build the world's first solar power station in space to provide "inexhaustible clean energy" . Space solar power system orbiting the Earth at an altitude of 36,000 kilometers could tap the energy of the sun's rays without disruption from atmospheric conditions or loss of sunlight at night.  Testing the technology and intend to build the station by 2050.

**Solar Power Stations In Space Could Supply The World With Limitless Energy** Scott SnowdenContributor
Science, 37 284 views|Mar 12, 2019,01:29pm EDT

Thank you for your attention