PV SYSTEMS
Modelling, measurements, design

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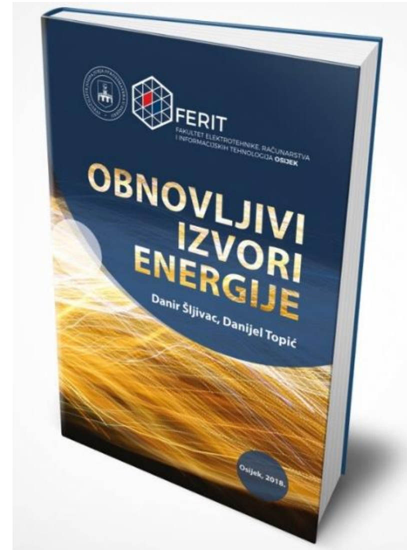
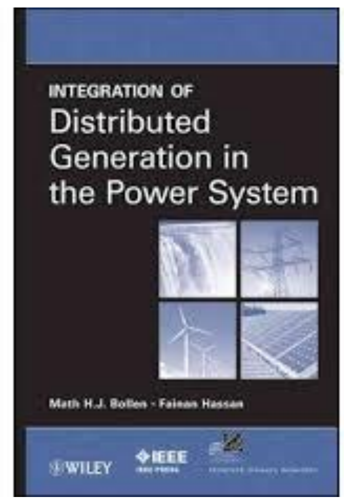
- Croatian Energy Market Operator (HROTE), www.hrote.hr ...





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Laboratory for RES and PV power plant ETFOS 1 10 kW

5 types of PV modules:

1. *Polycristalinne Si* ***BISOL BMU-250 245 W_p*** *(20+2 modules)*
2. *Monocristalinne SI* ***BISOL BMO-250 250 W_p*** *(20+2 modules)*
3. *Thin-film CIS (copper-indium-selenide)* ***SOLAR FRONTIER SF-150 150 W_p*** *(2 modules)*
4. *Thin-film amorpheus SI* ***MASDAR MPV-100S 100 W_p*** *(2 modules)*
5. *Heterojunction HTJ mono/thin-film Si* ***PANASONIC VBHN240SE10 240 W_p*** *(2 modules)*

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Laboratory for RES and PV power plant ETFOS 1 10 kW

- *PV power plant* ***10 kWp***
- ***PV modules: 5 different technologies***
- ***Virtual Lab***
- ***Constant on-line measurements of PV charteristics***
- ***Masurements of Power Quality and Influence on Grid at PCC***
- ***Off-line PV system with batteries and programable load***
- ***Development of FERIT building smart microgrid***

http://reslab.ferit.hr/

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Chapter 1:
SUN RADIATION

Basic theory on Sun radiation

- *Sun radiation energy that comes to the edge of Earth depending on the distance of the Earth to the Sun equaly* ***1307-1399 W/m² on optimal angle plate (vertical to irradiation)***
- *Mean value od Sun irradiation on optimal angle (vertical to irradiation) plate is called* ***solar constant*** *and equals* $E_{0mean}=1367.7\ W/m^2$
- *For different distances of Earth to Sun (eliptical rotation of Earth arround Sun) real value of Sun irradiarion on optimal angle plate:*

$$E_o = E_{0mean}\left(\frac{r}{R}\right)^2$$

where: *r – mean distance of Earth to Sun*

R - real distance of Earth to Sun (considered constant for actual day)

- **Sun irradiation (intesity)** *over year can be expressed by:*

$$E_o(n) = \varepsilon_0(n)E_{0sr} = \left(1 + 0.034\cos\frac{360^0 n}{365^0}\right)E_{0sr}$$ *[W/m²]*

gdje je: ε excentricity of elipse, n serial number of day in a year

- ***Total daily Sun energy on optimal angle plate in [J]:***

$$W_o(n,\phi,\delta,\omega_s) = \frac{86400}{\Pi}E_{0sr}\left(1 + 0.034\cos\frac{360^0 n}{365^0}\right)\left(\frac{2\Pi}{360}\omega_s \sin\phi\sin\delta + \sin\omega_s\cos\phi\cos\delta\right)$$

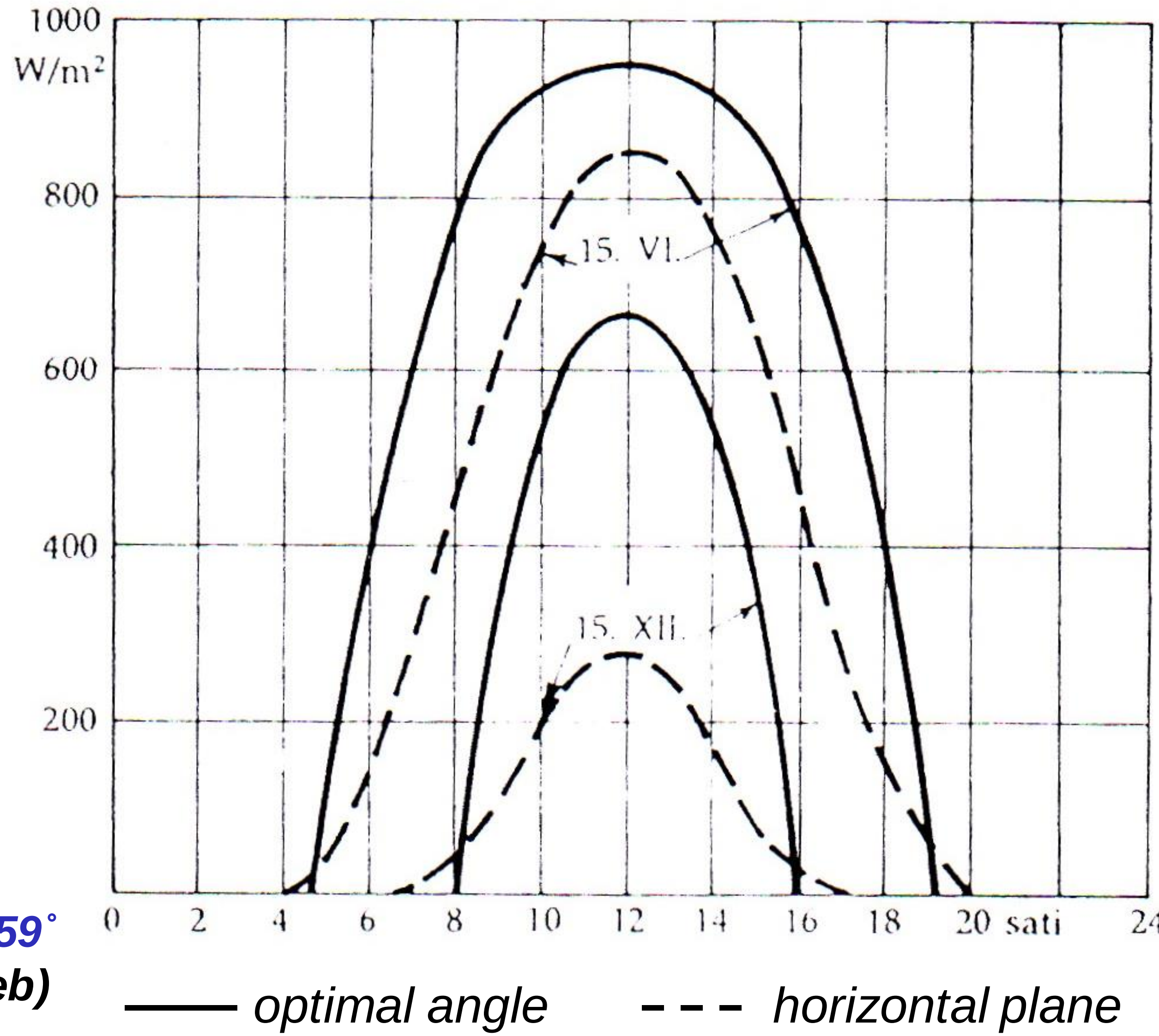
ω_s hourly angle of the Sun (12h=0^0, 13h=15^0, 15h=45^0);

Φ geographical width of actual place on Earth;

δ Sun declination (angle between connection of center of the Earth to Sun and Equator plane)

$$\delta = 23.45^0 \sin\left(360^0 \frac{248+n}{365}\right)^2$$

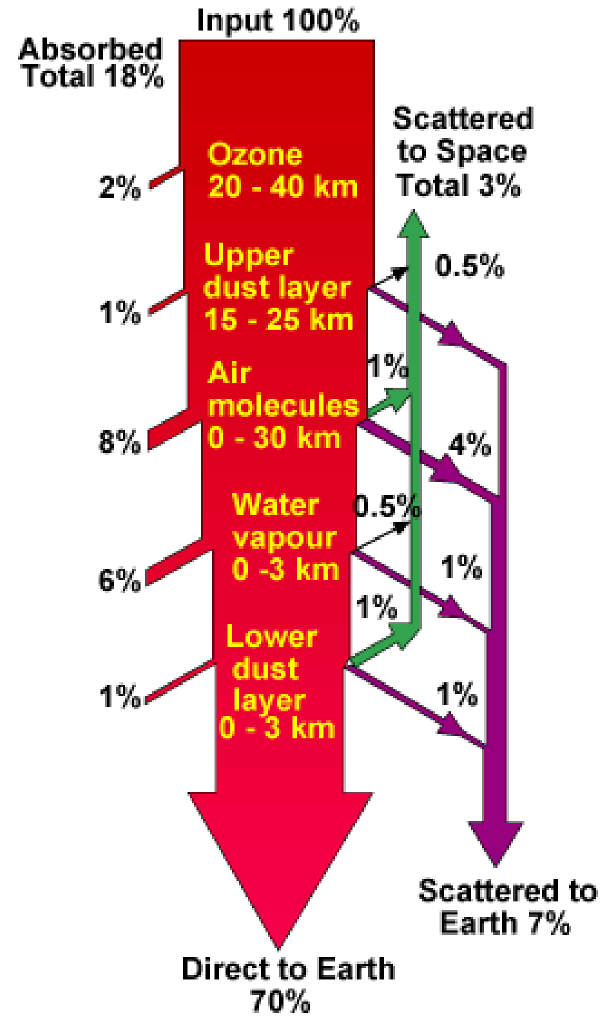
- Sun radiation intenstity in [W/m²] depending on time of the day and year (position of the plane to the Sun radiation).
- Decerases with decerasing of above sea level hight and with increase of geographical widht (lower incline angle of the Sun radiation)



Sun irradiation on a clear sky at 59˚ geographical width (city of Zagreb)

- *Average monthly or yearly energy of Sun irradiation is calculated as sum of daily energy for all days in cosidered months/year.*
- *However, **getting through athmosphere results in energy losses of direct Sun radiation, with some difuse (scattered) returning back to Earth**, depending on*

  - athmospheric conditions (sunny, cloudy...),
  - athmospheric pollution (dust) and
  - above-sea-level hight!
- *Maximal energy flow to Earth surface is in average 920 W/m^2 daily on optimal angle plane (vertical to irradiation) – at noon!.*
- *Sun energy is distributed due to Earth spinning (rotation) over Earth surface (day/night) so Sun irradtion to Earth is **in average daily 230 W/m^2** (depending on geographical widht!)*

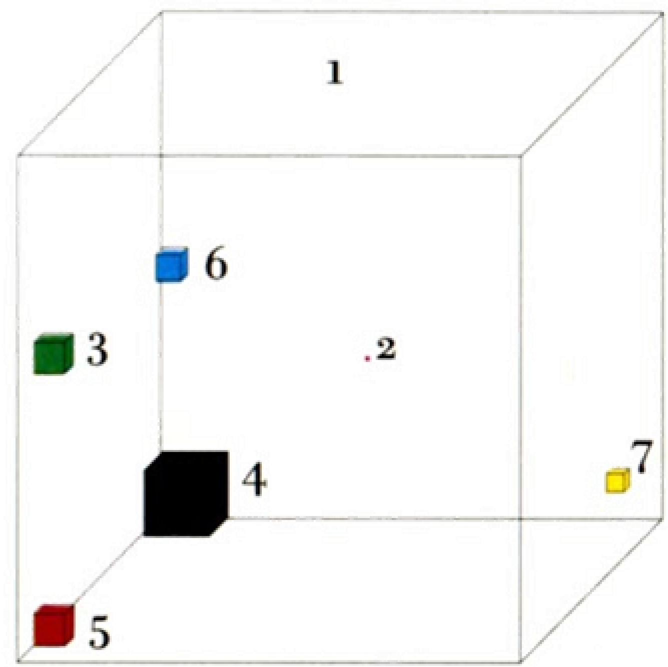


Athmospheric conditions influence on Solar irraditon

- *That equals* ***average daily Sun energy of 5.52 kWh/m²****, depending on actual insolation (geographical widht, time in a year), cloudness and pollution in athmosphere).*
- *Earth surface equaly approx. 510.1 10^6 km^2 which results in* ***Sun irradiation energy of approx. 10^9 (billion) TWh/god (enormous!)***

Cube volume ***comparison of yearly Sun irradiation energy (1)*** *to*

- *natural gas (3), coal (4), oil (5) and uranium (6) reserves*
- *Current global yearly usage of Sun irradiation energy (2)*
- *Current global yearly energy consumtption (7)*



- ***Many problems with usage historically*** *that are being overcomed:*

  1. Small energy density *of approx. up to 1000 W/m2 (at noon)*

  2. Intensity oscillation *during the day*

  3. Dependency on climate conditions

  4. Intensity is not coinciding the load intensity *- load management/smart grids*

  5. Very expensive storage (e.g. batteries) *- slowly decreasing*

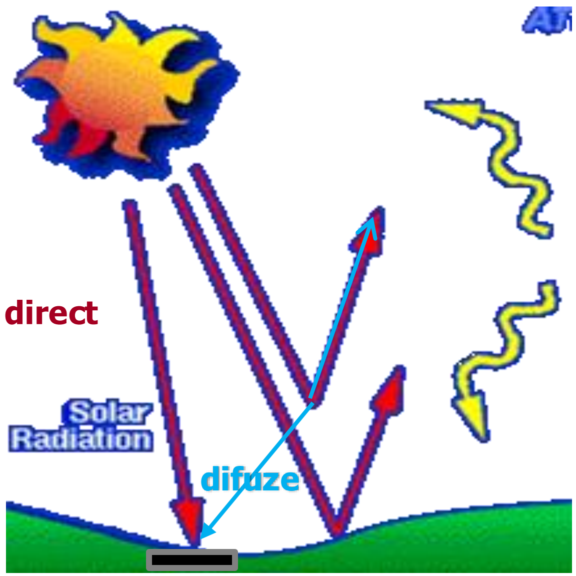
  6. Rapidly decreasing initially extremely high energy generation costs *(particularly for PV) compared to other primary energy sources*

- *So historically (untill 2017) majority of Sun irradiation was used for heating (solar thermal collectors) with much higher efficiency of both generation and thermal storage*

- *However, due to 20 years of extremelly high incentives (e.g. 2007 in Croatia 0,45 €/kWh (market generation price 0,05 €/kWh) and rapid tehnology development and fall of investments – results in enourmous increase of PV systems (402 GW in 2017!)*

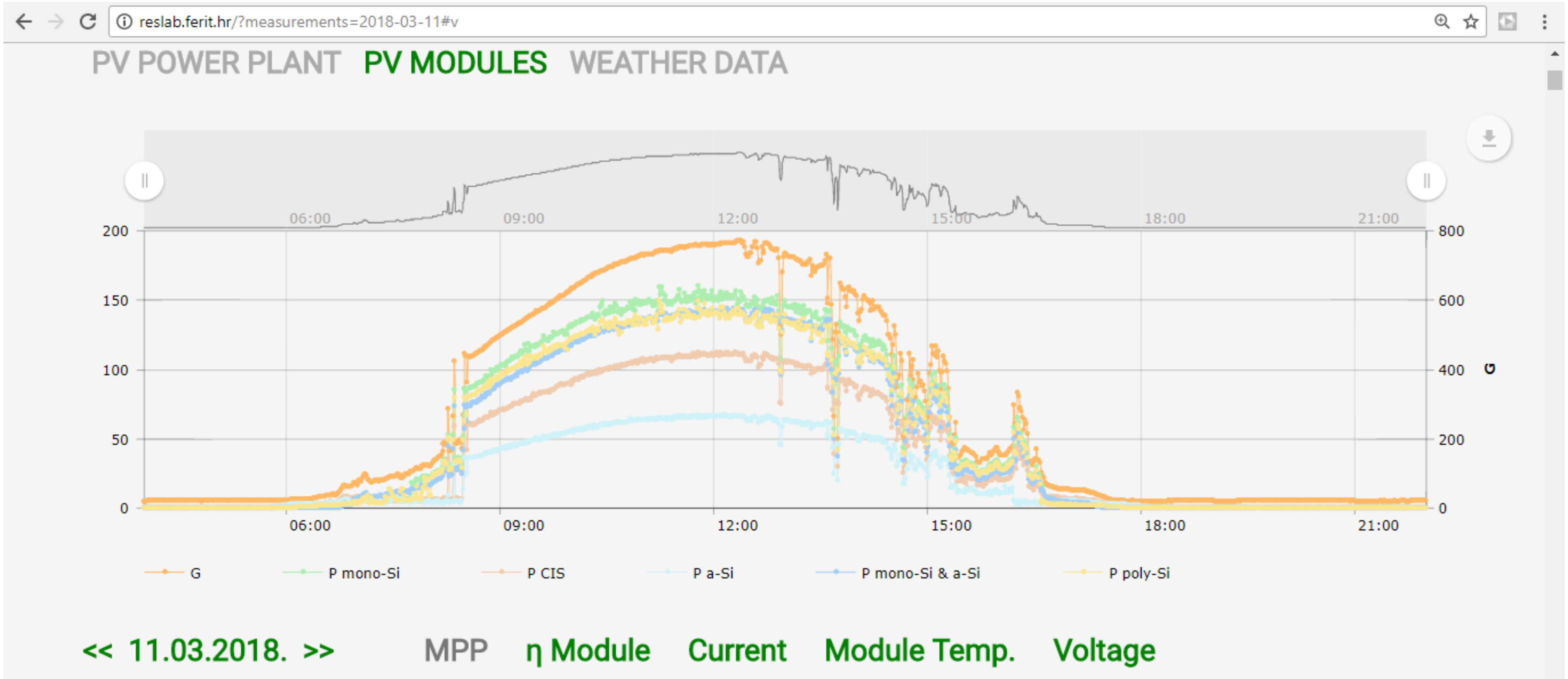
Sun radiation – analythical assesment and measurements

- *Fot certain (micro)location of interest Sun radiation potentials could be assesed by both: masurement or analythical.*
- *Measurements could be local or by satelite. Pyranometer (thermic or semi-conductor) is used for measurement of global (total), direct and i difuze (scattered) irradiation on a horizontal plate : **Sun radiation energy density H in [Wh/m²]** over time **or intesity G [W/m²]** instantly.*



Solar radiation and PV electricity production variation

- ***Sun radiation is highly variable*** *– on time of the day, day in the year, and particularly on atmosphere conditions (clouds) – almost instant changes in Sun radiation intensity (G) and PV electricity production*



Measurement of MPP of 5 PV modules during March 11, 2018 at Laboratory for RES FERIT Osijek

Source: reslab.ferit.hr

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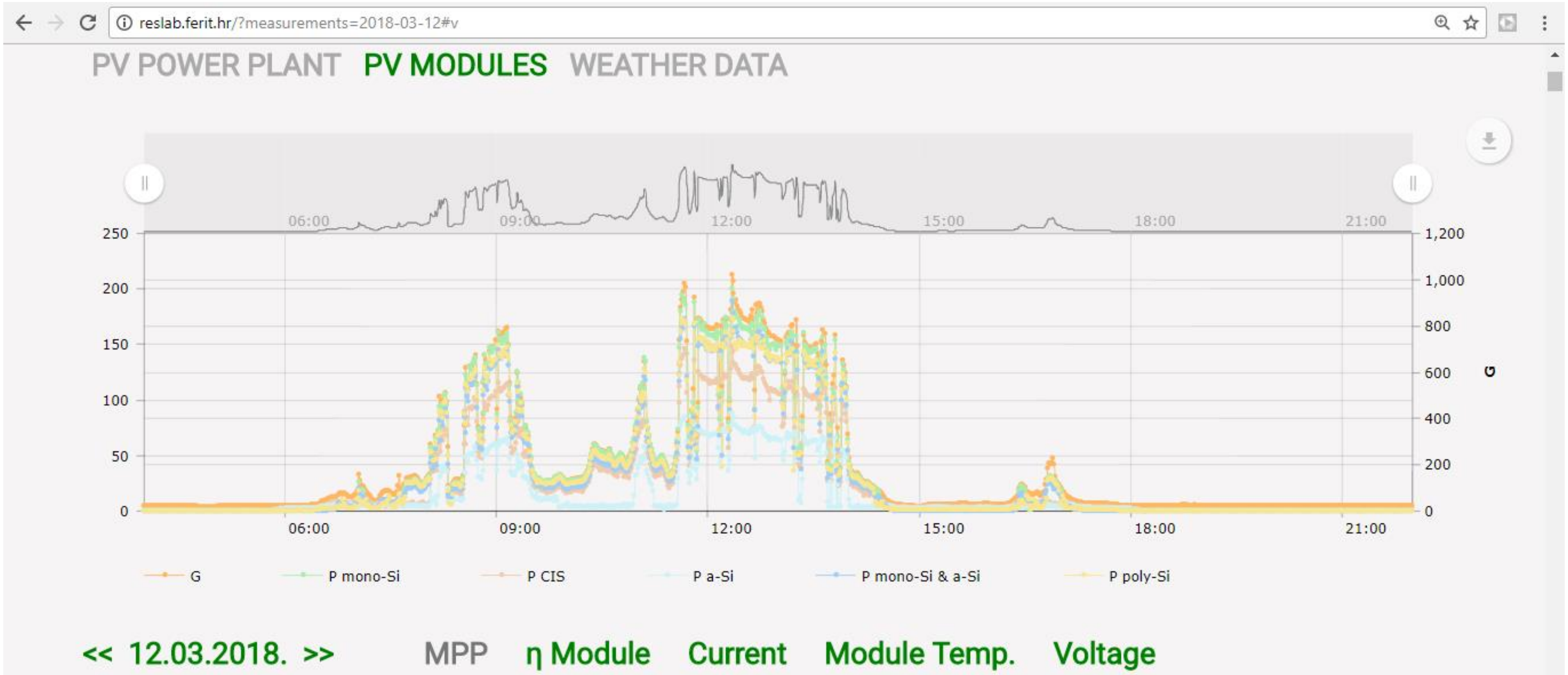
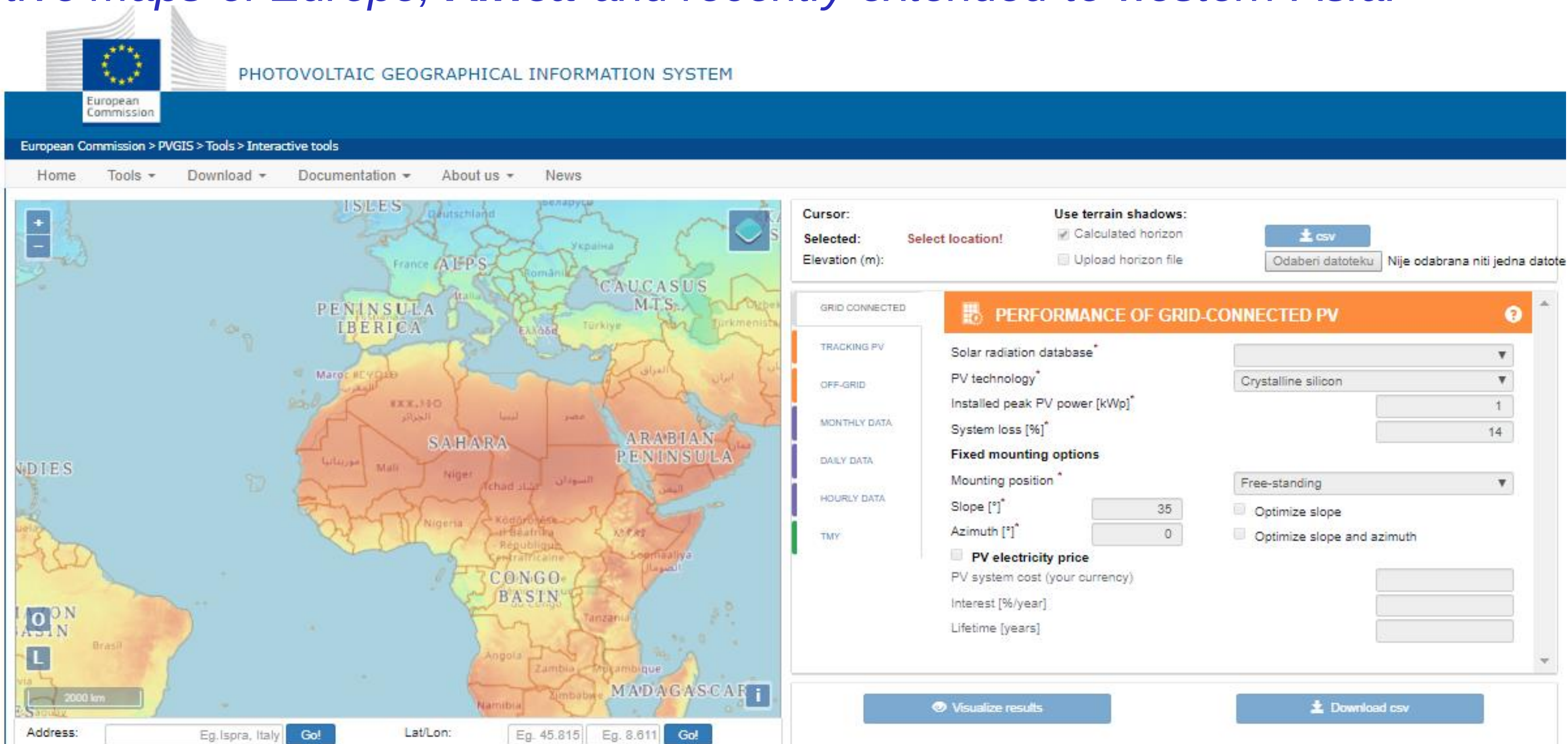


Measurement of MPP of 5 PV modules during March 11, 2018 at Laboratory for RES FERIT Osijek

Source: reslab.ferit.hr

Sun radiation assesment/measurements

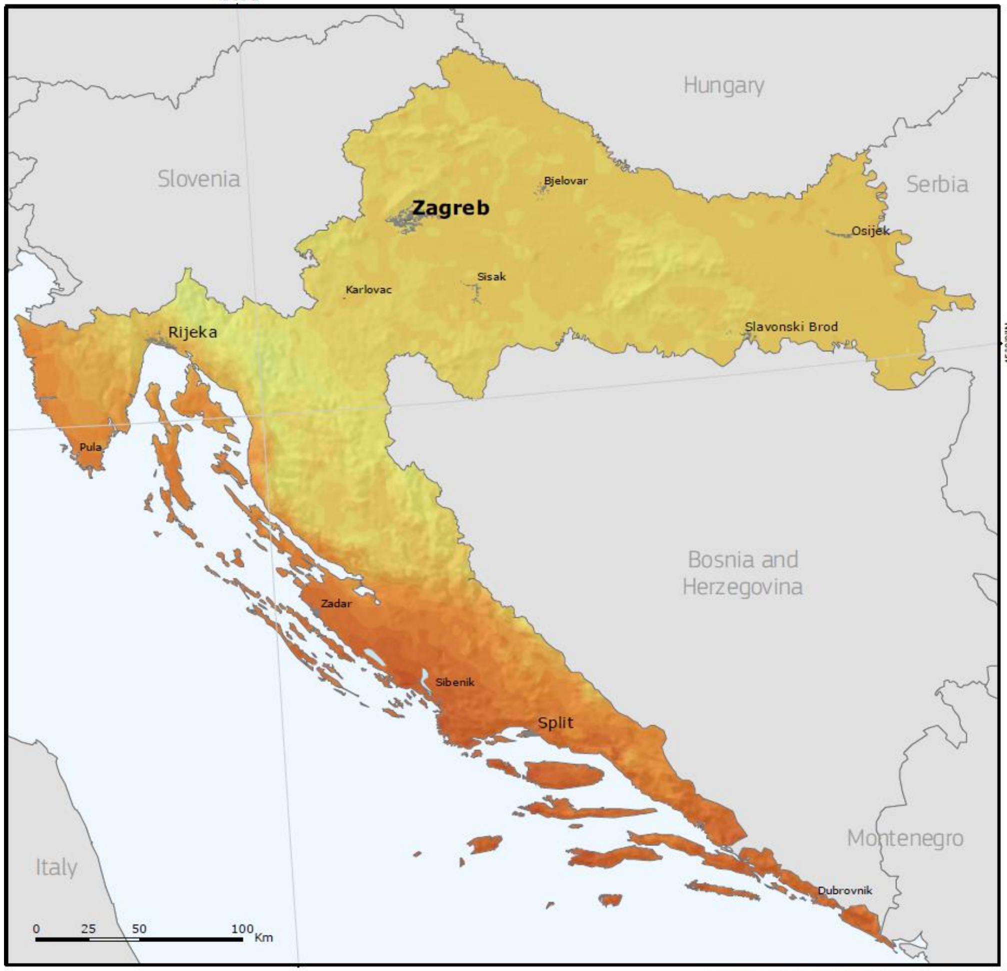
- *There are many sources of assesed data available from diffrerent institution that integrate metheorlogy measurement station and satellites with analythical assments for several years periods and different resloution and usually with descrepenacies to microlocation actual data up to 30% (but ussualy less). Historically, examples are European Centre for Medium Range Weather Forecast, or NASA Surface Meteorology and Solar Energy*
- *Developed and used in EU is E**C JRC Photovoltaic Geographical Information System (PVGIS)** with resolution of 1 do 2 km: http://re.jrc.ec.europa.eu/pvgis/ with interactive maps of Europe, **Africa** and recently extended to western Asia.*



Global irradiation and solar electricity potential

Optimally-inclined photovoltaic modules

CROATIA / HRVATSKA



Yearly sum of global irradiation [kWh/m²]

1300 1400 1500 1600 1700 1800 1900

975 1050 1125 1200 1275 1350 1425

Yearly sum of solar electricity generated by 1kWp system with performance ratio 0.75 [kWh/kWpeak]

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

Global irradiation and solar electricity potential

Optimally-inclined photovoltaic modules

EGYPT

Yearly sum of global irradiation [kWh/m²]

<2000 2200 2400 2600

<1500 1650 1800 1950

Yearly sum of solar electricity generated by 1kWp system with performance ratio 0.75 [kWh/kWpeak]

Urban area

Water body

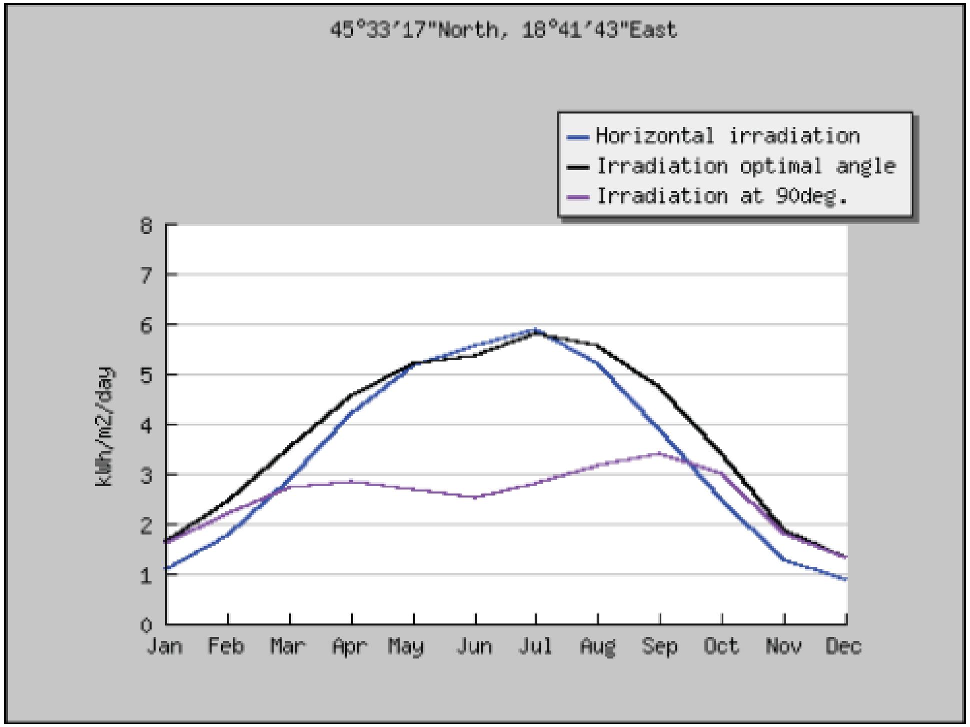
Projection: Lambert Azimutal Equal Area, WGS84, lat 0°N lon 18°E
Sources: CORINE Land Cover, Geonames, Natural Earth

- *According to PVGIS data optimal incline angle for Croatia starts from 33º on the north to 37º on the shouth jugu. Optimal angle is changing over year due to Sun position (e.g.. Osijek optimala angle on a year basis is 33º, and: 43º in March, 12º u June, 41º in September and 62º in December).*
- *When using fixed (solar/PV) instalations it is recomended to put the solar panels to optimal angle in order to produce maximal yearly energy but it can be put on different angle in order to produce maximal energy during certain period.*
- *The best soltuion is a Sun tracker – device that follows Sun in one (N-S) to two axes (N, S, E, W). This can increase yeilded energy by 25-40% - more with two axes on sunnier lokations*
- *For potential assesment and preliminary analysis of usage of Sun energy this rough PVGIS data are enough.*

Sun radiation assesment

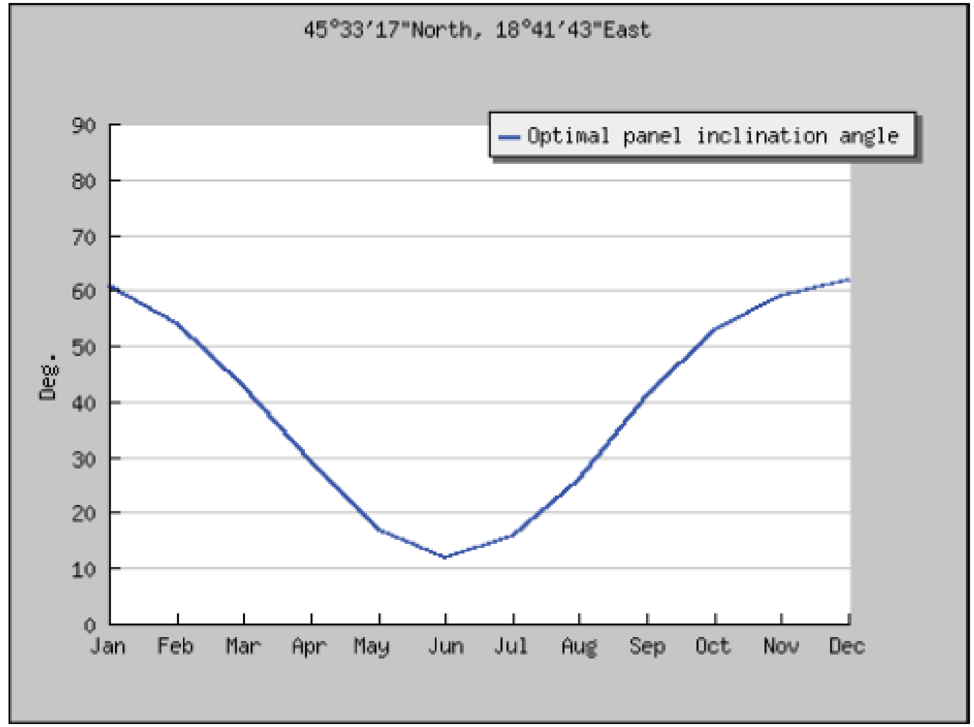
– example Osijek, Croatia, by months in year

Optimal yearly angle 33º



Average daily Sun irradiation by months

Similarity of optimal and horizontal plane energy production



Optimal angle of solar panel by months

Mar 43º, Jun 12º, Sep 41º, Dec 62º

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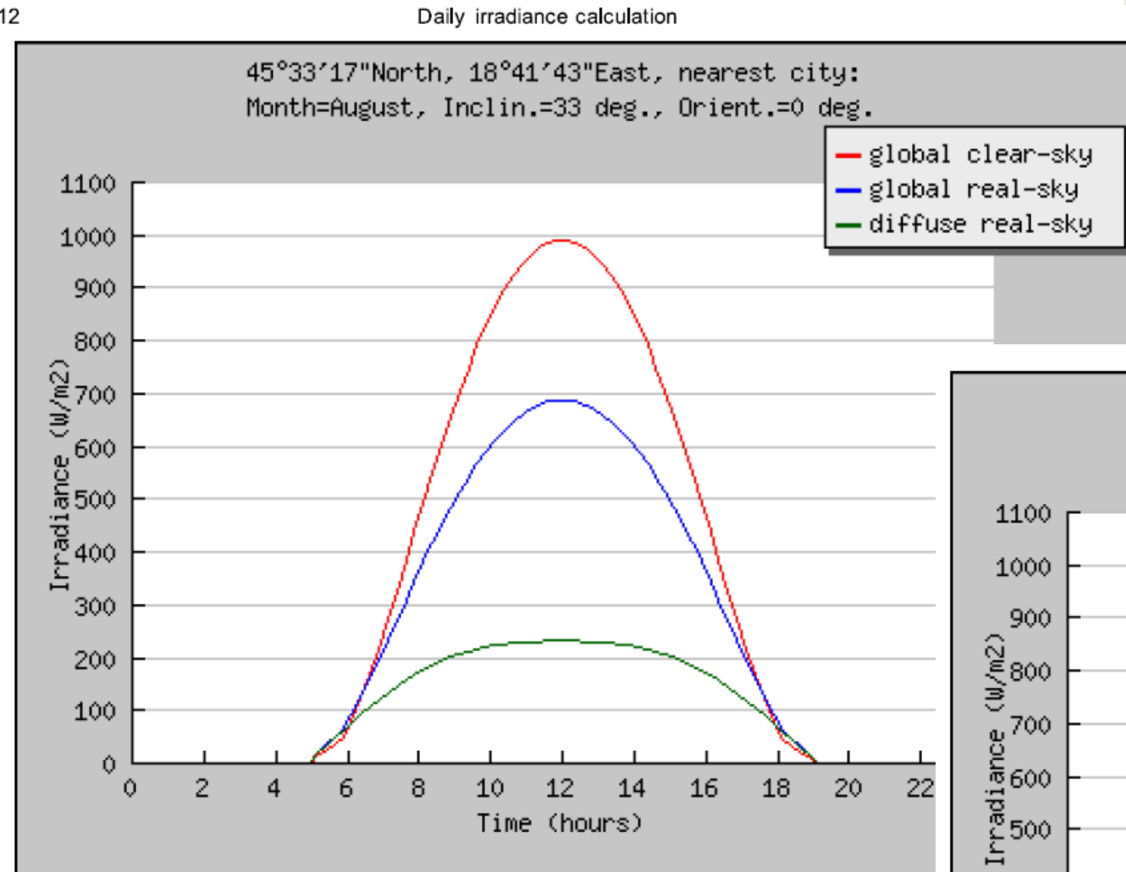
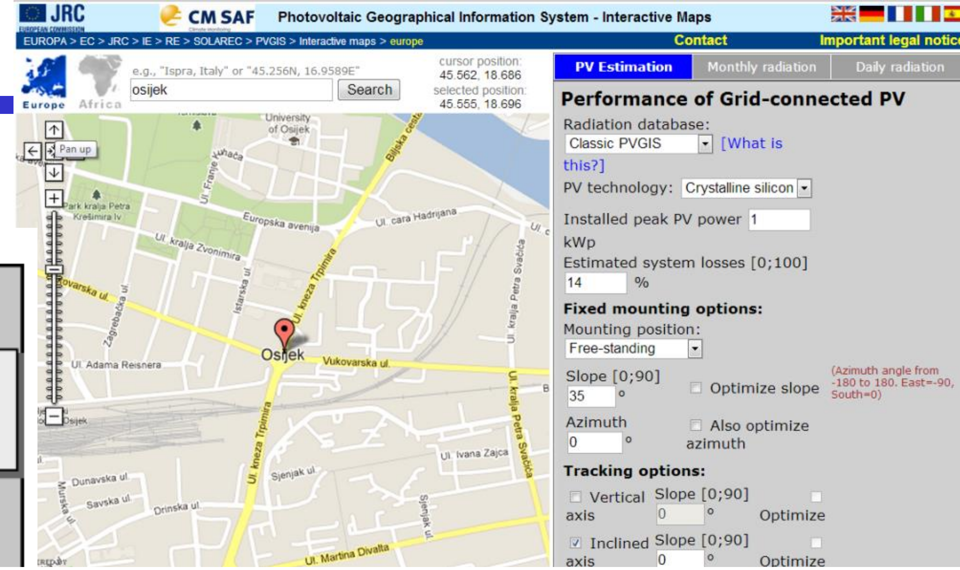
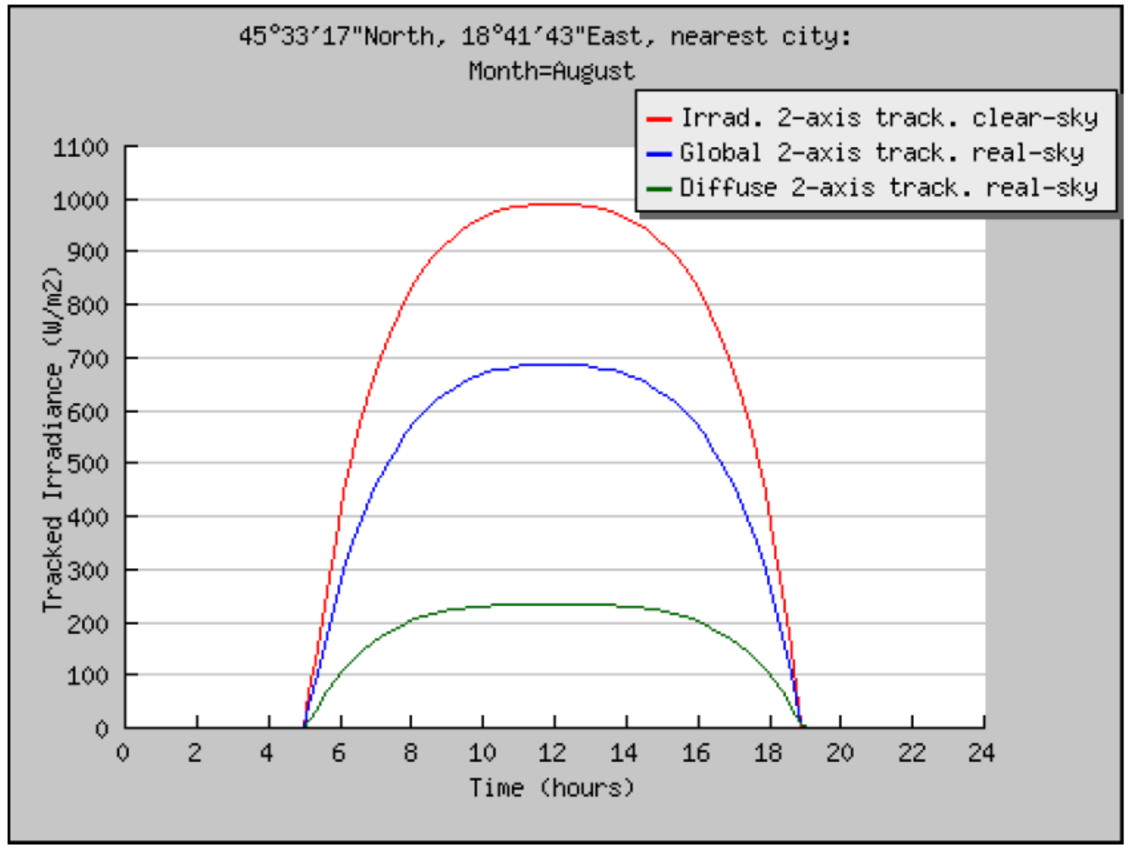
Sun radiation assesment

– example Osijek, Croatia, in August







Fixed system, 33º (year optimal angle)

Two-axes Sun tracker

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Chapter 2:
PHOTOVOLTAIC ENERGY CONVERSION, CELLS AND MODULES

Photovoltaic energy conversion

History

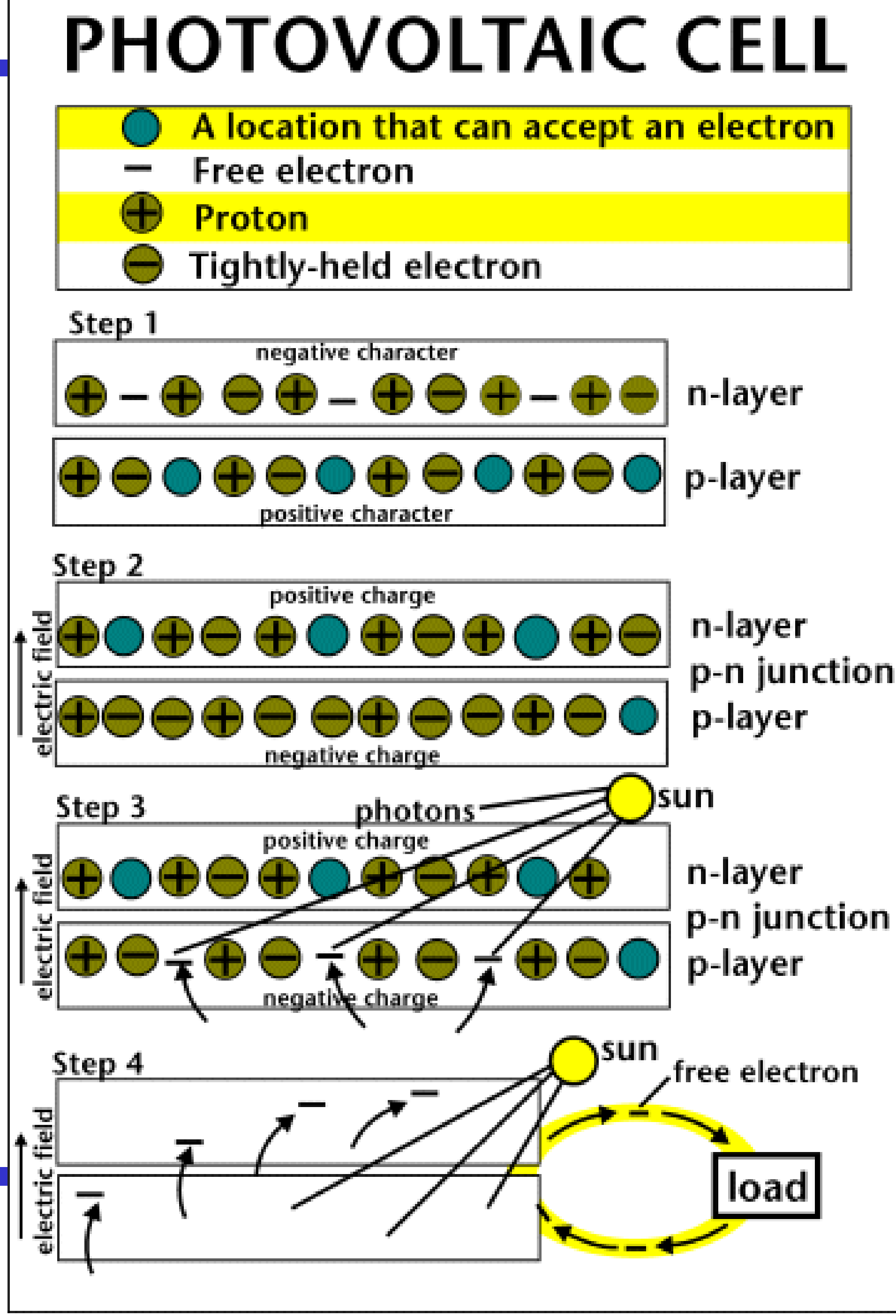
- ***1839: Henri Becquerel: Photovoltaic effect***
- *Beggining of 20th century: many research - only Nobel price for Einstein - for research in solar energy: explanantion of photovoltaic effect in 1905).*
- ***1954: Bell Telephone: PV cell dicovered,*** *during experiments on sensitivity of adeqately prepared silicone plate on Sun light. Firstr photovoltaic cell that generated usable ammount of electric energy presented.*
- ***Since 1958: installed in commercial aplication: for*** *for USA space programe, satelite supply). Sucsess of PV in space led to Earth commercial application of PV technology.*

Photovoltaic energy conversion - definition

- ***Photovoltaic conversion: direct conversion of Sun radiation (light) to electric current (energy).***
- *Sun radiation (light) consist of photons (parts of solar energy containing different ammounts of energy depending on the different wave lenghts (frequencies) of **solar spectrum.***
- *Photon energy: $E = h \cdot v$ where*

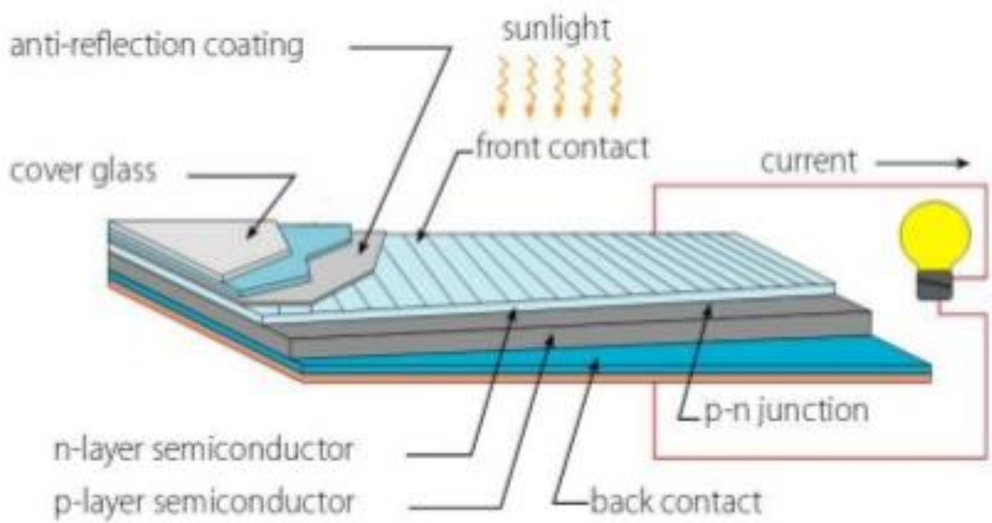
  h is Planck constant $6.625 \cdot 10^{-34}$ Js
  v is photon freqency (linear oposite to wave leght)
- *When photons hit the PV cells, they can, depending on the energy (wave lenght) reflect from, pass directly through or be absorbed in.*
- ***Only absorbed photons gives adequate energy for freeing electrons from a semi-conducting material (p-n layer) called PV cell and generation of electricity (electric current) i.e. trigger the photovoltaic effect!***

- *When semi-conductor absorbs enough of Sun radiation energy (light), electrons are being pushed out of p layer to n layer of the materials.*
- *N-layer is on the surface and collects electrons (more negativ carging) that leaves their position in p-layer forming holes (more positive charging).*
- ***Imbalance of charging rises between n-layer on surface and p-layer on bottom: resulting in voltage potential.***
- *Simillar to batteries – areas are connected using cable (wires) on load and generate current (current = free electrons flows).*



- *Semi-conductor of p-type (p-layer) is made with doping crystalinne silicon (4- valent electrons) with 3-valent boron, while n-type (n-layer) have free wholes made by doping crystalline silicon with 5-valent phosphorus.*
- *On p-n juction is a neutral area with electric field. In order to photon in collision with a p-n junction (PV cell) shift electron through this field it needs to gain at leaste the energy equal to that field.*
- *In practice, this mean that all photons with energy less that needed (energy threshold) could not achive photoefect, and also all electrons with energy larger than necessary achieve shifting only one electrone.*
- *Different materijals have different energy treshold or forbidden area. Voltage on Pv cell fis detremined by treshold voltage (e.g. Crystalline (mono/poly) Si 1,1 eV, Gallium Arsenide GaAs 1,4 eV and Amorphous a-Si 1,7 eV).*

Photovolatic energy convercion - basic structure of PV cell



- *For collecting PV current: metal contacts are set on both sides of the cell to collect. Contacts are enabled on back (dark) surface and on one edge of front (light) surface. Thin conducting strings on upper surface collects electrons (current) while lething trough the light (photons). Distance between conducting strings (usualy silver/ lately copper) is comprimise between increasing elecic conductivity and lowering light transmittance.*
- *Front of the PV cell have anti-reflection coating to limit light reflection and hard protective cover glass as a mechanical protection with transparent glue.*

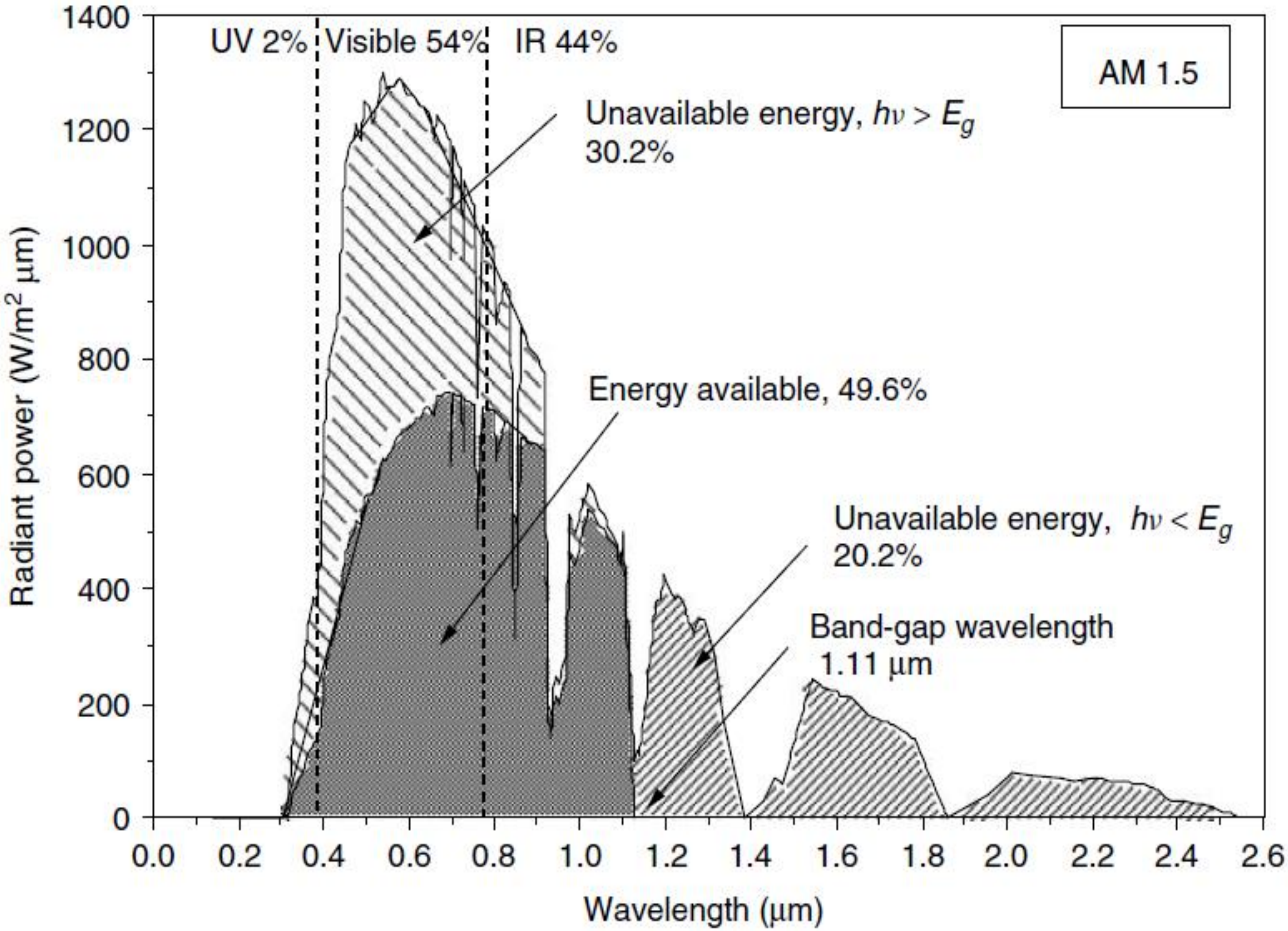
Photovolatic energy conversion – theoretical efficiency

- Max 'efficiency of a single-layer crystalline PV cell is limited to 35%:
  1. Losses in photon energy lower then energy treshold approx. 20%
  2. Losses in photon energy higher then energy treshold approx. 30 %
  3. Losses due to limitation of voltages smaler that E_g/e, gdje Eg is lower limiting energy and e electron charge (Si: E_g/e = 0.8V and losses 12%)
  4. Losses of other thermodynamic reasons related to short-circuit to open circuit ratio (Si ration 0.9 and losses approx. 3%)

  Overall PV cell conversion losses: min 65 %.

- Low efficiency of crystallinr Si PV cells was a major obstacle for wide usage (in theory 0.35 in rality even less) as well as very low voltage (up to 0.7 V).
- Solution - different technologies development: cheaper (thiner) materials or multi-layers of materials with different so-called 'spectral response' (1. i 2.)

Spectral distribution of Sun radiation and spectral response of PV cell



1. Mono- and poly- crystalinne Silicon

- *Maximal surface area depends on area of a cros-section of crystalinne layers and ranges from 5 do 20 cm, with decreasing thickness of 0.2 to 0.3 mm. Electromotor force of 0.55 to 0.70 V.*
- *For production of crystalline Si cells apsolutly clean semi-conduction material is neccessary. Crystalline sticks are madfe from liquified Si and cut into thin plates – which enable relatively (to thin film) !! high efficiency. In commercialnim application efficiency is higher than 21 % (2014!).*
- *High material prodaction costs (complicated technology procedure) of crystalline PV cells was a shortage, but technology advanced rapidly, with huge production costs decrease: e.g. decrease in price of pure poly-Si from 67 USD/kg u 2010 to 20 USD/kg in 2012 and remaining low; efforts in thining the cells (lower the usage of pure Si from 5 g/W to 3 g/W and lower); using copper instead of silver in conducting strings...*

Source: IEA Technology Roadmaps Solar PV - 2014 edition

- *Heterojunction, HTJ PV cells – multi layers of microcrystalline and amorphous Si rezults in higher efficiency (Sanyo/Panasonic HTJ 25.6%) and better performanses due to better resistance to higher temperatures.*

2. Thin film technologies

- *Thin film of materials on glass or other surface are called amorphousd or thin-film PV cells:*

  - amorphous Silicon,

  - CI(G)S –Copper Indium (Gallum) Selenide thin-film,

  - CdTe Cadmium Telluride thin-film.

- *Coating (film) thicknes is less than 1 µm, resulting in lower production costs depending on the material price (lower than crystalline Si).*
- *Affordable price, but lower efficiency (incerasing), tipically 4-9% for a-Si, 10-11% for CdTe (2014. First Solar 19%), 7-11% for CI(G)S (2014. 12-14%)*

Source: IEA Technology Roadmaps Solar PV - 2014 edition

3. *Multy-layer PV cells*

- *Gallium–arsenide (GaAs) are made as thin-films of two components (layers) In theory should be highly efficient (25-40%) due to better usage of solar spectrum.*
- *3-layers, 4-layers PV cells in development with even hjgher efficiencies (in 2014. 44.4% 3 slojne Spectrolab, Sharp; 44.7% četveroslojne* Soitec i Fraunhofer*). Problem: high price, due to cheaper crystalline Si it is possible to combine it in layers.*

4. *New concepts – lower price/higher eficiency/transparent PV cells*

- *Quantum dots, dye-sensitized (12% Sharp), organic cells (2014. 11% Mitsubishi chemicals), thermoelektric devices – lower price with small efficiency, or higher price with higher efficiency – fast reserach development, commercial expected in near future.*
- *Advantages: small weight, transparency, flexibility, choice of colours and shapes... extra reasons for faster market entrane*
- *New development:concentrated solar PV cells (increased efficiency).*

Source: IEA Technology Roadmaps Solar PV - 2014 edition

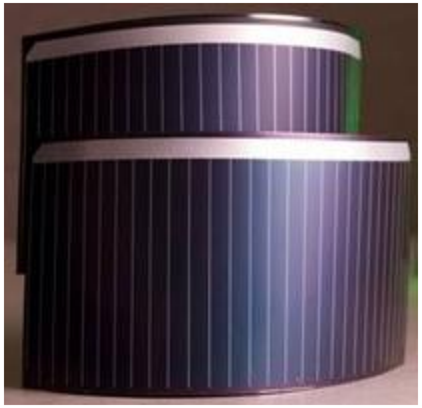
PV cells technologies development

Mono- crystalinne Si

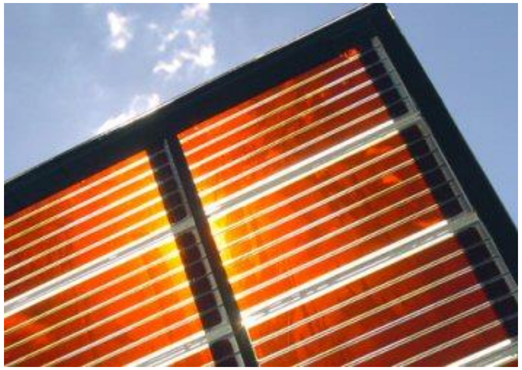
Poly-crystalline Si

Amorphous Si (thin film)

CdTe



CI(G)S



Dye-sensitized

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Concentrated solar PV cells (modules)

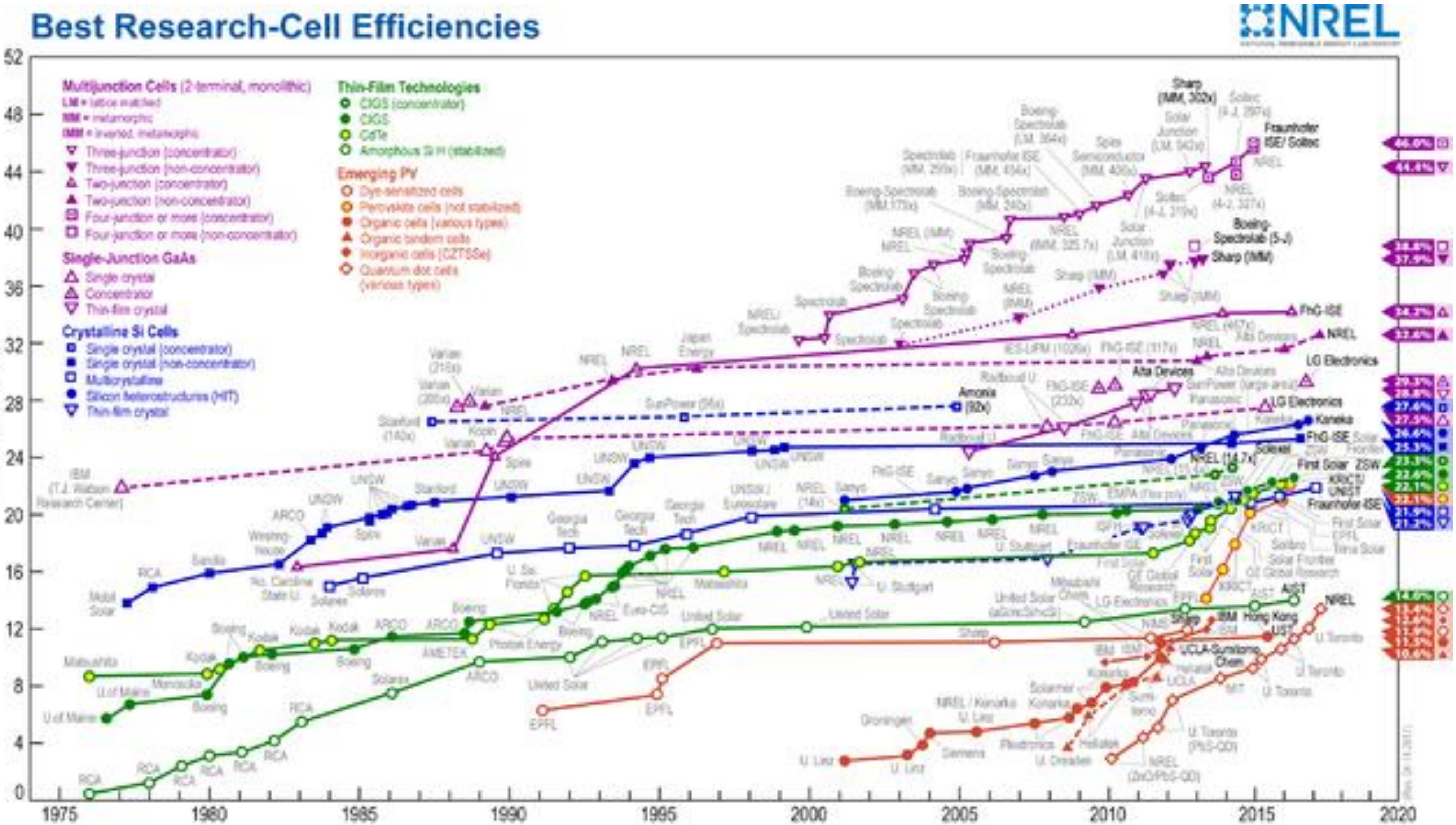
- *CPV (eng. Concentrated PV) usfull for areas with high direct Sun radiation (e.g. South Europe, North Africa)*
- *Concentrirating optics are used for focusing solar light to small PV cells - currently (2017) with over 400x concentration.*
- *More designs commercially avaliable with up to 43% efficienca (in lab research up to 46%).*

Soitec CPV with multylayer cells

Efficiencies	Lab Record	Commercial
Solar Cell	46.0 % (ISE, Soitec, CEA)	38-43%
Minimodule	43.4% (ISE)	N.A.
Module	38.9% (Soitec)	27-33%
System (AC)	N.A.	25-29%

Source: Photovoltaics Report Fraunhofer Institute for Solar Energy Systems, 2017

Laboratory research PV cell efficiency up to 2018



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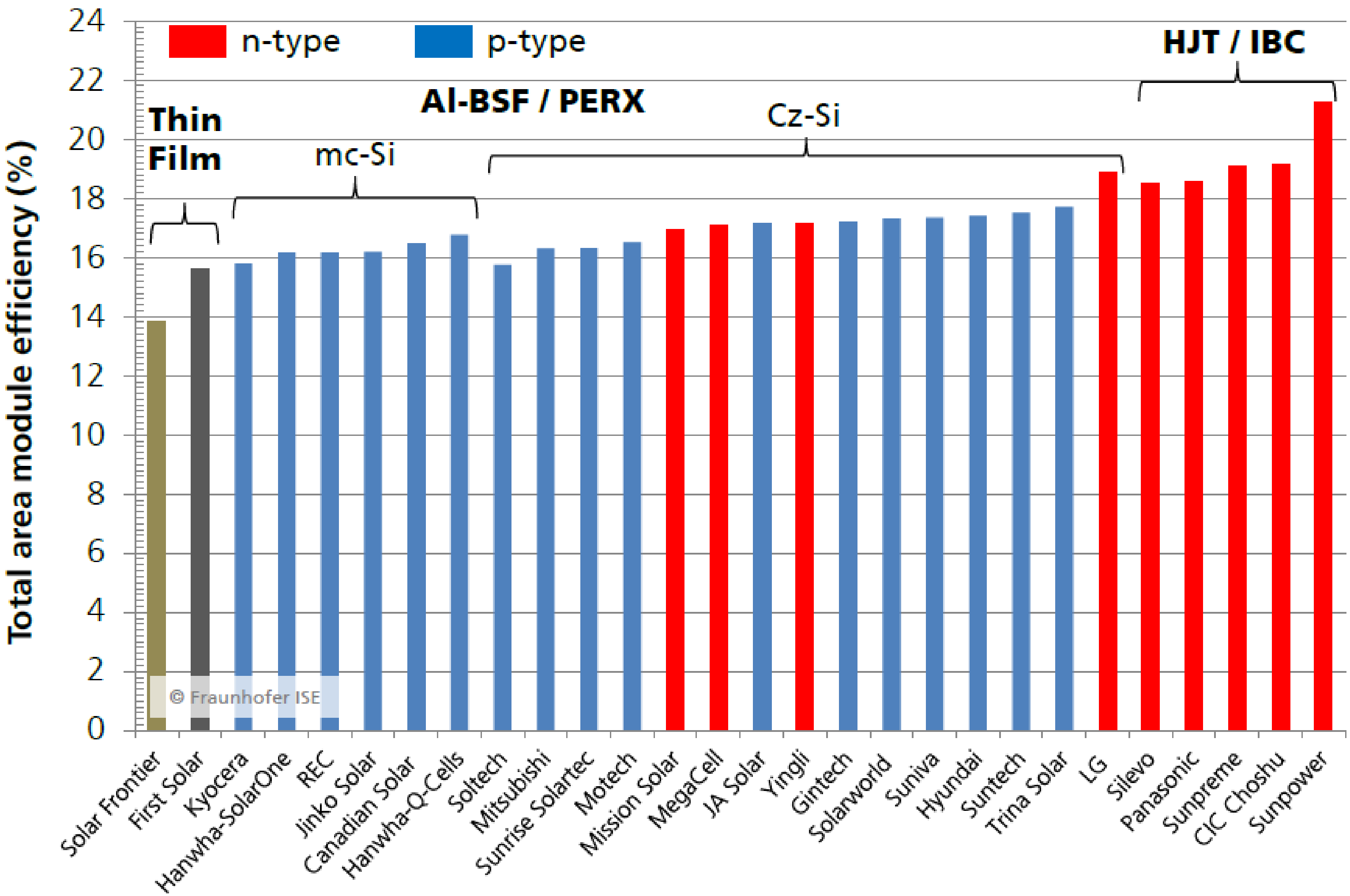
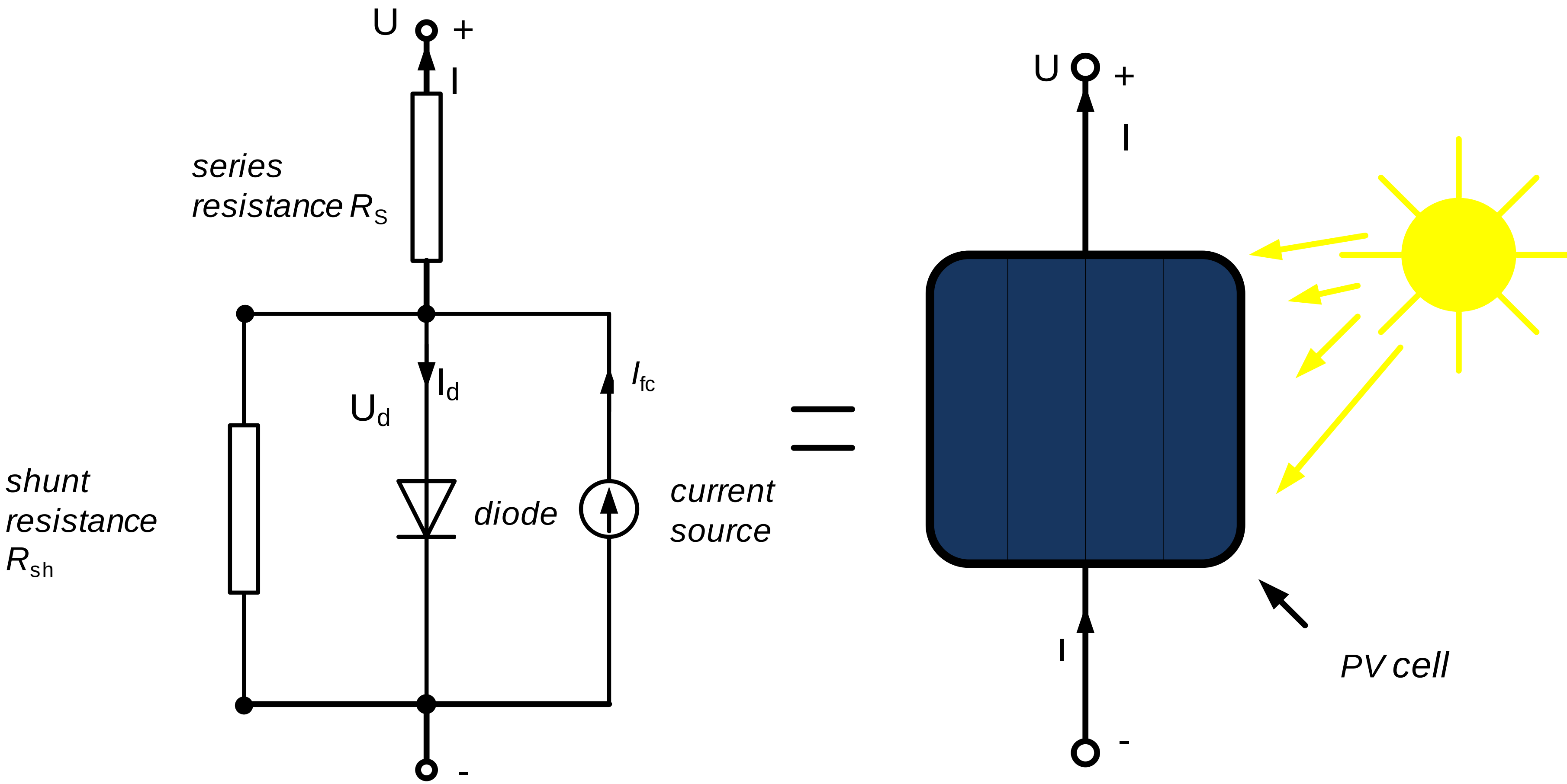
Commercial PV module efficiency 2017



Source: Photovoltaics Report Fraunhofer Institute for Solar Energy Systems, 2017

Equivalent scheme of a photovoltaic cell



- *In general, photovoltaic cell behaves as a current source since electric current is proportional to the solar irradiance (photo cell current).*

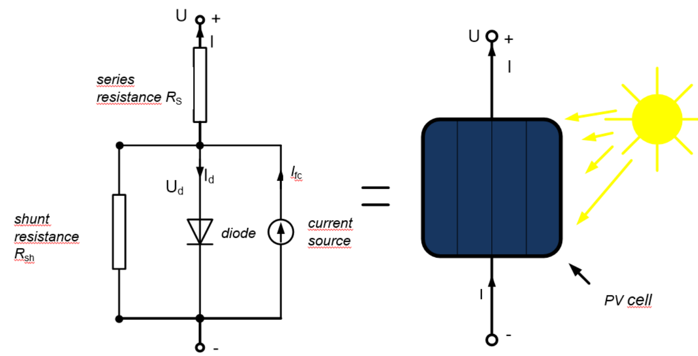
Equivalent scheme of a photovoltaic cell

- *Output current I is equal to the current generated by solar irradiation (photo cell current) I_{fc} reduced by diode current I_d and current that flows through the shunt resistor I_{sh}*

$$I = I_{fc} - I_d - I_{sh} = I_{fc} - I_0\left[e^{\frac{e(U+IR_s)}{mkT}} - 1\right] - \frac{U}{R_{sh}}$$

- *Because of large shunt resistance, current I_{sh} can be neglected*

$$I = I_{fc} - I_0\left[e^{\frac{e(U+IR_s)}{mkT}} - 1\right]$$



where: *U – voltage, R_{sh} – shunt resistor of PV cell,*

I_0 – saturation current, e – elementary charge, $e=1.602176462 \cdot 10^{-19}$ As

R_s – series resistance of PV cell, m – diode ideality factor, m=1

k – Boltzmann constant, $k=1,3806 \cdot 10^{-23}$ J/K

T – absolute temperature [K]

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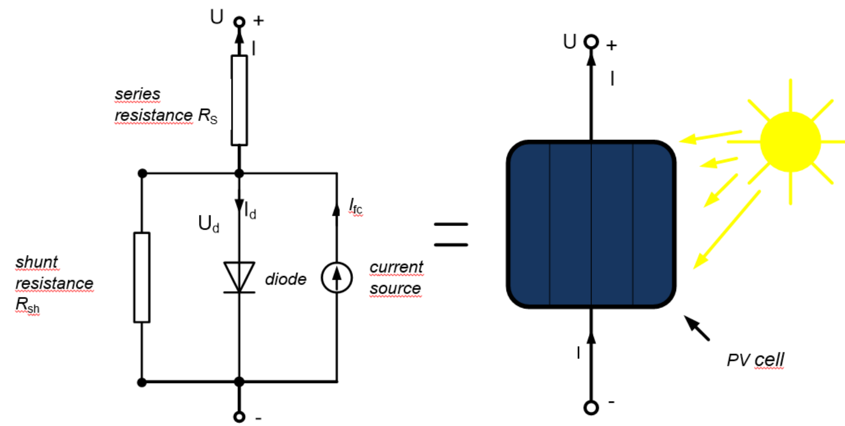
Equivalent scheme of a photovoltaic cell



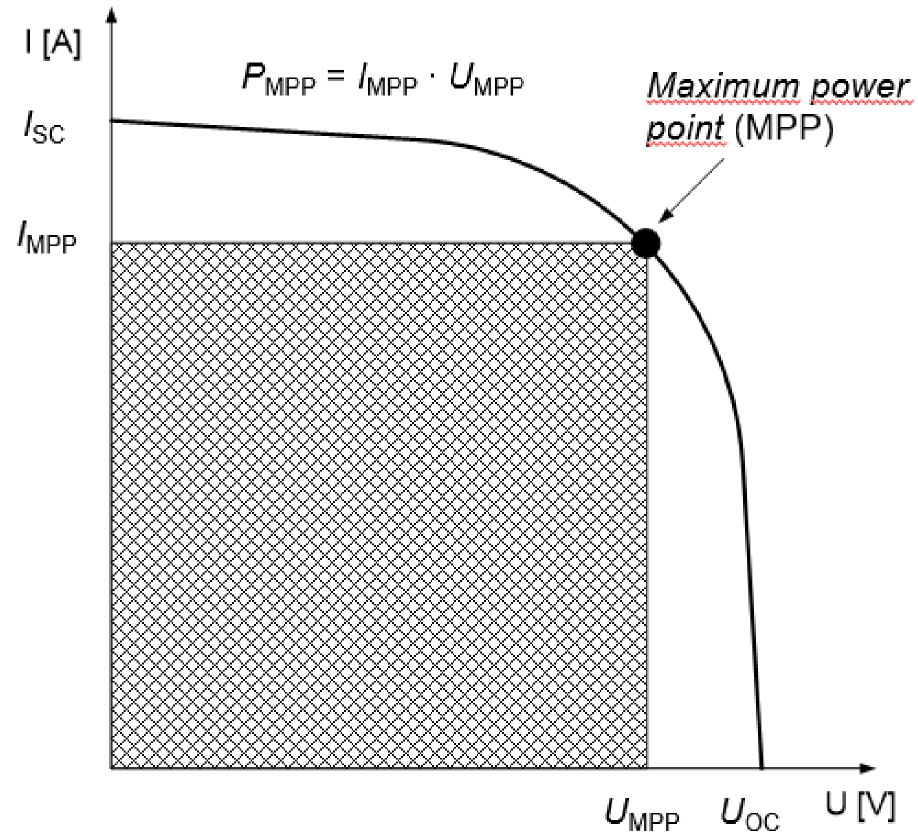
- *Series resistance of a PV cell R_s is ohmic resistance that is generated when current flows through the PV cell's surface to the ohmic contacts which lead to the output terminals (material resistance, contacts and so on). Product of series resistance and PV cell surface area equals approximately to 0.0025 Ωm2 for typical PV cells.*
- *Shunt resistance of a PV cell R_{SH} is caused by defects in the PN junction.*
- *In an ideal PV cell, series resistance equals to R_S=0 (no losses) while shunt resistance equals to R_{SH}= ∞ (no defects in PN junction).*
- *In a typical high-quality silicon PV cell, series resistance per square inch equals to R_S = 0.05 to 0.10 Ω while the shunt resistance equals to R_{SH} = 200 to 300 Ω (proportional to the voltage).*

Three characteristic points:

1. *Short-circuit: short-circuit current I_{SC} – current while shorted terminals of a PV cell. Resulting voltage is U=0, while short-circuit current equals to the photo cell current,* $I_{SC} = I_{fc}$.
2. *Open-circuit: open-circuit voltage U_{OC} – voltage while open terminals*

$$U_{OC} = \frac{k \cdot T}{e} \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

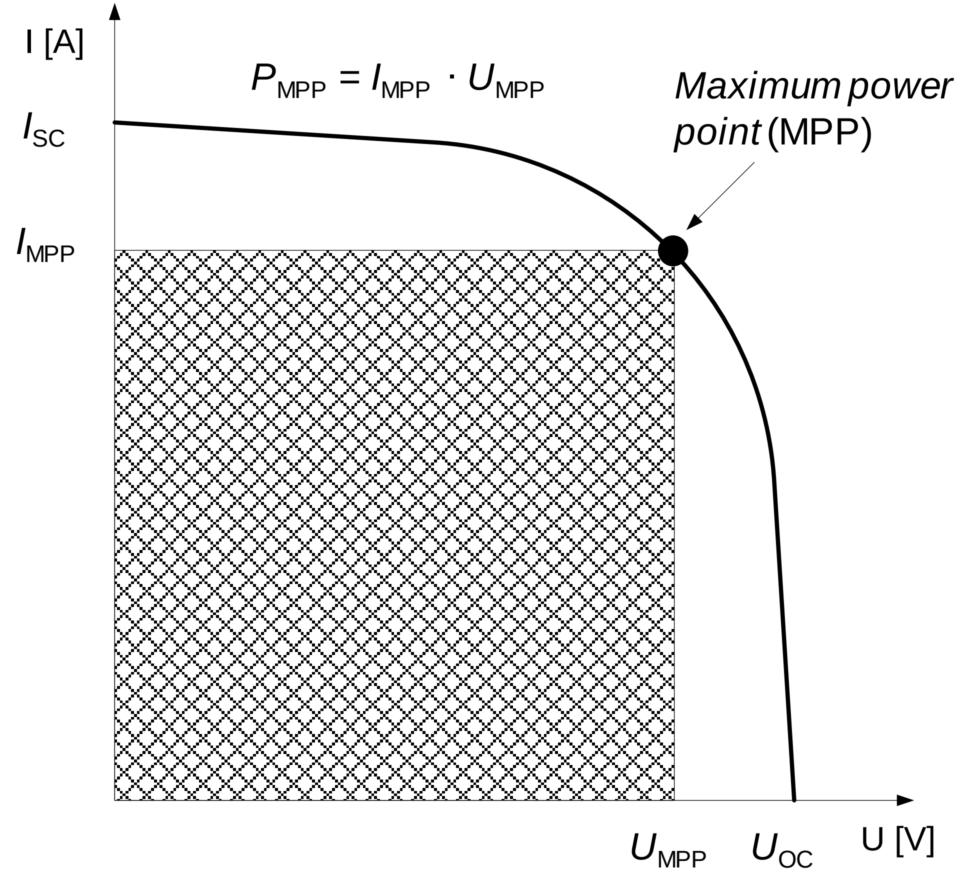
3. *Maximum power point (MPP).*



Current-voltage characteristic of a PV cell under light

Current-voltage (I-V) characteristic of a PV cell

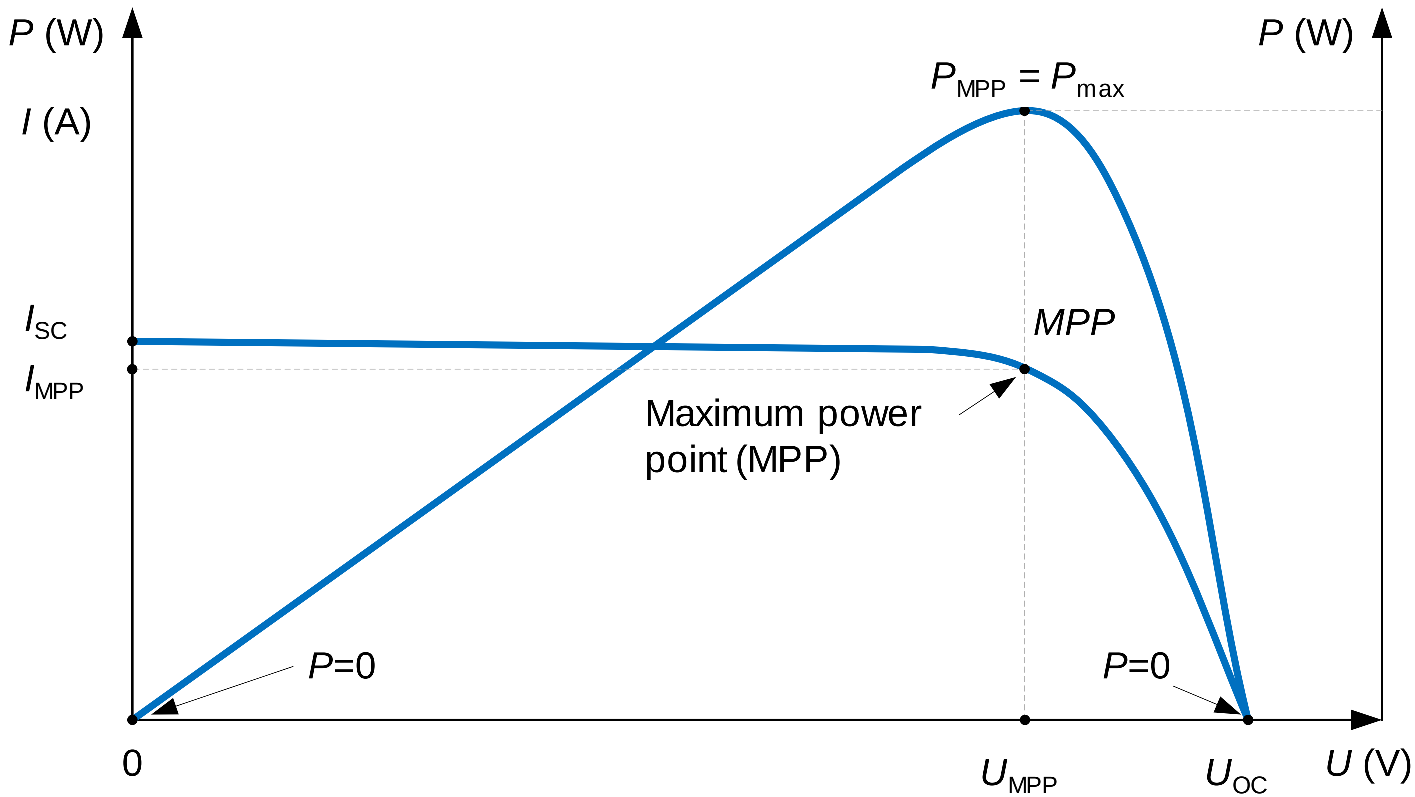
- *In the left part of the characteristic, PV cell works as constant current source, generating voltage which is load dependent.*
- *In the right part of the characteristic, current quickly decreases with a little voltage increase. In this area, PV cell works as a constant voltage source with internal resistance.*
- *Between the mentioned areas, characteristic has a bending point (unstable) – maximum power point (MPP)!*



Current-voltage characteristic of a PV cell under light

Power characteristic of a PV cell

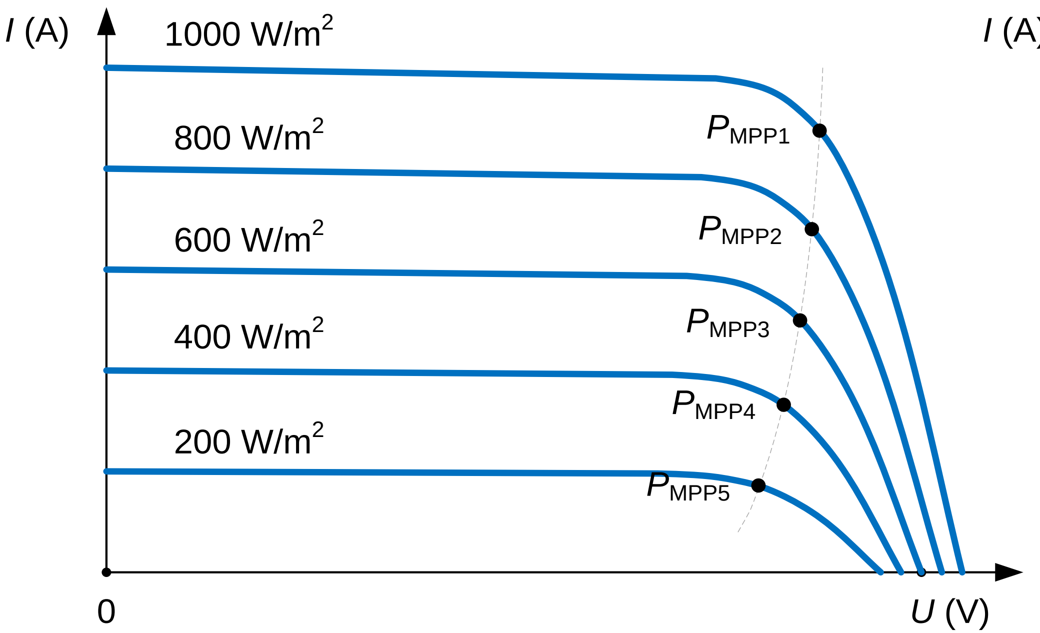
- *Maximum power at the load is generated only in one point (bending point)!*
- *Modern installations use devices for maximum power point tracking (maximum power point tracker, MPPT (typically in inverter) which depends on load change and solar irradiance change.*



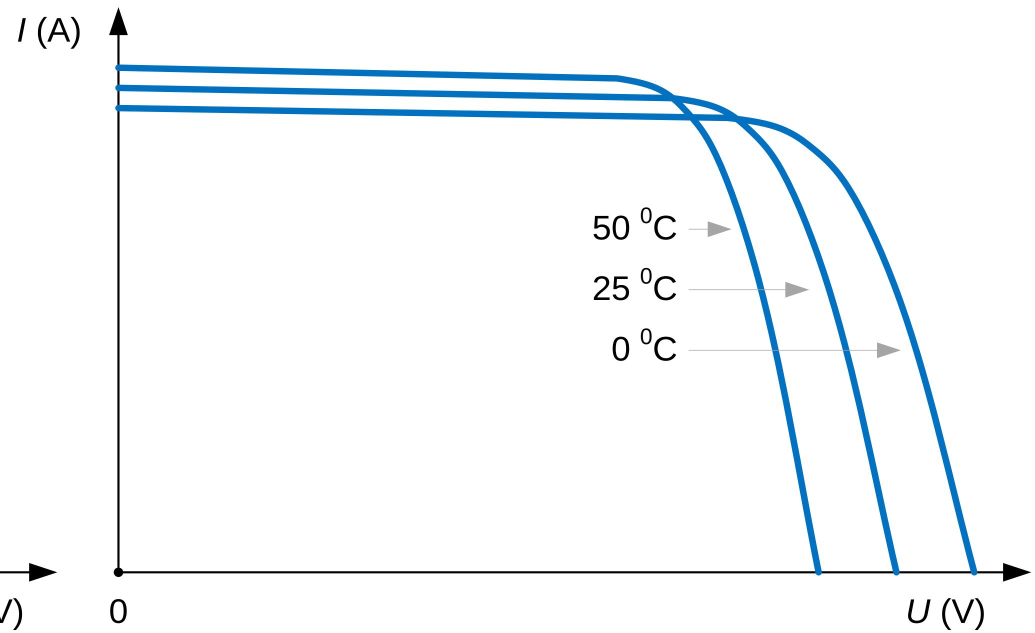
Power characteristic of a PV cell

Influence of solar irradiance and cell temperature

- Current densisty of short-circuit current J_{SC} is approximately equal to the current density of a photo cell current which is proportional to the solar irradiance G [W/m²].

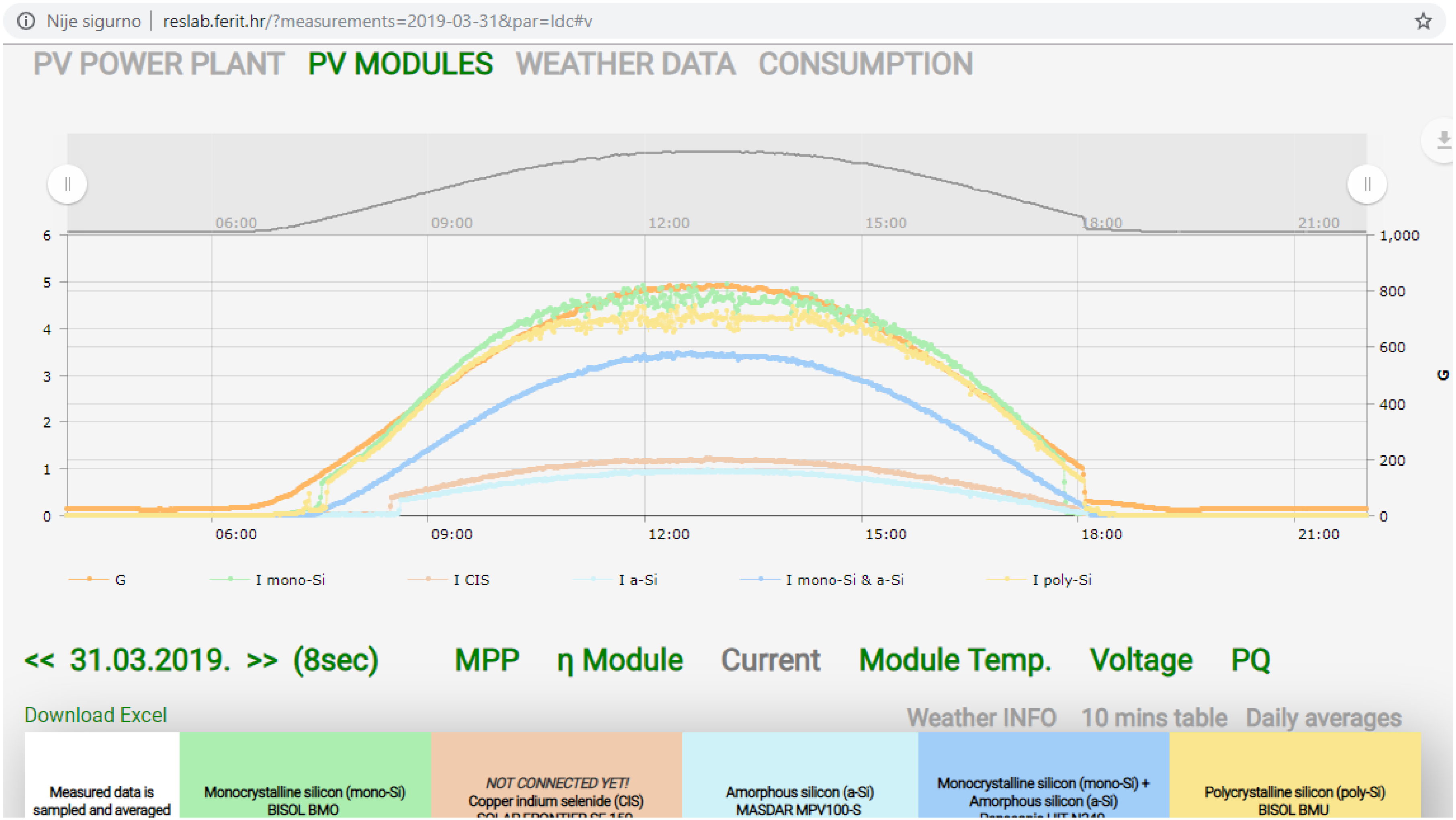


Influence of solar irraidance on a PV cell voltage-current characteristic



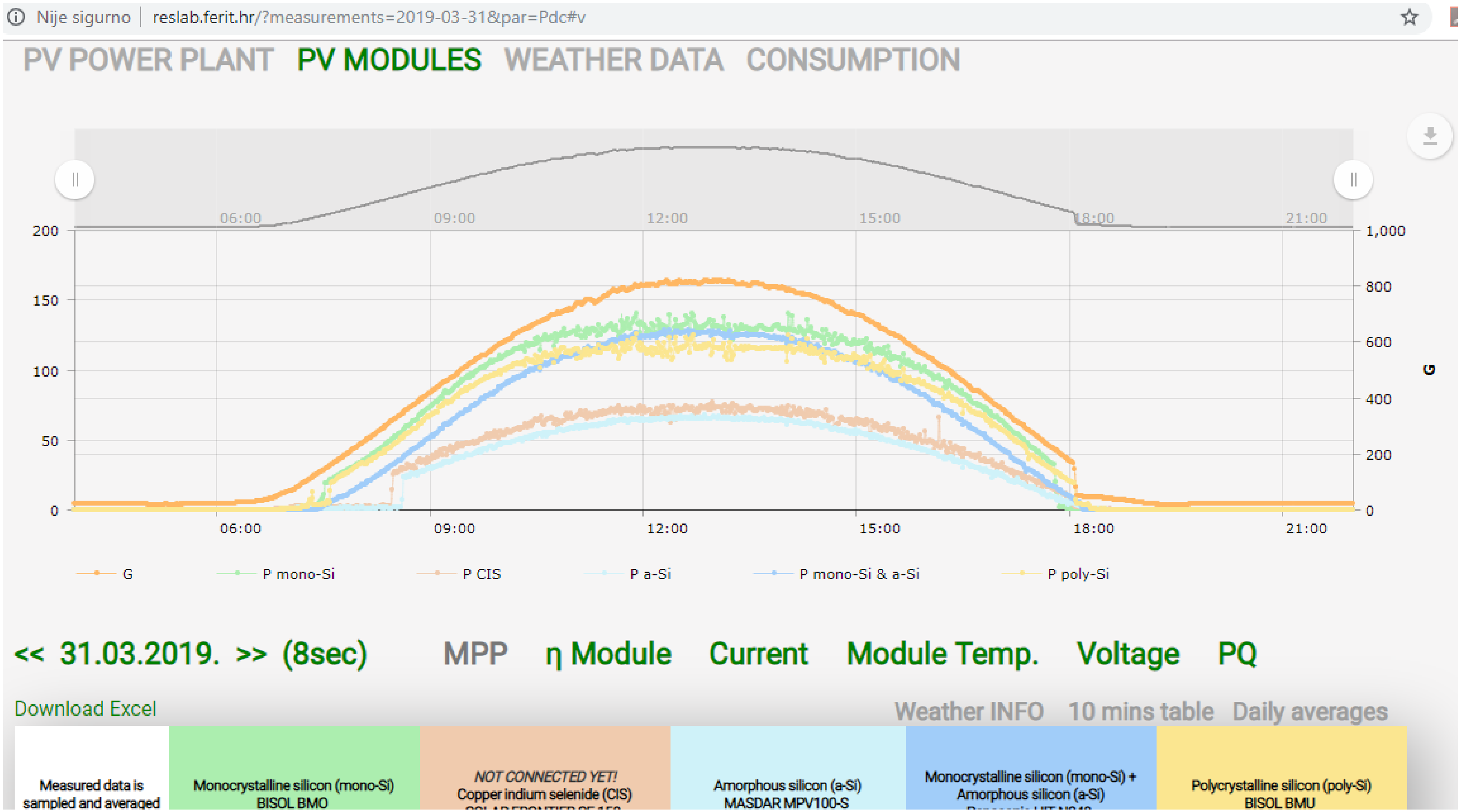
Influence of cell temperature on a PV cell current-voltage characteristic

Influence of solar irradiance on current



Source: reslab.ferit.hr

Influence of solar irradiance on power



Source: reslab.ferit.hr

Influence of cell temperature

- *During the installation process of PV modules, it is important to have in mind that efficiency of a PV cell decreases with cell temperature increase (almost 0.5% for +1 ^oC). Also, cell temperature influences the shape of current-voltage characteristic.*

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^0}{0.8} \right) \cdot G$$

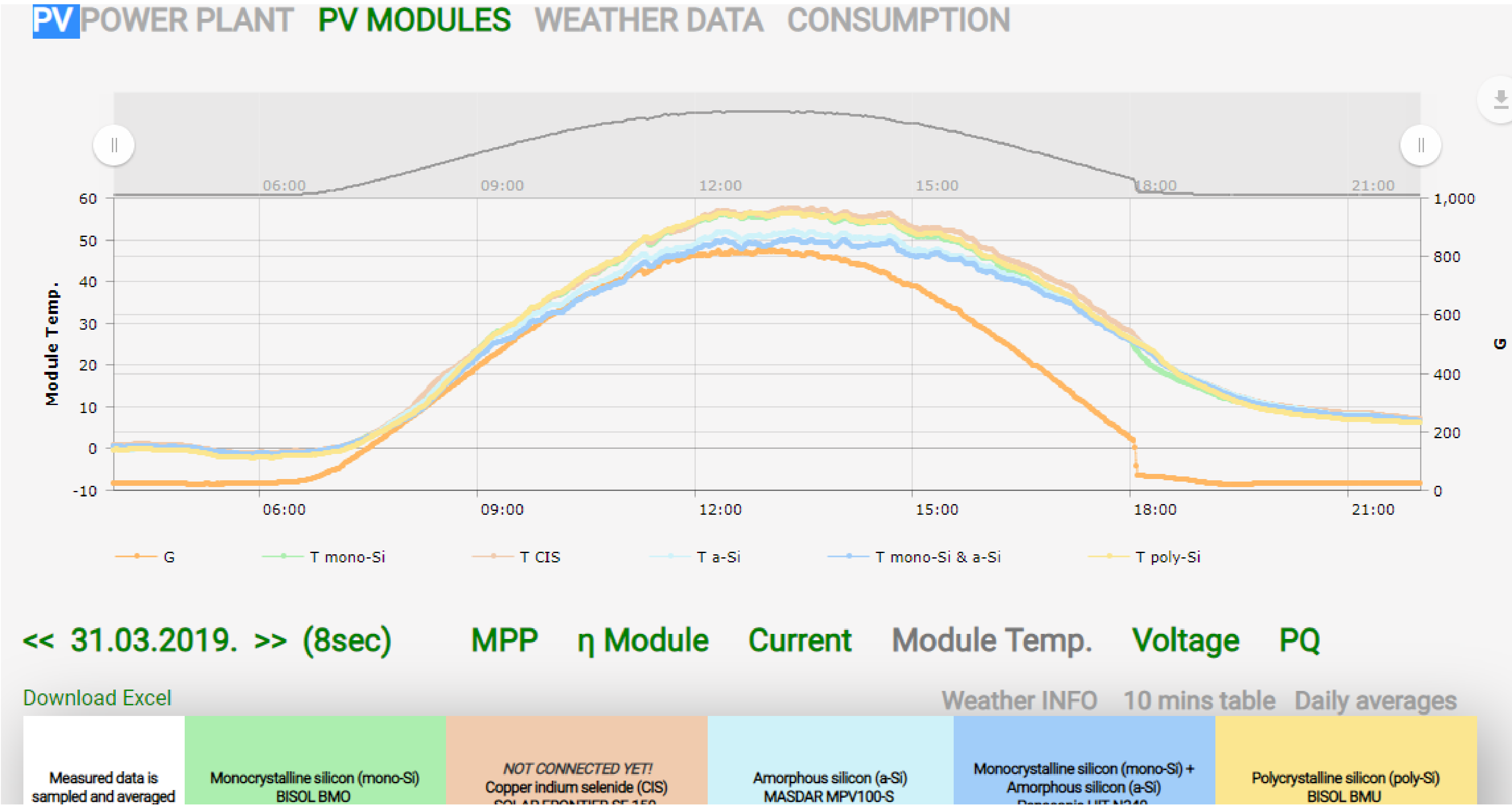
Where:
NOCT – nominal operating cell temperature when ambient temperature is 20^0C (manufacturer data)
G – solar irradiance [kW/m^2]

- *Even in the constant solar irradiance (constant photo cell current I_{fc}), diode current I_d is a function that strongly depends on cell temperature, therefore output current of a PV cell shows negative change in open-circuit voltage in relation to the temperature.*

Current-voltage (I-V) characteristic of a PV cell

Cell temperature

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^0}{0.8} \right) \cdot G$$



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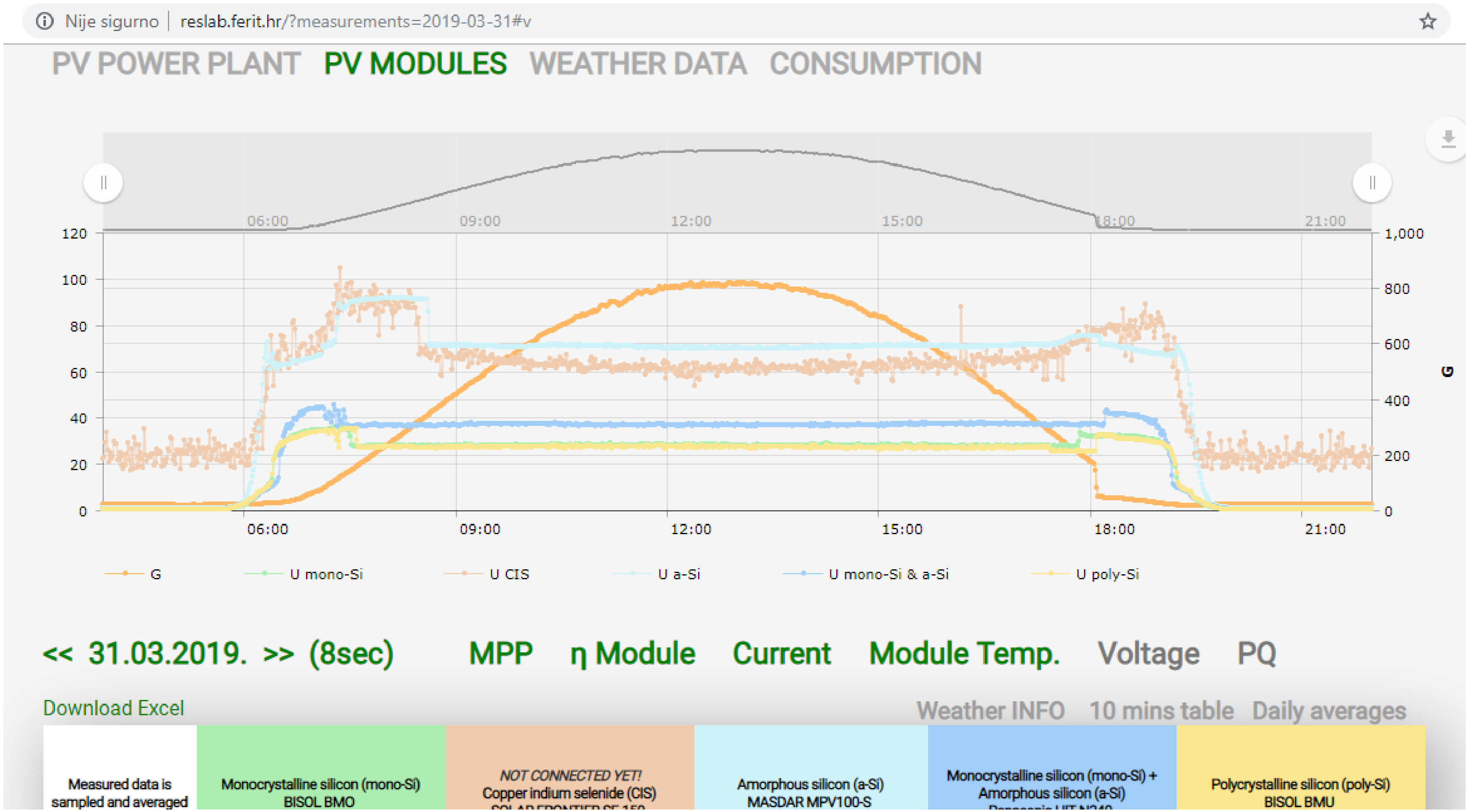
Influence of cell temperature on voltage



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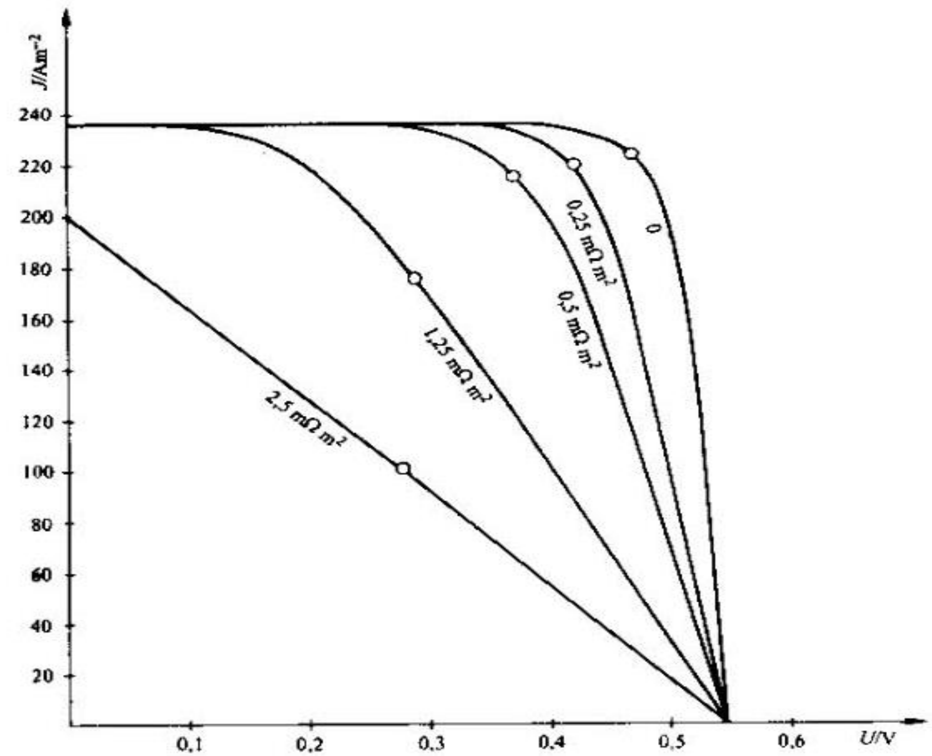
Source: reslab.ferit.hr

Influence of series resistance on current-voltage characteristic of a PV cell

- *I-V characteristic shape is determined by internal resistances, depending on the technology type, especially on series resistance.*

$$I = I_{fc} - I_d - I_{sh} = I_{fc} - I_0\left[e^{\frac{e(U+IR_s)}{mkT}} - 1\right] - \frac{U}{R_{sh}}$$



Influence of series resistance on current-voltage characteristic of a PV cell

PV cell efficiency and fill factor

- *I-V characteristic shape is determined by internal resistances, depending on the technology type, and outdoor conditions (solar irradiance, temperature) which finally directly influences the efficiency determined as a ratio of maximum power P_{MPP} solar irradiance G that falls on PV cell surface area A_{FC}:*

$$\eta_{FC} = \frac{P_{MPP}}{G \cdot A_{FC}} \cdot 100 = F \cdot \frac{U_{OC} \cdot J_{SC}}{G} \cdot 100$$

- *Where fill factor is:* $$F = \frac{P_{MPP}}{U_{OC} \cdot I_{SC}} = \frac{U_{MPP} \cdot I_{MPP}}{U_{OC} \cdot I_{SC}}$$

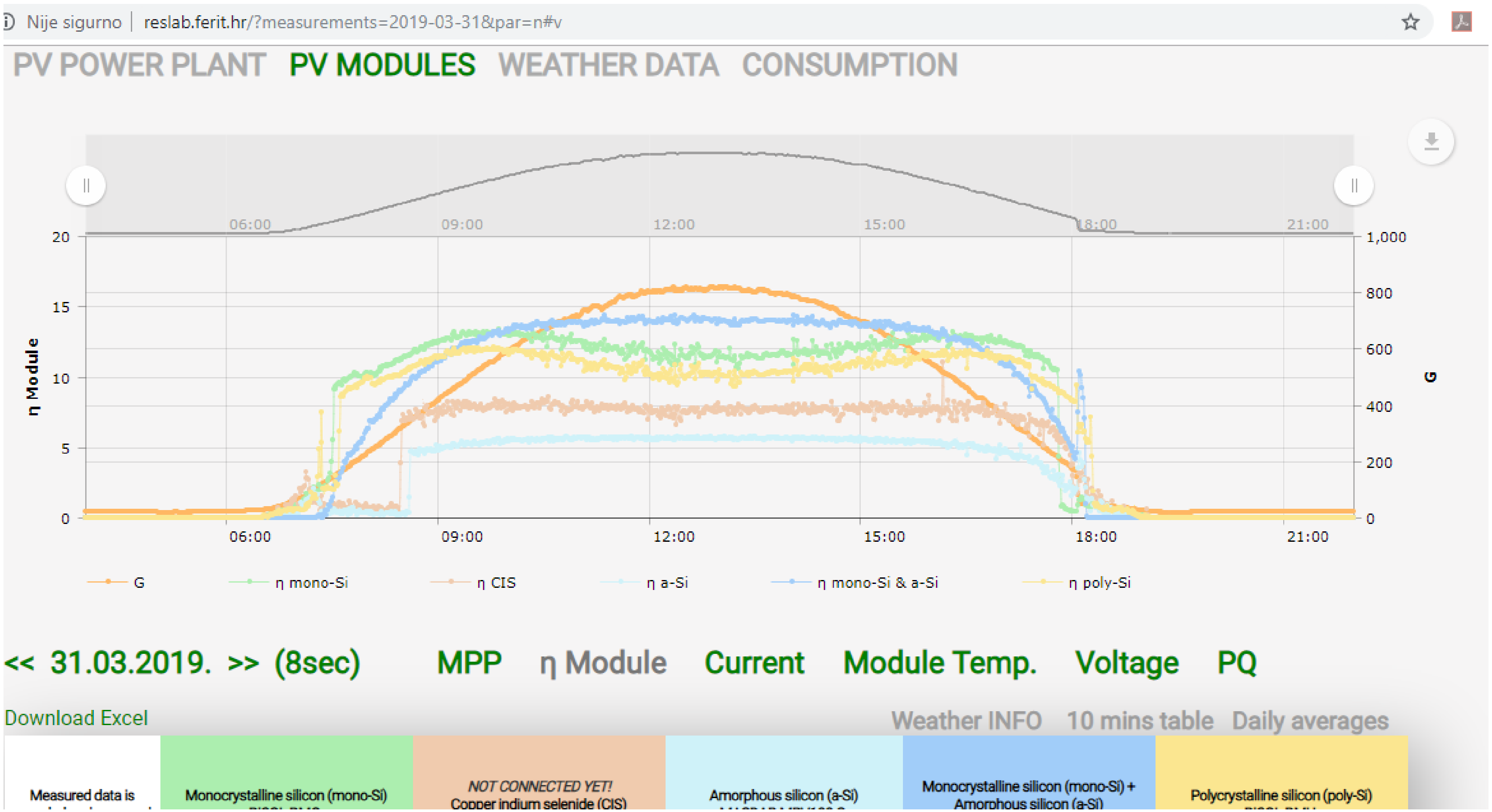
which is determine as a ratio of rectangle defined by U_{MPP} and I_{MPP} lines and rectangle defined by U_{OC} i I_{SC} lines. Fill factor shows how much a PV cell is close to an ideal (quality of it) – what is the influence of series resistance.

Usually $0.7 < F < 0.9$.

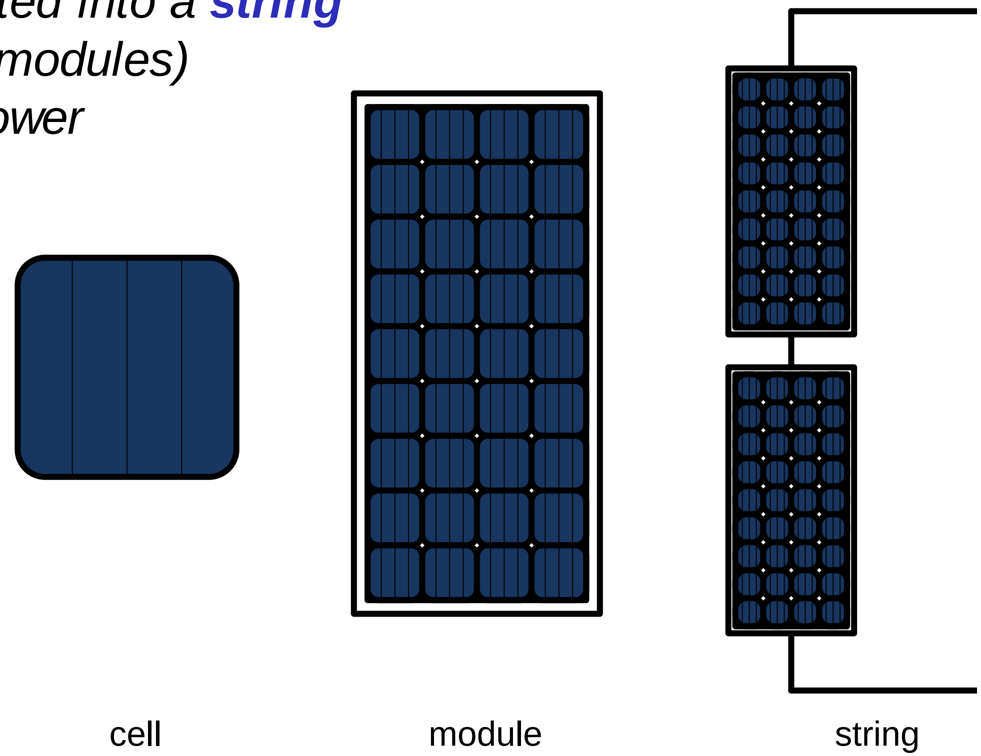
PV cell efficiency - measurements

- Dependent on both I(and G) and U (and T)

$$\eta_{FC} = \frac{P_{MPP}}{G \cdot A_{FC}} \cdot 100 = F \cdot \frac{U_{OC} \cdot J_{SC}}{G} \cdot 100$$



- *Photovoltaic cell is founding element of a photovoltaic system.* ***Individual cell size vary between 1 to 10 cm (0.5 to 4 ”).***
- ***One PV cell produces between 1 or 2 W****, and voltage around 0.6 V which is too low for any application: they are electrically connected into a* ***module*** *(series-parallel combination of PV cells)* ***protected from outdoor conditions****.*
- *Modules can further be connected into a* ***string*** *(series-parallel combination of modules) depending on wanted output power*



Photovoltaic modules – technical characteristics

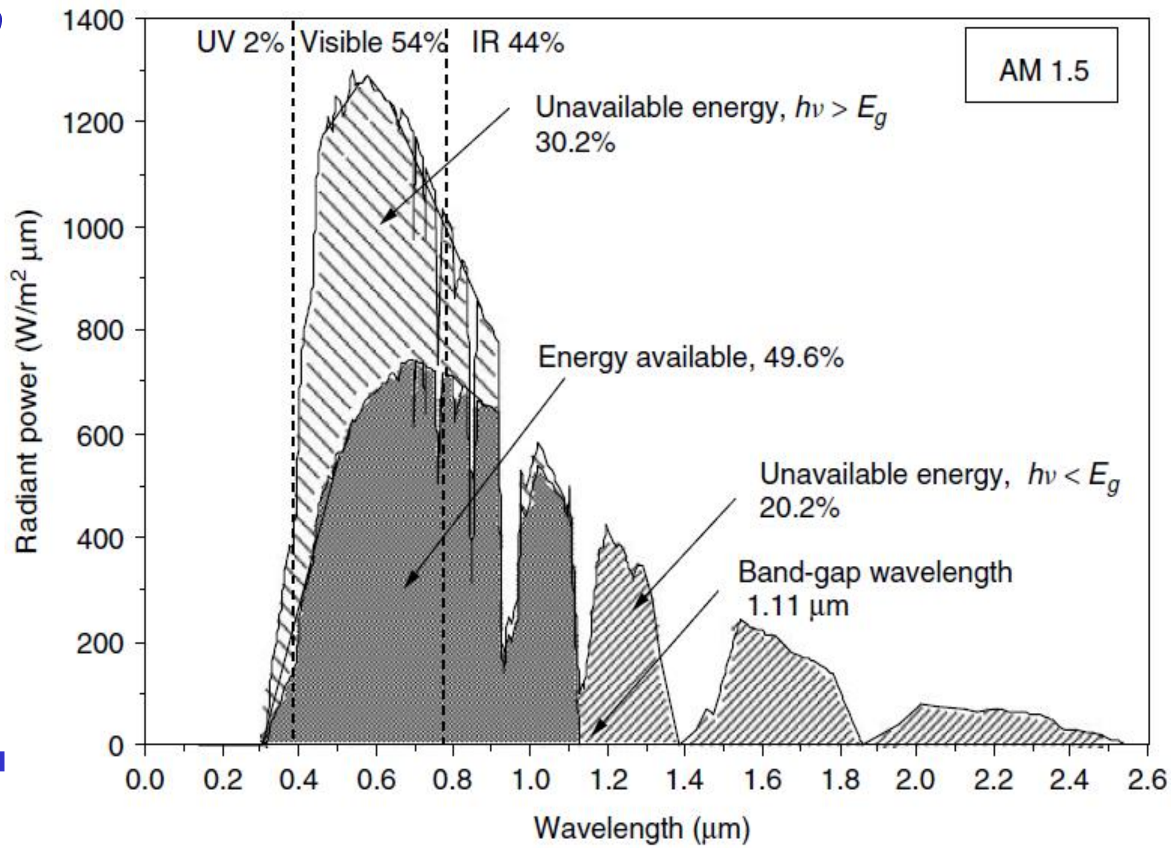
Technical characteristics of PV modules usually mirror technical characteristics of a PV cell. Technical characteristics of PV modules are defined for ***standard test conditions (STC).*** *For every photovoltaic module following characteristics are defined (under STC):*

- *Rated output power* P_{MPP} *(*kW_p*)*
- *Efficiency η (%) – module efficiency is usually slightly lower than cell efficiency (due to losses in conductors between cells)*
- *Open-circuit voltage* U_{OC} *(V); short-circuit current* I_{SC} *(A)*
- *Maximum power point voltage* U_{MPP} *(V); maximum power point current* I_{MPP} *(A)*
- *Power temperature coefficienct* γ *(W/^{0}C) or sometimes in (%/^{0}C).*
- *Current and voltage temperature coefficients α (%/^{0}C) and* β *(%/^{0}C), respectively*
- *Lenght x width x thickness (mm x mm x mm)*
- *Mass m (kg).*

Photovoltaic modules – standard test conditions (STC)

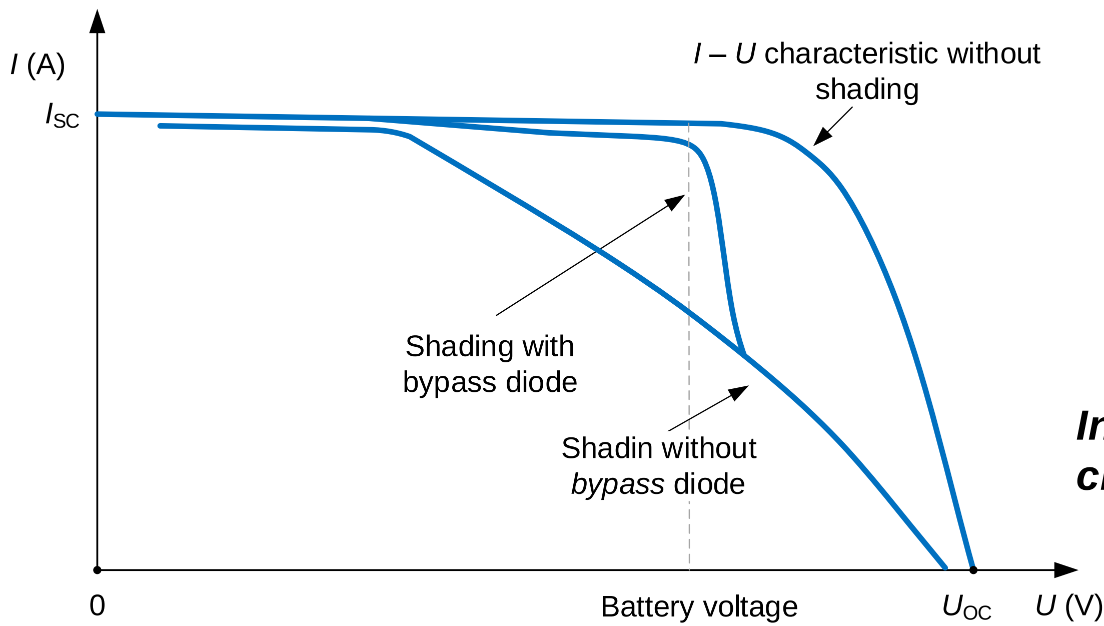
- *Nominal characteristic of PV modules are given on a nameplate of photovoltaic module (manufacturer data), achieved under **standard test conditions**:*

1. *Solar irradiance of 1 kW/m^2 under light spectrum on picture below*
2. *PV module temperature o*



Photovoltaic module – influence of shading

- *Shading of only one cell in a PV module can generate large loss of power. This can be partially avoided by integration of bypass diodes. Manufacturers integrate one bypass diode to protect PV string or integrate few of them in one PV module, each for every set of PV cells.*



Influence of shading on I-U characteristic of PV module

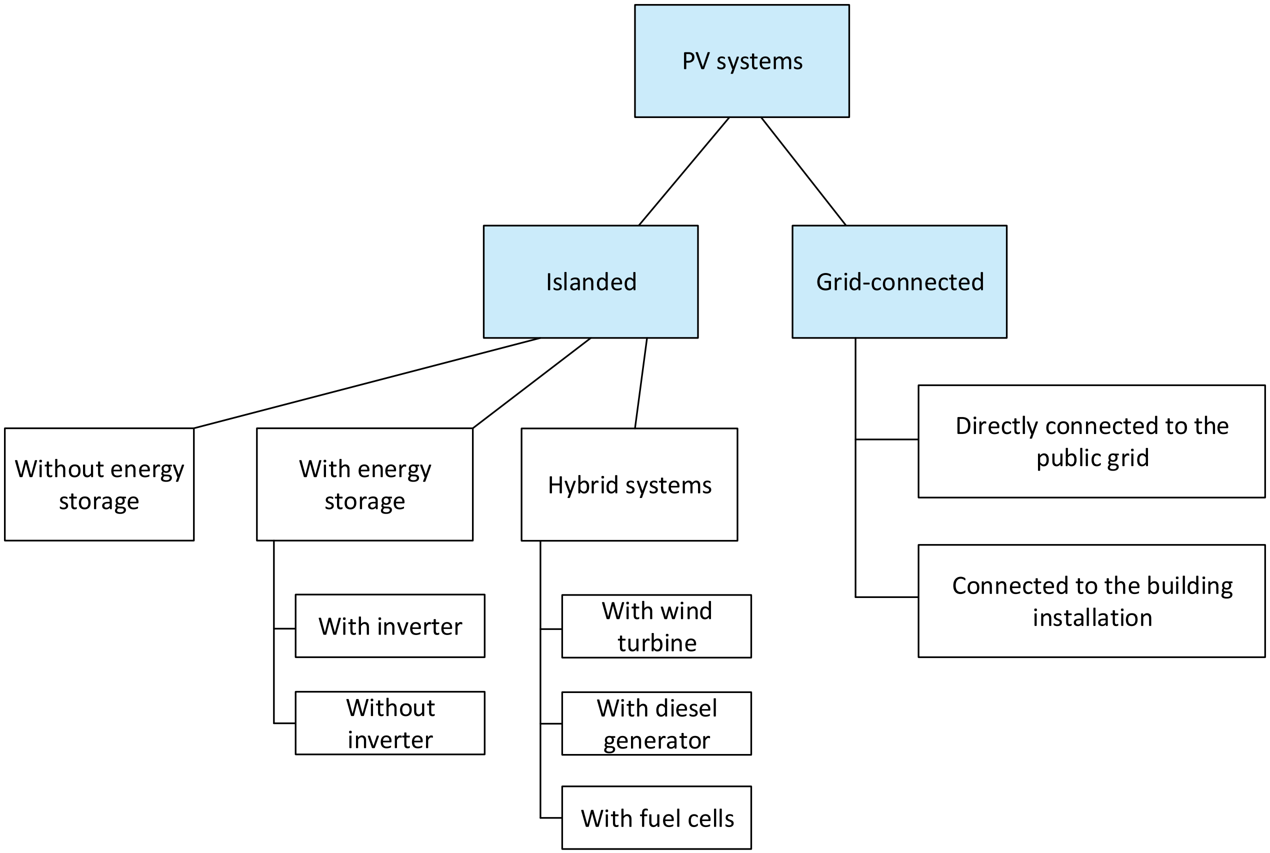
- *Beside bypass diode, manufacturers integrate blocking diodes – when PV string are connected in parallel. They prevent reverse current (dark current) through modules which do not function properly.*

Chapter 3:
PHOTOVOLTAIC SYSTEMS (POWER PLANTS)

PV system types (power plants)

Depending on mode of operation, photovoltaic systems can be divided into:

1. *Islanded photovoltaic systems (off grid, stand alone)*
2. *Grid-connected photovoltaic systems (on grid)*



Photovoltaic systems (power plants)

- *Photovoltaic systems (power plants) present set of photovoltaic modules and other parts designed to directly convert Solar energy into electricity which is used for supply of certain number of DC or AC loads, independently or with some additional source of electricity.*
- *Photovoltaic string (device) does not represent photovoltaic system itself. We have to have:*

  - mounting system oriented to Sun

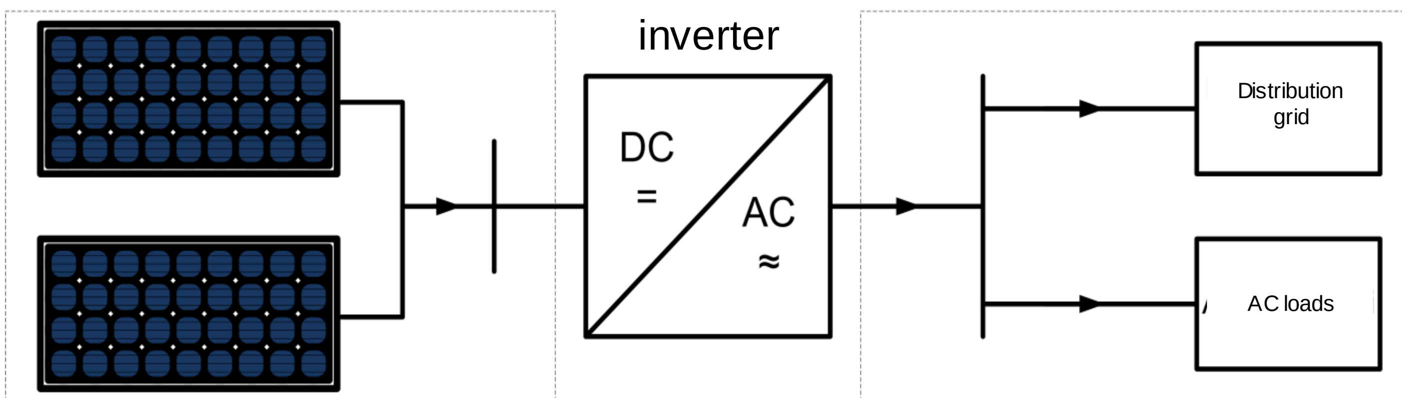
  - maximum power point tracker and regulation devices

  - components which take DC currents produced by devices (batteries, charger...) (mandatory for islanded systems) or

  - if consumer demands AC current or is connected to the grid, system needs energy converter (inverter)

  - eventual additional sources of electricity (in hybrid systems)

- *Grid-connected photovoltaic systems (power plants) are system that are connected to the power grid. DC electricity is firstly converted to the AC eletricity using inverter. Grid-connected PV systems do not need charger and batteries because all of produced energy is fed into power grid over energy meter. Battery is eventually needed for small critical loads like supervisory system an*



- *Depending on PV string connection, following connection configuration of PV systems can be defined according to [2]:*

1. *With single central inverter*
2. *With one inverter per PV string*
3. *Multi inverter*

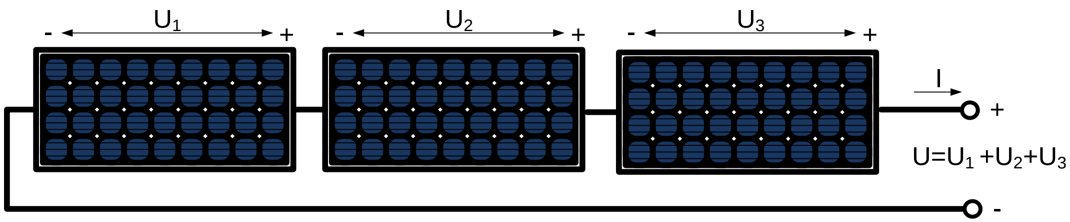
PV inverter/string (array) selection

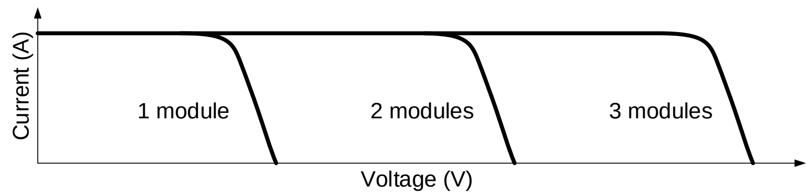
Technical characteristics of a PV inverter (e.g. KACO 12 kW)

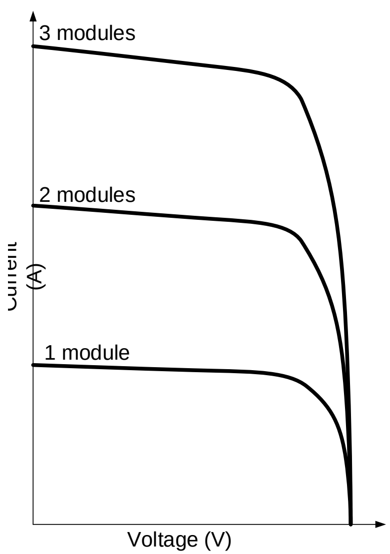
- *Rated DC power P_{DC} (W) – (e.g.. 12 000 W)*
- *Voltage range on DC side $U_{DC,min}$ – $U_{DC,max}$ (V) – (e.g.. 350 – 800 V)*
- *Max voltage on DC side $U_{DC,max}$ (V) – (e.g.. 1 000 V)*
- *Max current on DC side $I_{DC,maks}$ (V) – (e.g.. 18,6 A)*
- *Rated AC P_{AC} (W) – (e.g.. 10 000 W)*
- *Rated voltage on AC side U_{AC} (V) – (e.g.. 230 V)*
- *Rated frequency f (Hz) – (e.g.. 50 Hz)*
- *Power factor cosφ– (e.g. 1)*
- *Max efficiency η_{maks} (%)– (e.g.. 98 %)*

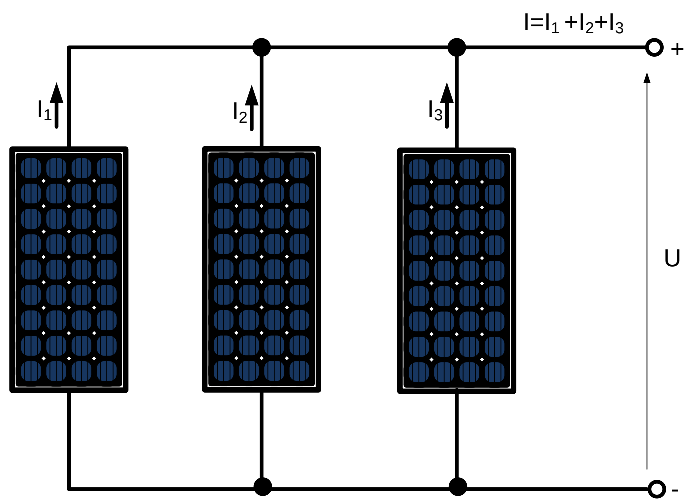
In order to proprely design the PV system it is neccessary to ensure that PV strings (arrays) characteristis are compatible with PV inverter characteristics.

- ***Modularity of PV string current-voltage characteristic*** – *possible fast and custom determined installation sizes of PV strings.*









I – U characteristic of series-connected PV modules

Design for optimal voltage ofn the DC side of inverter

$U_{OC,\ max}$ *(string)* < $U_{DC.max}$ *(inverter)*

$U_{MPP,\ min}$ *(string)* < $U_{DC.min}$ *(inverter)*

$I_{SC,\ max}$ *(string)* < $I_{DC.max}$ *(inverter)*

$I_{OC,\ max}$ *(cables)* > *1,25 x* I_{SC} *(string)*

$I_{AC,\ max}$ *(cables)* > $P_{AC} / (U_{AC} \times \cos\varphi)$

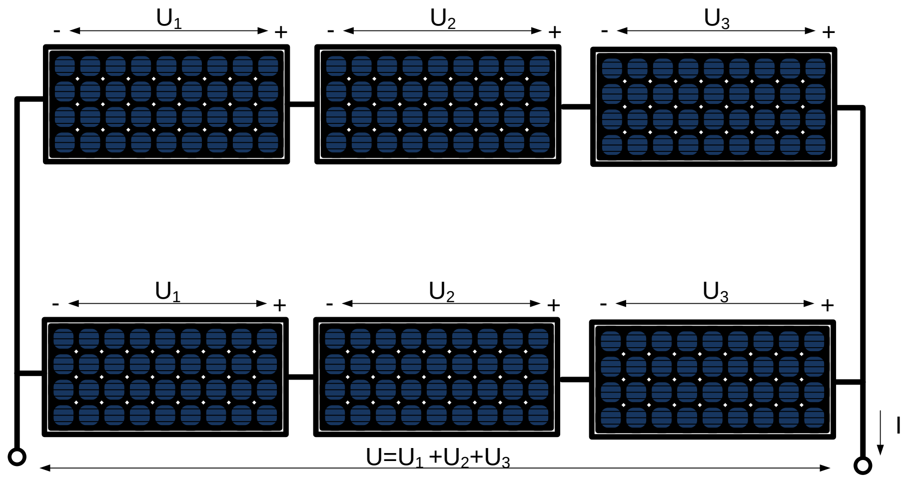
I – U characteristic of parallel-connected PV modules

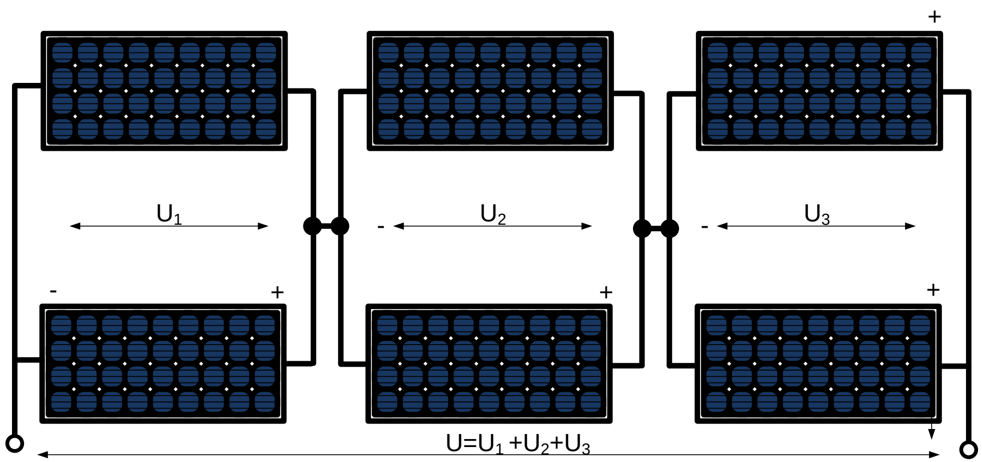
Desgin for optimal current and power on the DC side of inverter

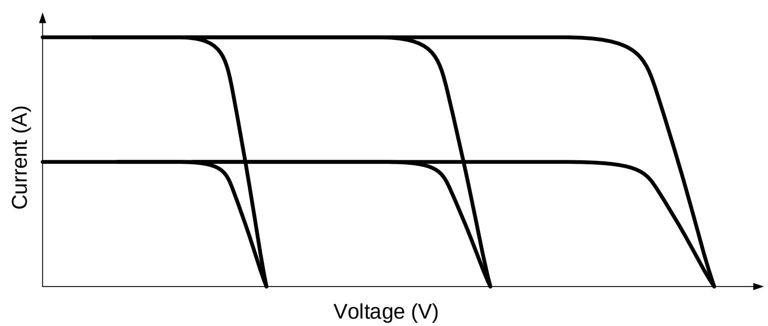
Design of an on-grid PV system

Modularity of current-voltage characteristic of PV strings

Desgin for optimal voltage and power on the DC side of inverter





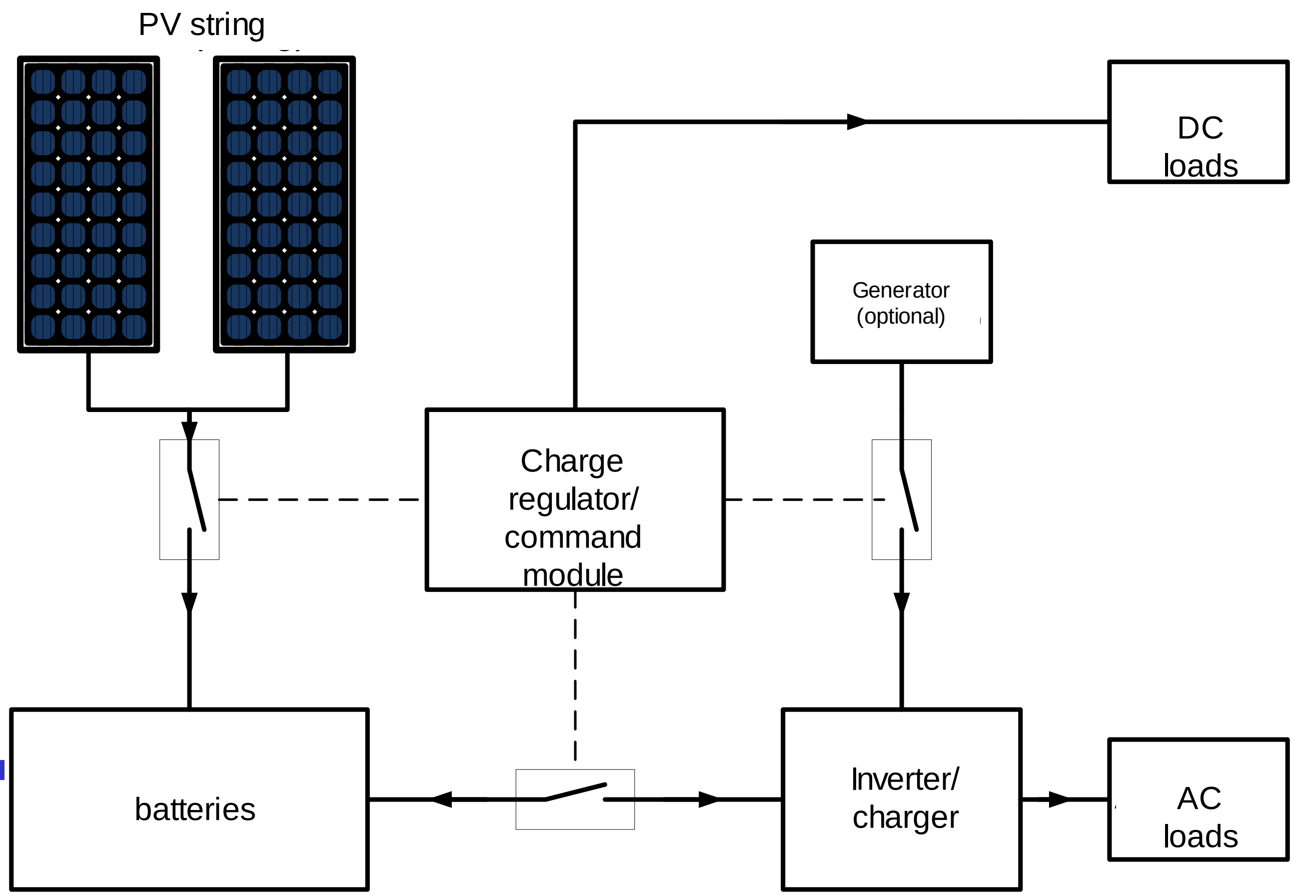


I – U characteristic of series-parallel connected modules (strings)

Desgin of an islanded (off-grid) PV systems (power plants)

- *Islanded PV systems (power plants) are systems that supply consumers on its own, without connection to the power grid and need to satisfy all electricity demand. Since solar irradiation is variable and dependent on current meteorological conditions, production of PV systems can not follow consumer electricity needs (load profile) – batteries are mandatory or some else type of energy storage.*

- *Islanded PV systems can operate with or without batteries – used for loads which use electricity when it is available (e.g. irrigation system).*



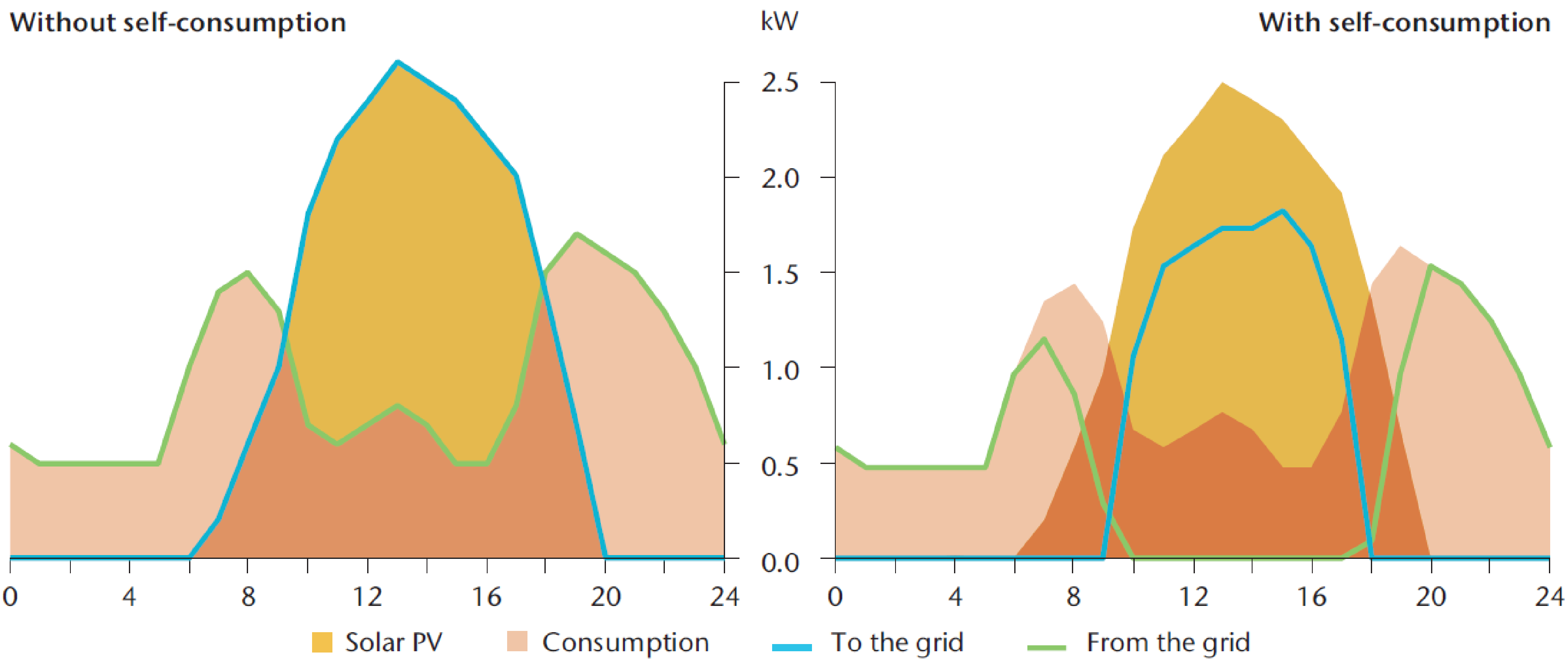
Schematic of an islanded PV system

Desgin of an islanded (off-grid) PV systems (power plants)

- *With batteries and/or inverters, basic elements of islanded PV systems are:*

1. *Maximum power point tracker: recognizes current voltage and current values and continuously adjusts operating point so it would maximize output power. Output is leading to the energy converter (inverter) which converts DC electricity into AC electricity or it can be used for battery charging.*
2. *Charge regulator is usually DC-DC converter. If the electricity is still available after the batteries have been fully charged, electricity is directed to the heater which can be space heater. When solar energy is not available, batteries are discharged over energy converter in order to satisfy the demand. Battery diode – isolates device from the battery that is prevents battery discharge during night*
3. *Supervisory and control system (command module) acquires system signals like currents and voltages of device and battery; monitors battery charge/discharge by storing energy flow data, controls the charger and turns on/off the charger.*

On-grid PV system - problems with households



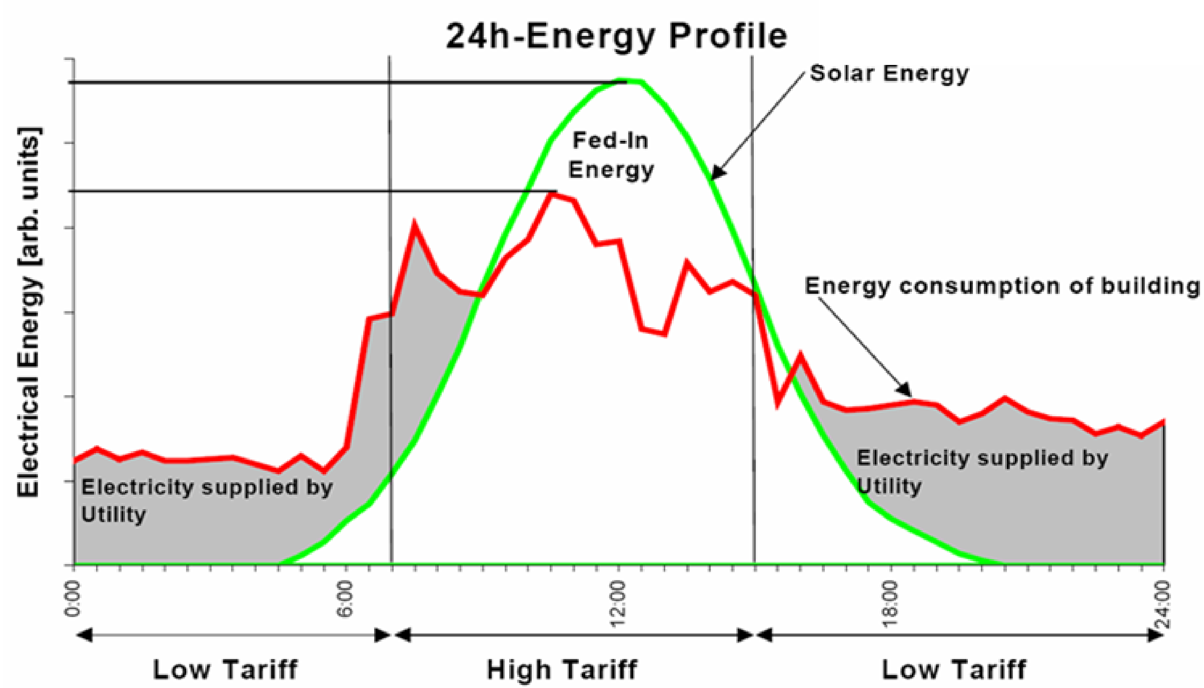
Incompatible PV generation and load in hausholds – huge problem i integration – need for grid and/or storage (batteries) - microgrid

Izvor: IEA Technology Roadmpas Solar PV - 2014 edition

On-grid PV systems
bussines building integration

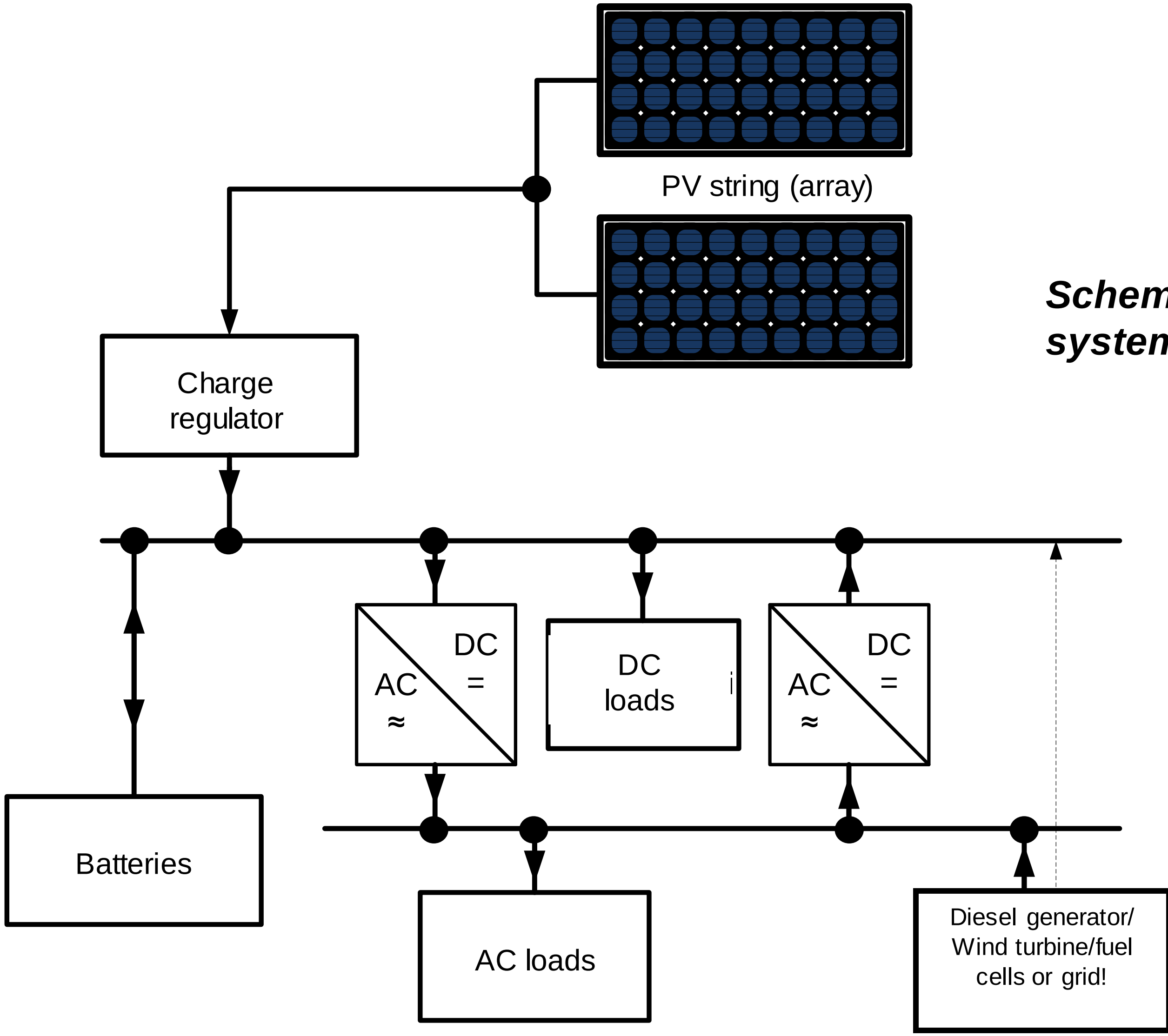
Compatiblr PV generation and bussines building load

Doxford Int. PLC office, USA: First comercial building with building integriated PV system



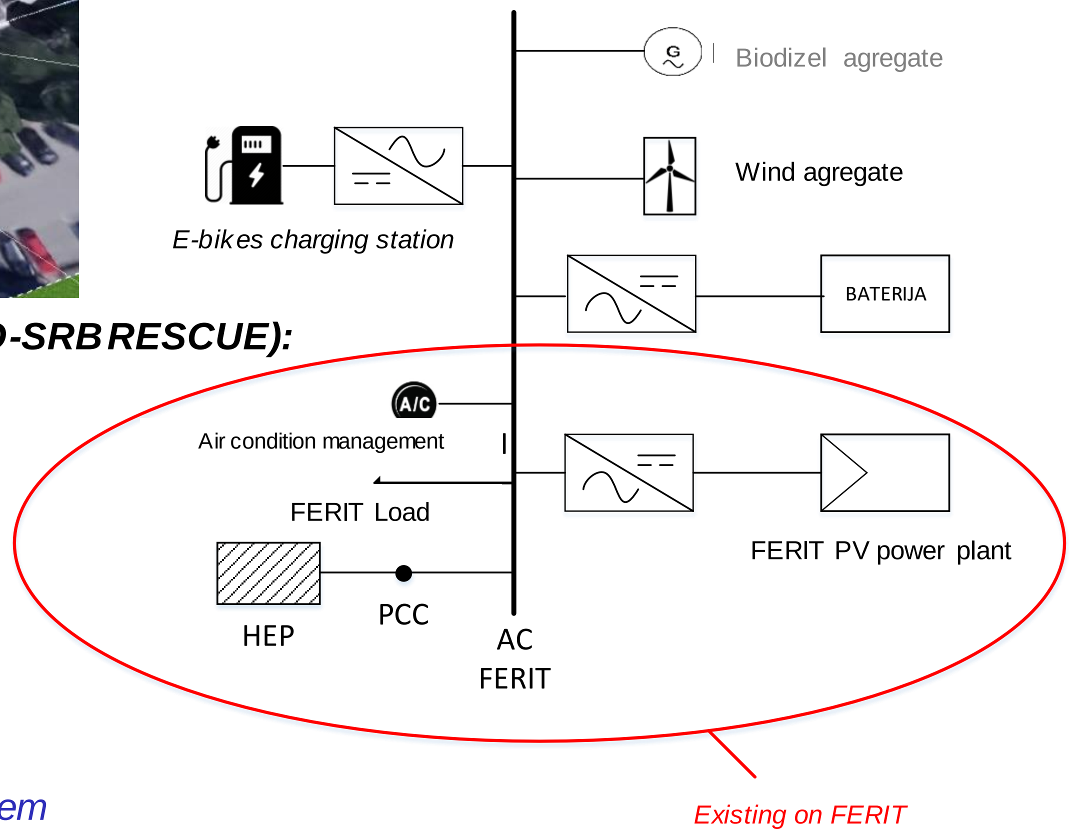
Zero energey (passive) building, Vienna, Austria

- *Since **battery prices are still quite high**, solution to this problem is integration of additional electricity source (generator) into the islanded system. Commonly, additional generators represent **wind turbines, diesel generators or fuel cells**.*
- *Solution with wind turbines have advantage that during night hours when it is 100% sure that there is no solar irradiation, there is certain possibility that there is wind energy available. If the energy produced by wind turbine is bigger than consumption of loads, energy can be stored during the night.*
- *Solutions with diesel generator – it should pay attention that generator is 70-80% loaded since lower loaded generators have lower efficiency – for peak load supply.*
- *Solutions with fuel cells – when there is excess solar energy, par of it can be used for hydrogen production from water electrolysis which can be used for load supply whene there is not enough solar energy.*



Schematic of hybrid photovoltaic system or microgrid

Scheme of FERIT hybrid photovoltaic system or microgrid



2020 future microgrid (IRI project SEGIP, Interreg CRO-SRB RESCUE):

- *10 kW PV power plant expanding to 90 kW*
- *6 kW wind power plant*
- *20 kW batteries+chargers*
- *Min 10 kW charging station for (with) 10 e-bikes*
- *6,5 kW biodiesel agregate*
- *Load (air-condition) management*
- *With data aquisition monitorring and control system*

Renewable energy sources

Mostly <u>Fulfilled</u> Desirable Characterics

Characteristics	Desire	(Small) Hydro	Solar Heat	**Solar PV**	Wind	Bio	Geo
Renewable	Fulfilled	Fullfiled	Fullfiled	Fullfiled	Fullfiled	Fullfiled	Fullfiled
Potential	As larger	Unfullfiled	Fullfiled	Fullfiled	Fullfiled	Partially fullfiled	Partially fullfiled
Diversification	As larger	Partially fullfiled	Fullfiled	Fullfiled	Partially fullfiled	Fullfiled	Fullfiled
Energy ammortization	As smaller	Fullfiled	Partially fullfiled	Unfullfiled	Partially fullfiled	Fullfiled	Fullfiled
Energy for obtaining	As smaller	Fullfiled	Fullfiled	Fullfiled	Fullfiled	Unfullfiled	Fullfiled
Environmental impact	As smaller	Fullfiled	Fullfiled	Fullfiled	Partially fullfiled	Partially fullfiled	Fullfiled
CO_2-neutrality	As larger	Fullfiled	Partially fullfiled	Unfullfiled	Fullfiled	Fullfiled	Fullfiled

Fullfiled characteristic	(green)
Partially fullfiled characteristic	(yellow)
Unfullfiled characteristic	(red)

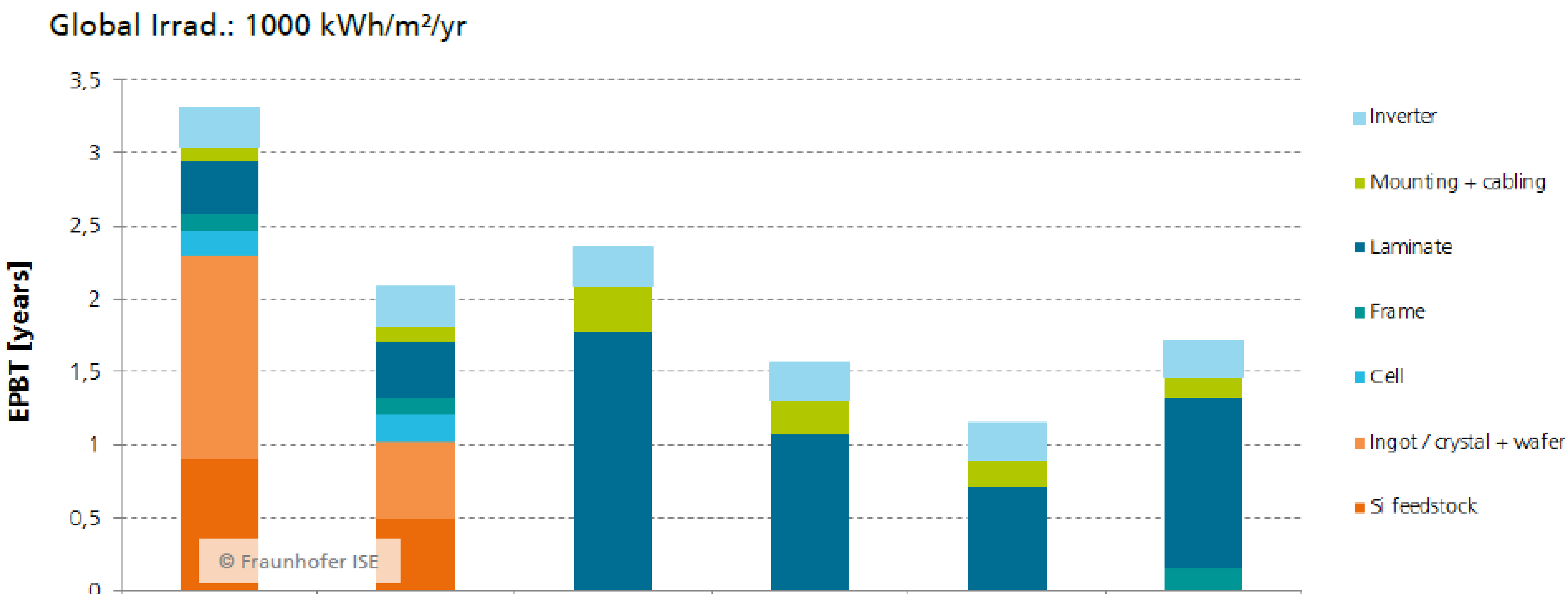
RES - mostly Fulfilled Desirable Characteristics

CO2-equivalent emissions of Power Plants Technologies

Power Plant Type	Direct emissions CO_2-equivalent (g/kWh)	Indirect emissions CO_2-equivalent (g/kWh)	Overall emissions CO_2-equivalent (g/kWh)
Large Hydro	3,5-40	10-20	13,5-55
Small Hydro	3,5-35	15-20	18,5-55
Wind 600 kW	0	40	40
Wind 1,5 MW	0	50	50
Biomass 700 kW	13	50	63
Biomass 11,5 MW	18	45	63
Large PV system	0	180	180
Small PV system	0	220	220
Conventional thermal – natural gas	340	80	420
Conventional thermal – coal	820	100	920

- ***Direct emissions*****:** *power plant operation (electricity production).*
- ***Indirect emissions****: power plant instalation and decommission (building, equipment).*
- *Nuclear power plants have* ***zero*** *direct emissions!*

Energy amortization/pay back time (EPBT) – with 1000 kWh/m²,god



Mono-Si	Multi-Si	a-Si	µm-Si	CdTe	CIGS	Technology
Glass-EVA-backsheet	Glass-EVA-backsheet	Glass-PVB-glass	Glass-EVA-glass	Glass-EVA-glass	Glass-Eva or PVB-glass	Module composition
2011	2011	2008-2011	2013 estimate	2010-2111	2011	Status
14,8%	14,1%	7,0%	10,0%	11,9%	11,7%	Efficiency
~300 MWp	~300 MWp	33-45 MWp	120 MWp	963 MWp	20-66 MWp	Scale of production

Source: Photovoltaics Report Fraunhofer Institute for Solar Energy Systems, 2017

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Renewable energy sources

Mostly <u>Unfulfilled</u> Desirable Characterics

Characteristics	Desire	(Small) Hydro	Solar Heat	Solar PV	Wind	Bio	Geo
Areal distribution	Equal	red	green	green	red	green	red
Areal density	As larger	green	red	red	red	red	green
Space needed	As smaller	green	red	red	yellow	green	green
Storage in natural form	Possible	red	red	red	red	green	green
Natural oscilation	As smaller	red	red	red	red	red	green
Efficiency	As larger	green	green	red	yellow	yellow	yellow
Cogeneration	Possible	red	red	red	red	green	green

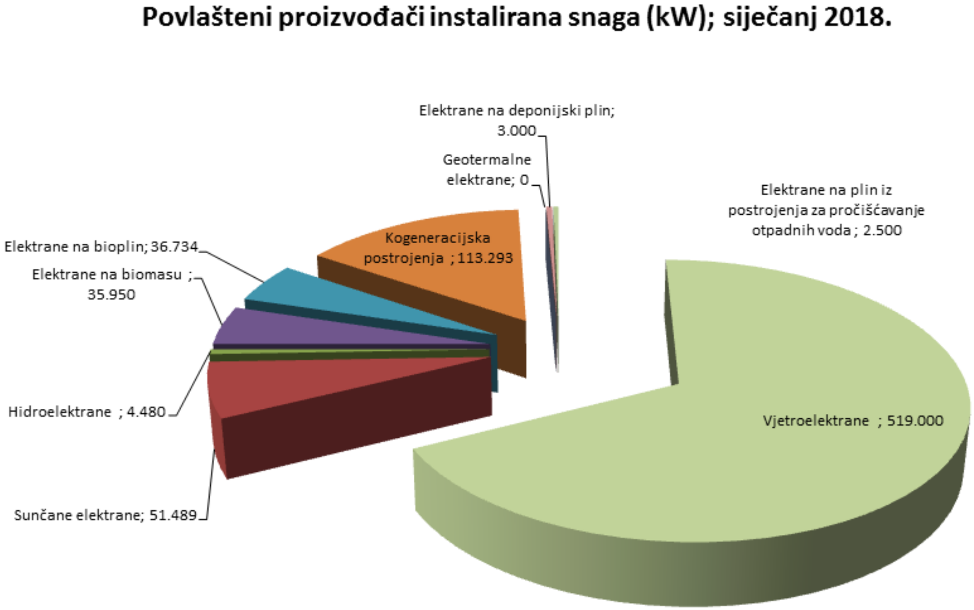
Fullfiled characteristic	green
Partially fullfiled characteristic	yellow
Unfullfiled characteristic	red

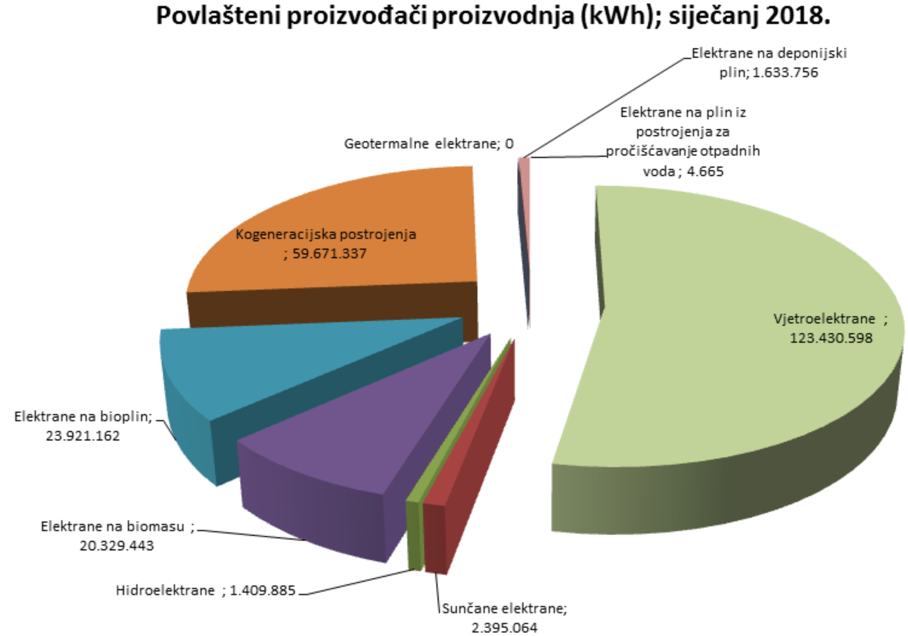
Low capacity factor and durarion –generation/installed power ratio

- PV power plants: lowest capacity factor and duration:
- **World average: 13%**
- Continental Croatia: e.g. Osijek 1100 h/year (kWh/kWp) or capacity factor 12,6% (optimal angle 33%)
- Mediterranean Croatia: e.g. Split 1350 h/year (kWh/kWp) or capacity factor 15,4%.
- Egypt: e.g. Cairo 1770 h/year (kWh/kWp) or or capacity factor of 20,2% (optimal angle 29%), source PVGIS
- Compared to:
- Nuclear thermal power plants: 85% up to more than 90%; biomas and biogas often over 90% (thermal power plants, only planned and forced failures)
- Small hydropower 40-50% (world average with large hydro 50%): e.g. in 2013 in Croatia arround 42,1% (variation in water flow)
- Wind power plants 20-40% (world average 27%): e.g. in 203 in Croatia arround 23,2% (variation in wind flow)

PV electricity production variation – low capacity factor

Low capacity factor and durarion – example: January 2018 Croatia





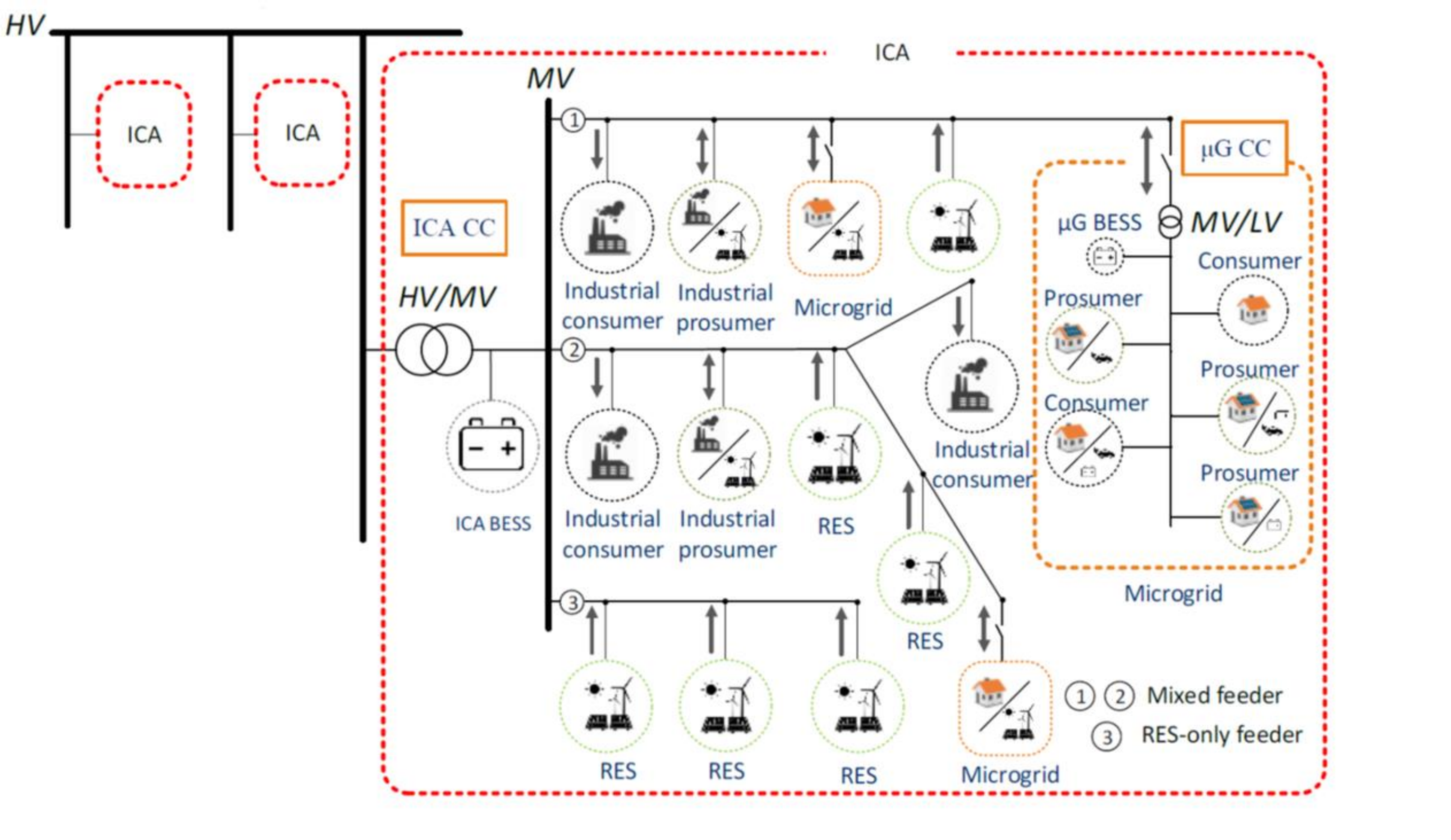
RES in incentive scheme (contract with Croatian Energy Market Operator HROTE) in Croatia, January 2018

- ***Monthly capacity factor: Generation/Power*(31*24) h***
- *For Wind PP (January >) = 0,32; for TPP on biomass = 0,76; for TPP on biogas = 0,87; for small HPP = 0,42; for PV power plants (January <<) = 0,06*

PV systems electricity production characteristics

- ***Low efficiency of generating electricity**: Electrical efficiency of PV commercial plants 12-16 % for Si cristalline modules, 8 – 14 % for thin-film (CI(G)S, CdTE, a-Si).*
- ***Impossible to co-generate heat and electricty:** lowering final (overall) energy efficiency*
- ***With recpect to power system:** large variation od Sun and electricity generation – results in **necessary reserve** in other (usually conventional power plants (TPP on fosile fuels or large accumulation HPP) to be ready to fullfil the neccessary energy missing.*
- *This is a reason why for wind and PV system usuall term used was additional rather than alternative energy sources, however – advances in storage and smart grids and microgrids – enables 100% alternative to fossile fuels*
- *Distribution (power) grid with distributed generation from RES (PV system mainly) becomes active (from passive): resulting in voltage rise, changes in power flows and losses, influencing power quality, protection schems etc. - need for complex energy management (load/generation/storage) using ICT and automation – **from passive – via active – to smart grid!***

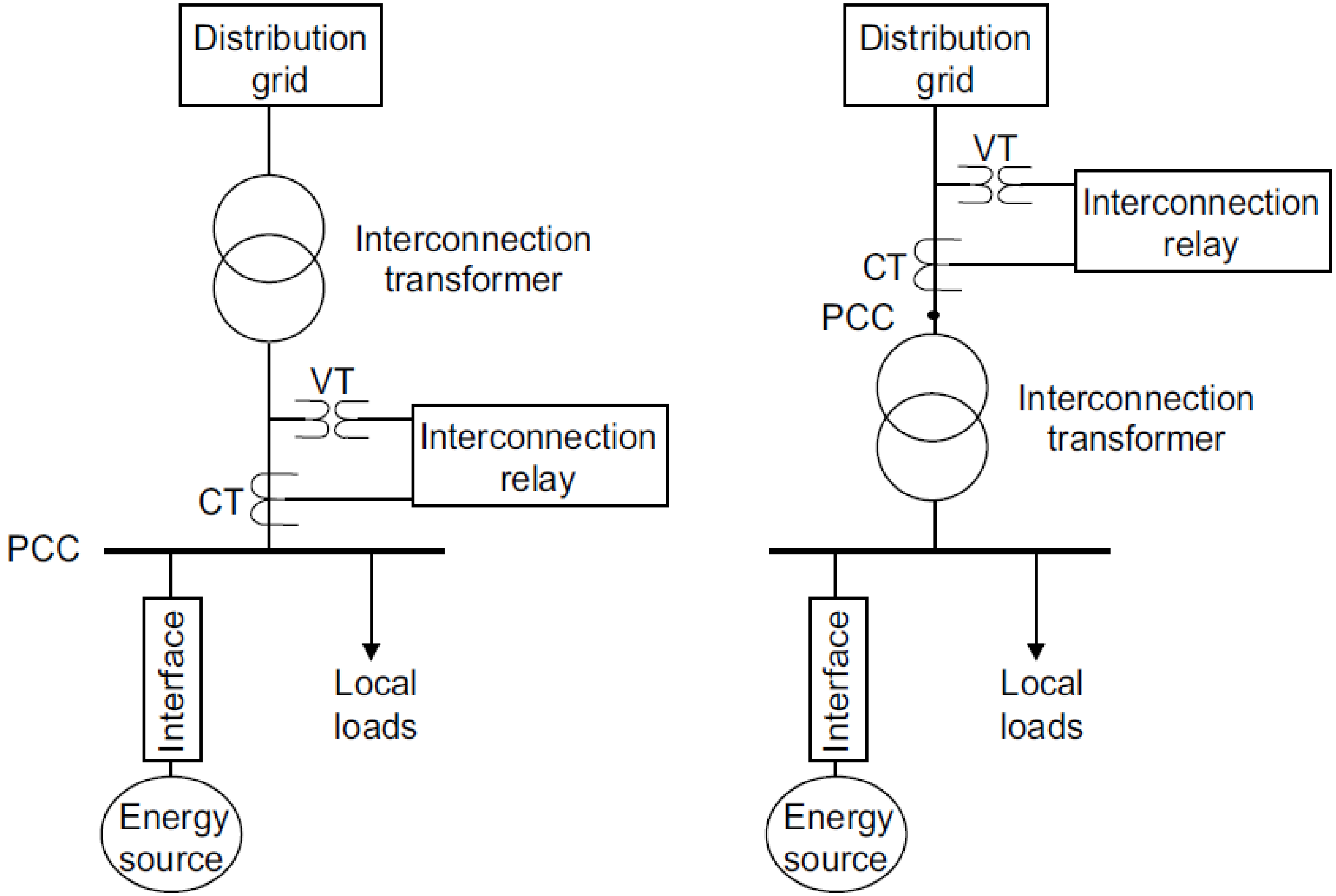
Distributed generation (RES)/consumer/prosumer/microgrid connection to distribution (MV/LV) grid



Individual Control Area (ICA)

Source: TU Delft

Point of common coupling (PCC) – grid connection point



Izvor: Bollen, Hassan

- *There are **different technologies** connecting distributed generation from RES on PCC but usually generators (synchronous and asynchronous/induction) and/or power electronics converter in order to comply to the technical grid codes (technical grid requirements).*

TABLE 2.11 Interfacing Technologies for Different Energy Sources

Energy source type	Source of energy	Electrical generator	Power electronics
Wind power	Wind	SG, PMSG, IG, DFIG	Optional, AC/AC
Hydropower	Water	SG	N/A
Fuel cell (CHP)	Hydrogen	N/A	DC/AC
Biomass (CHP)	Biomass	SG, IG	N/A
Microturbines (CHP)	Diesel or gas	SG, IG	Optional, AC/AC
Photovoltaic (solar power)	Sun	N/A	DC/AC
Solar thermal (solar power)	Sun	IG	N/A
Wave power	Ocean	LSG	AC/AC
Flow of river (small hydro)	Rivers	PMSG	AC/AC
Geothermal	Earth temperature	SG, IG	No

SG, synchronous generator; PMSG, permanent magnet synchronous generator; IG, induction generator; DFIG, double-fed induction generator; N/A; not applicable; LSG, linear synchronous generator.

Source: Bollen, Hassan

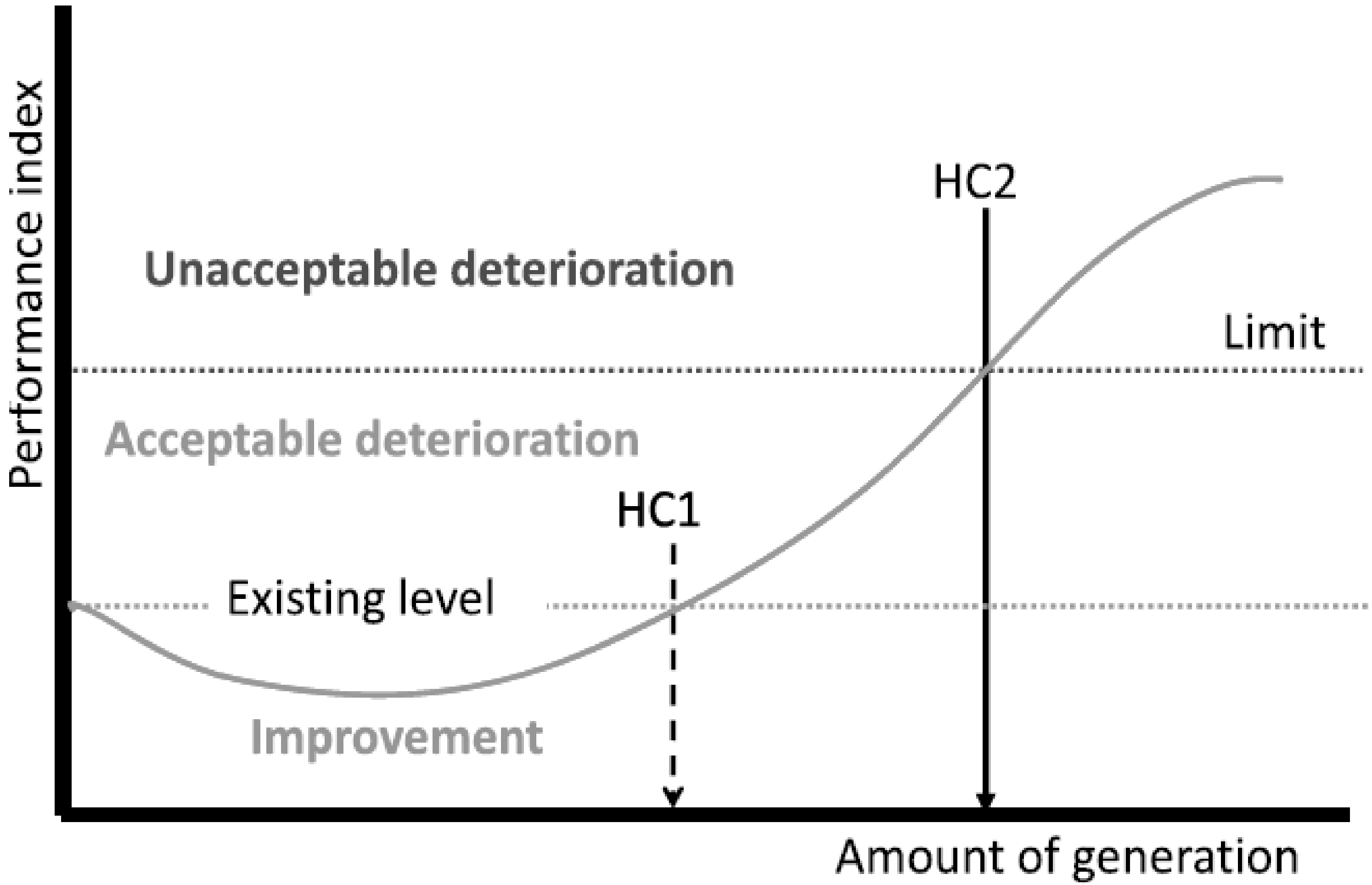
Distributed generation on RES or prosumer from PV systems influence on point of common copuling (PCC) and surrounding network *required/limited by by the grid codes are:*

- ***Power flows** – **current (thermal) restraints and branch losses** (lines and transformers) as well as **voltage rise and regulation** in network nodes (substation and cunsumer buses)*
- ***Rise of short circuit currents** and possible influence on overload of **switching gear equipment** particularly circuit breakers and related **protection scheme** changes*
- ***Power (voltage) quality** – voltage variations, harmonic distorsion, voltage drops, flickers and consumer supply reliabiliyt (security)*

On the system level (mainly large scale PV plants):

- ***Regulation of active power and frequency and reactive power and voltage** (dispatching to other generators)*
- ***System dynamic stability** – stabillity of voltage, frequency and angle*

- *This influence can be **pozitive or negative** depending on grid conditions and **RES penetration level (amount of RES generation)**.*

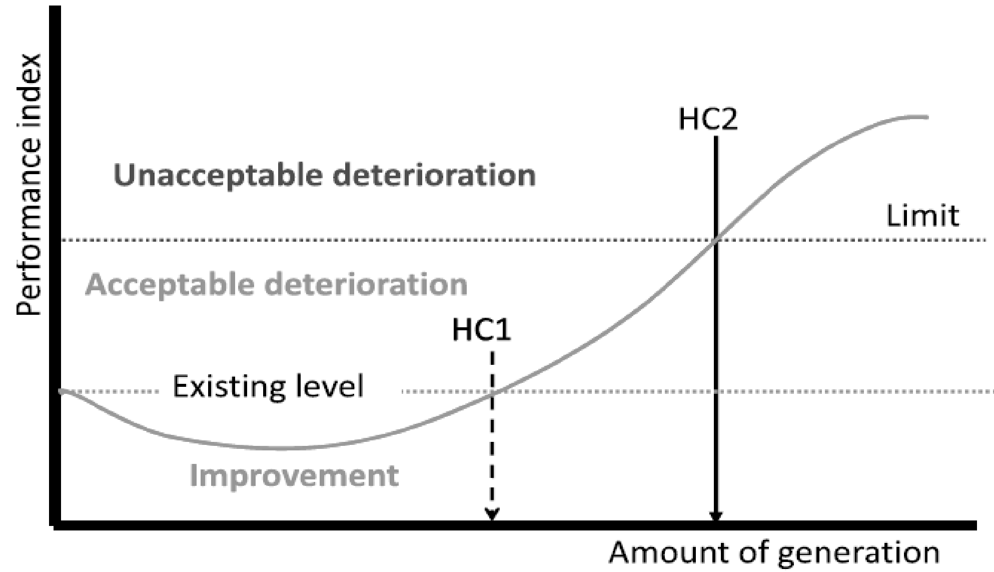


Source: Bollen, Hassan

Example: grid voltage conditions

• *Voltage rises with amount of PV integration*

• *If the voltage at existing level was lower than nominal (usually true in radial distribution grid) – at first rise of volate is up to nominal (point HC1) in considered* ***pozitive influence*** *(improvement).*



- *Further RES (PV) integration leads to further voltage rise (from point HC1 to HC2) considered* ***acceptable negative influence*** *(deterioriation)*
- *Over upper limit of voltage (+10%) (point HC2) cames the* ***unaccebtable negative influence (deterioration)...***

- *This can result in* ***limitiation of further RES grid integration and need for technical measures in grid****, such as grid power/volatege regulation, energy (load and generation) management, automation and ICT monitoring - smart grids etc.*

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Source: Bollen, Hassan

Influence of RES (PV) on power system

- *PV systems (plants) have no generator, so at interfacing PCC they are always using full, modular or distributed power electronics*

Interfacing technology	Controllability	Robustness	Efficiency	Cost
Induction generator	–	–	+	–
Synchronous generator	+	+	++	+
Partial power electronics	++	–	+	++
Full-power electronics	+++	–	–	+++
Modular or distributed power electronics	++++	+	+++	++

"–" for Less and "+" for More.

Source: Bollen, Hassan

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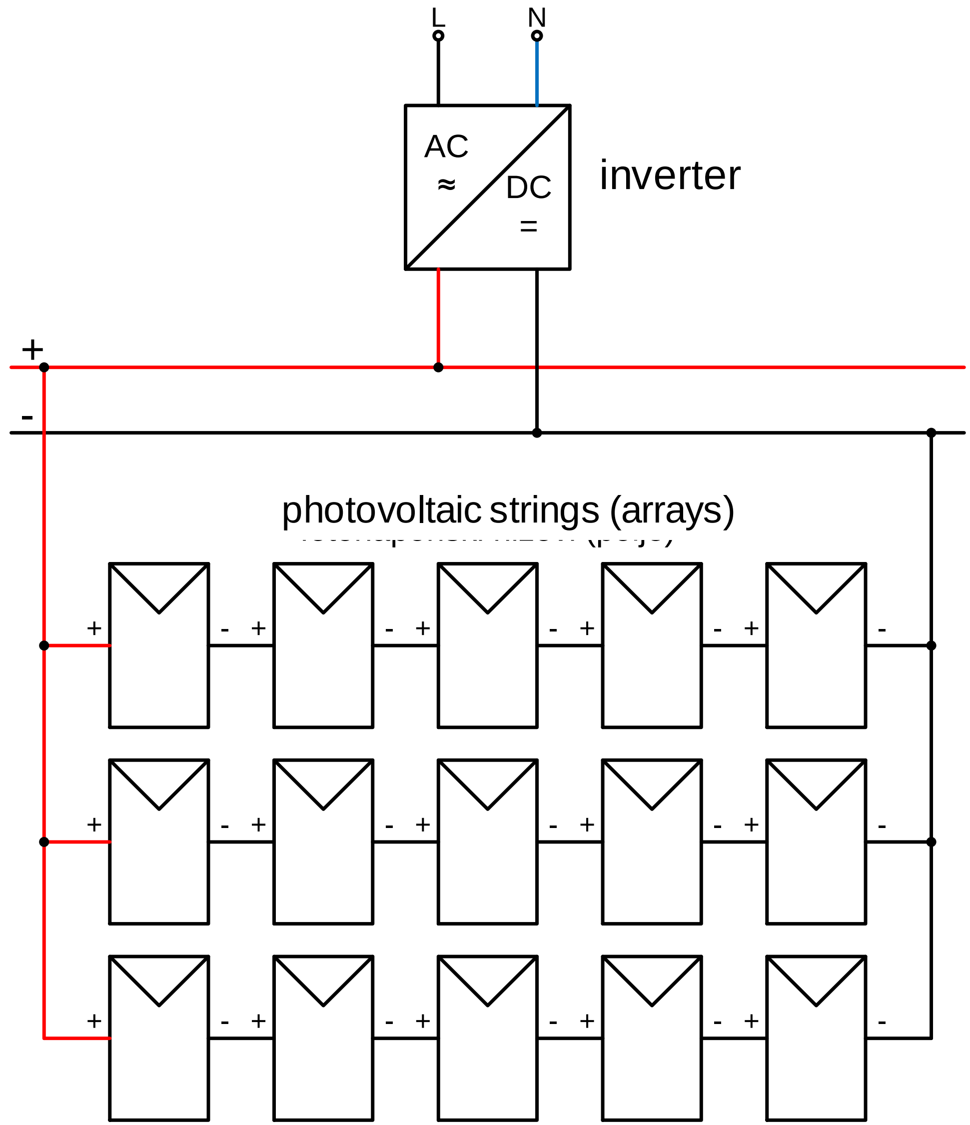
Influence of RES (PV) on power system

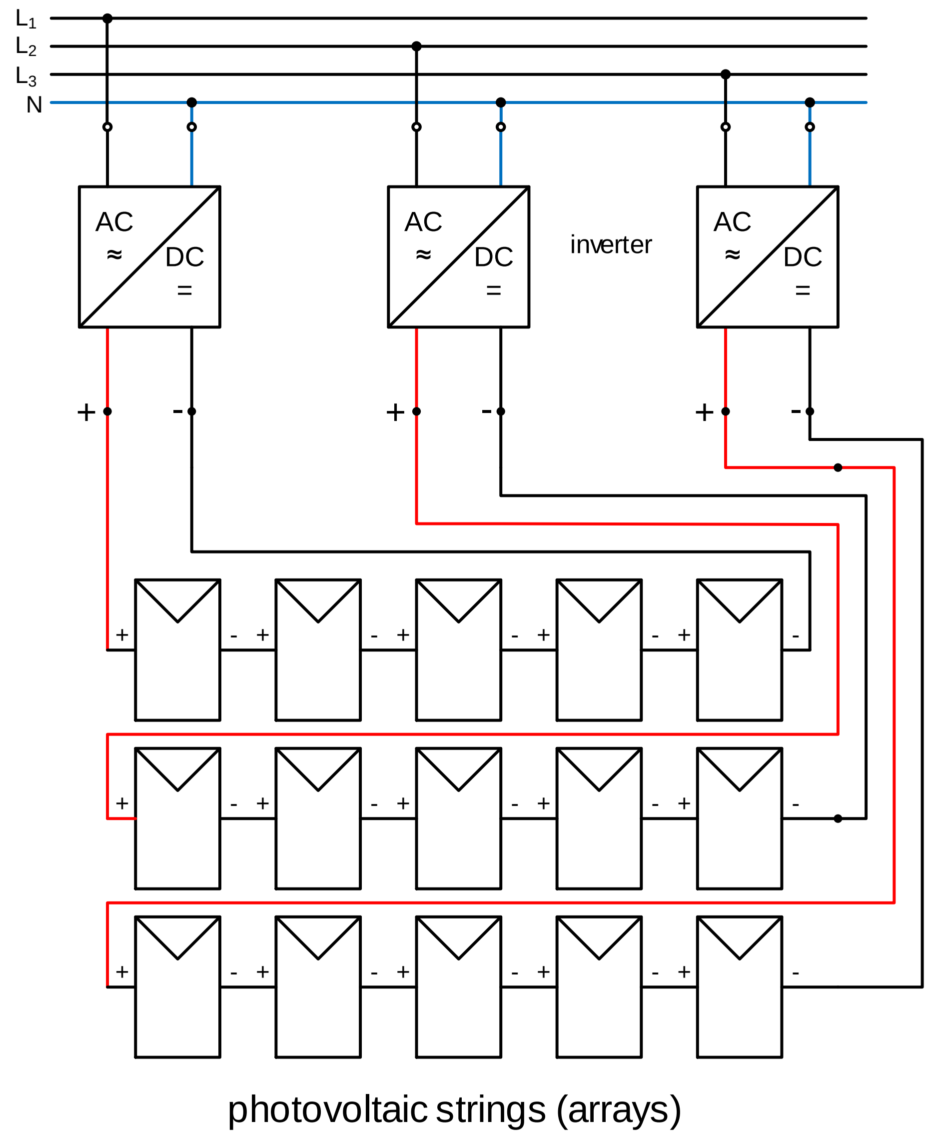
Central-inverter on-grid PV system

- ***Full power-electronics grid connection***
- ***Small scale PV systems***
- *All equal characteristis PV strings (arrays) connected to one inverter.*
- *Less controlable, in case of inverter failure shotdown of the whole PV plant,*
- *Problems with extending the system due to overcurrent protection, need for larger inverter,*
- *In case of shadowing – larger electricity generating losses...*
- *Smaller investement and O&M costs*

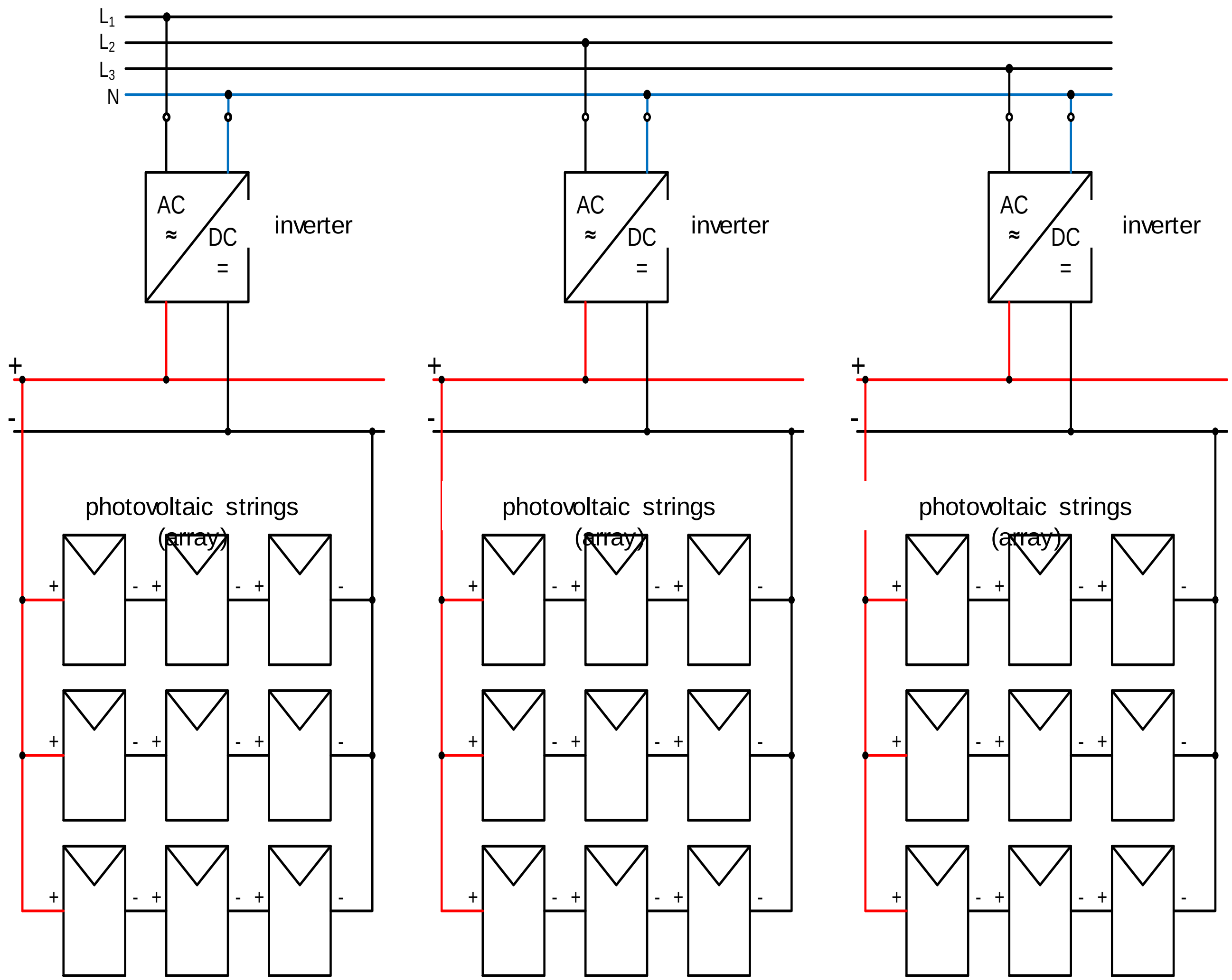


On-grid PV system with one inverter for each PV string

- **Modular power-electronics grid connection**
- **Medium size PV power plants**
- *Each PV string (array) has MPPT that increases efficiency and reliability;*
- *In case of failure of one inverter other operates normally*
- *Each PV string (array) can have different number and modules characteristics.*
- *Higher costs.*



- ***On-grid PV system with many inverters***
- ***Distributed power electronics***
- ***Large-scale PV power plants.***
- *Limits in inverter capacity*
- *Each PV field divided in many sub-fields with inverter and paralel PV strings (arrays)*
- *Advantage: more flexible, reliable, controlable*



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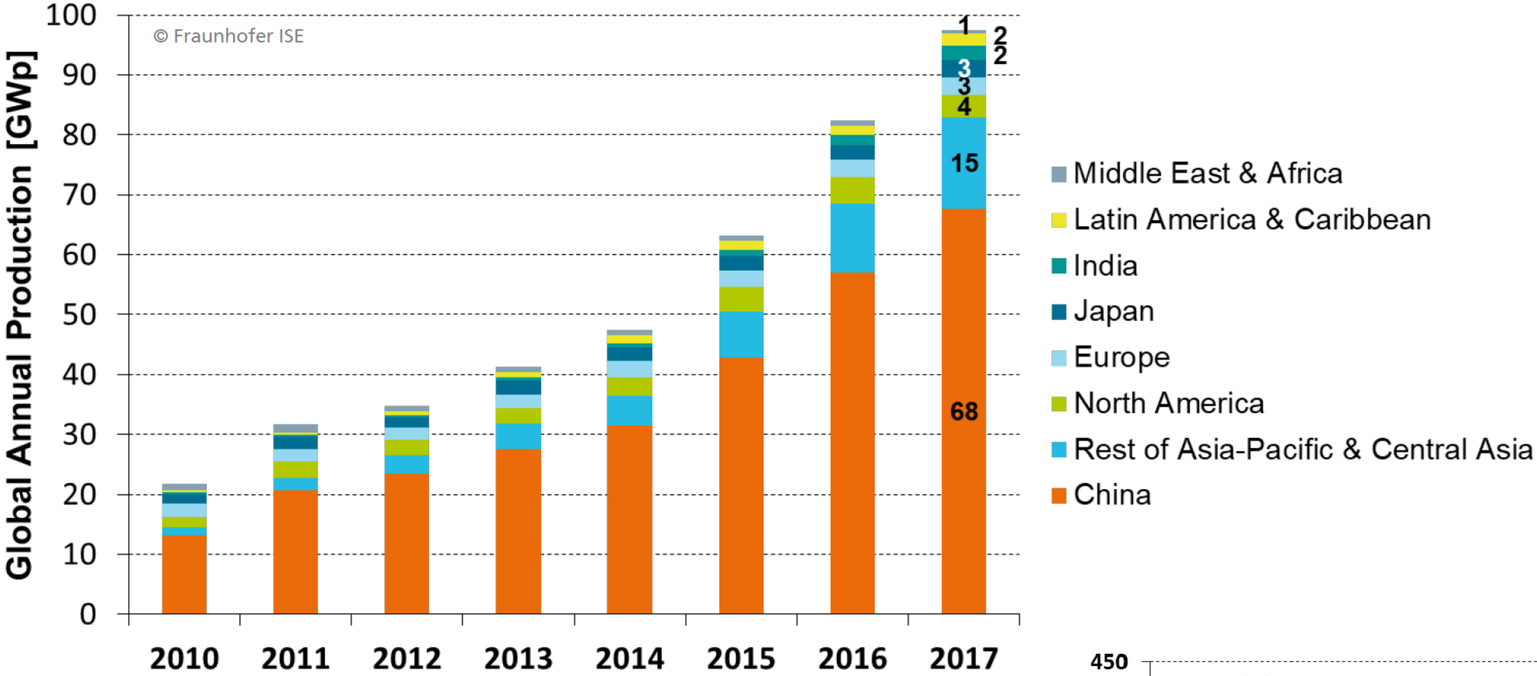
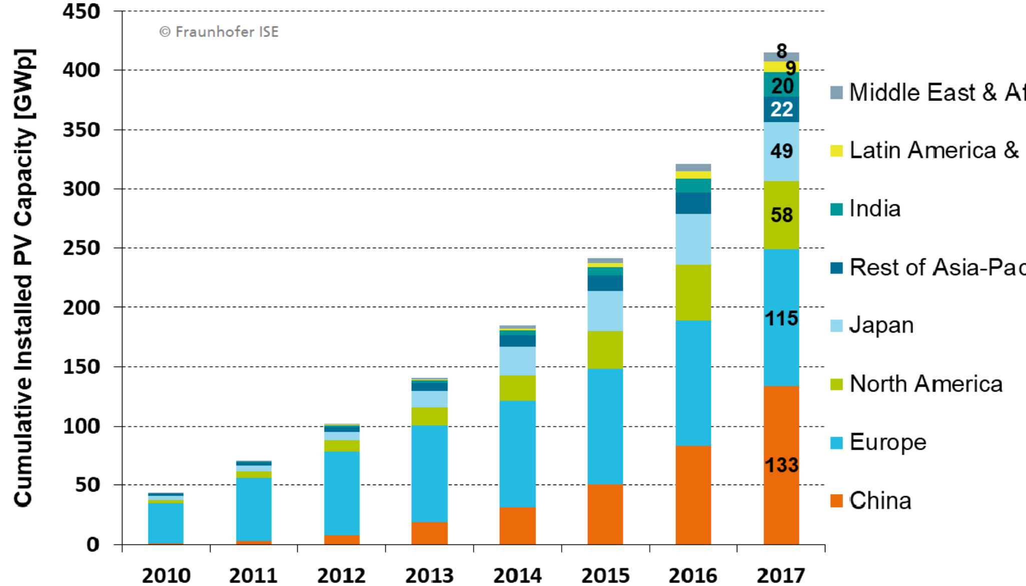
Smart grids with large RES and electric vehicles share

Global annual production/cumulative installation of PV modules 2005 - 2017

by regions





Source: Photovoltaics Report Fraunhofer Institute for Solar Energy Systems, 2018

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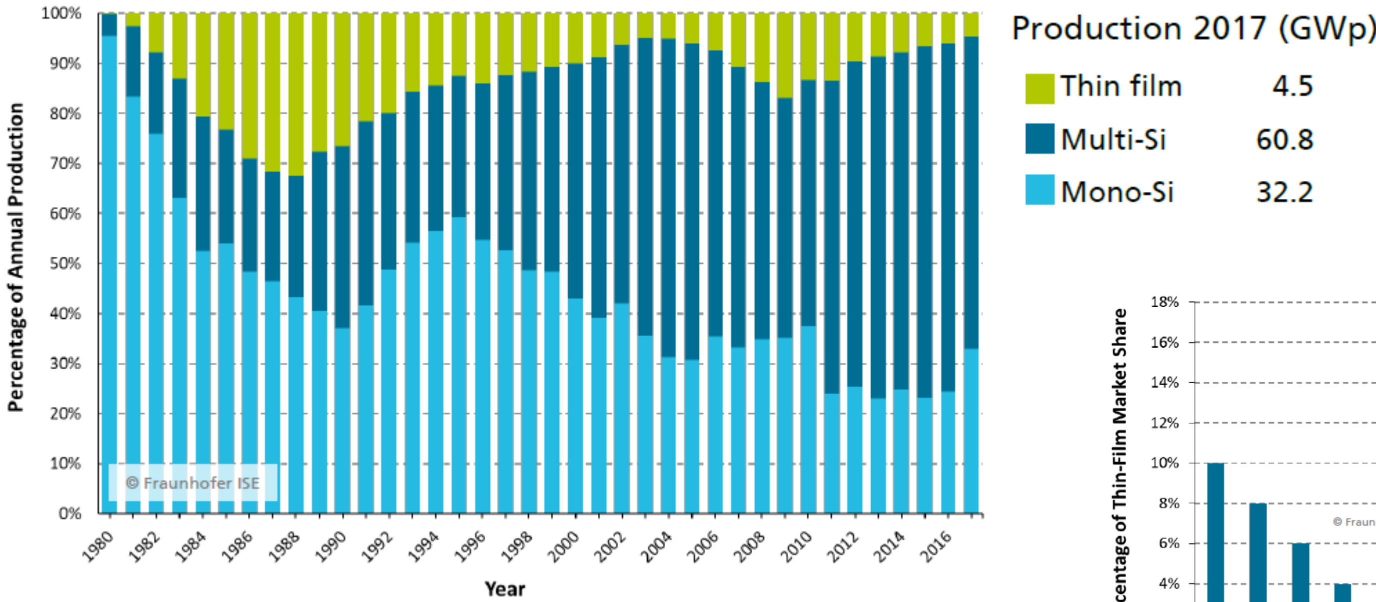
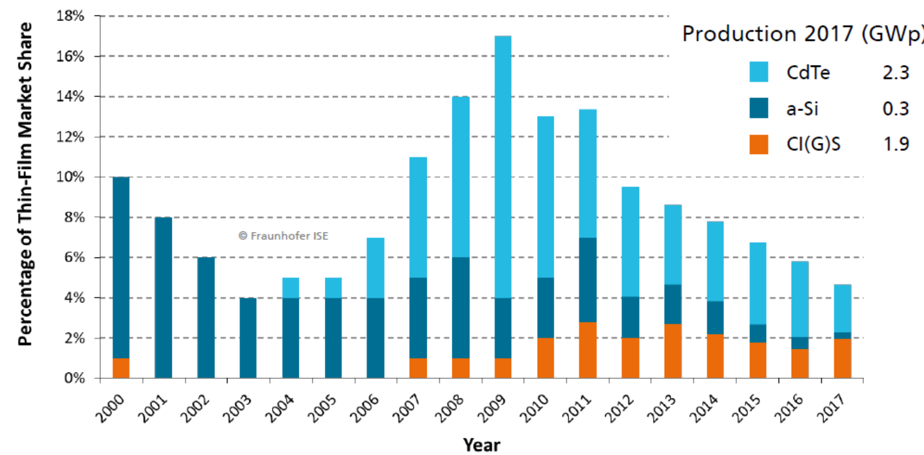
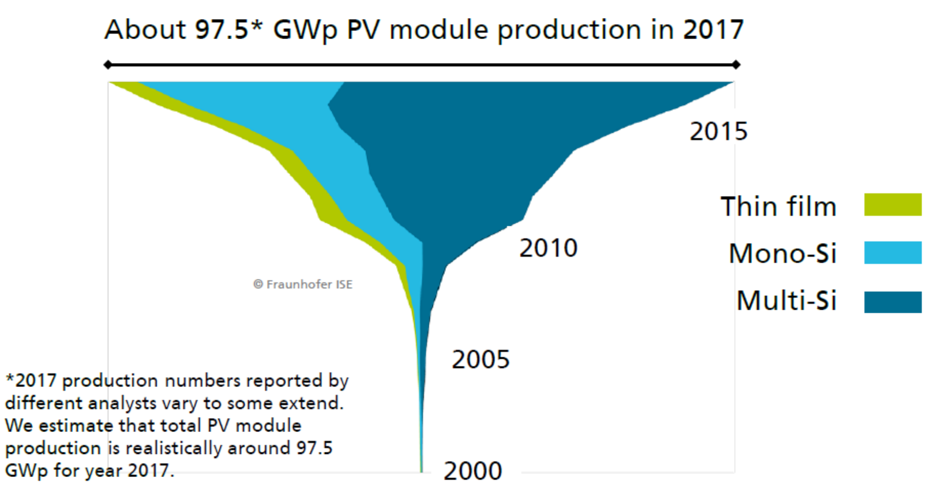
Global production of PV modules 1990 (2000) - 2017



Annual PV Production by Technology
Worldwide (in GWp)

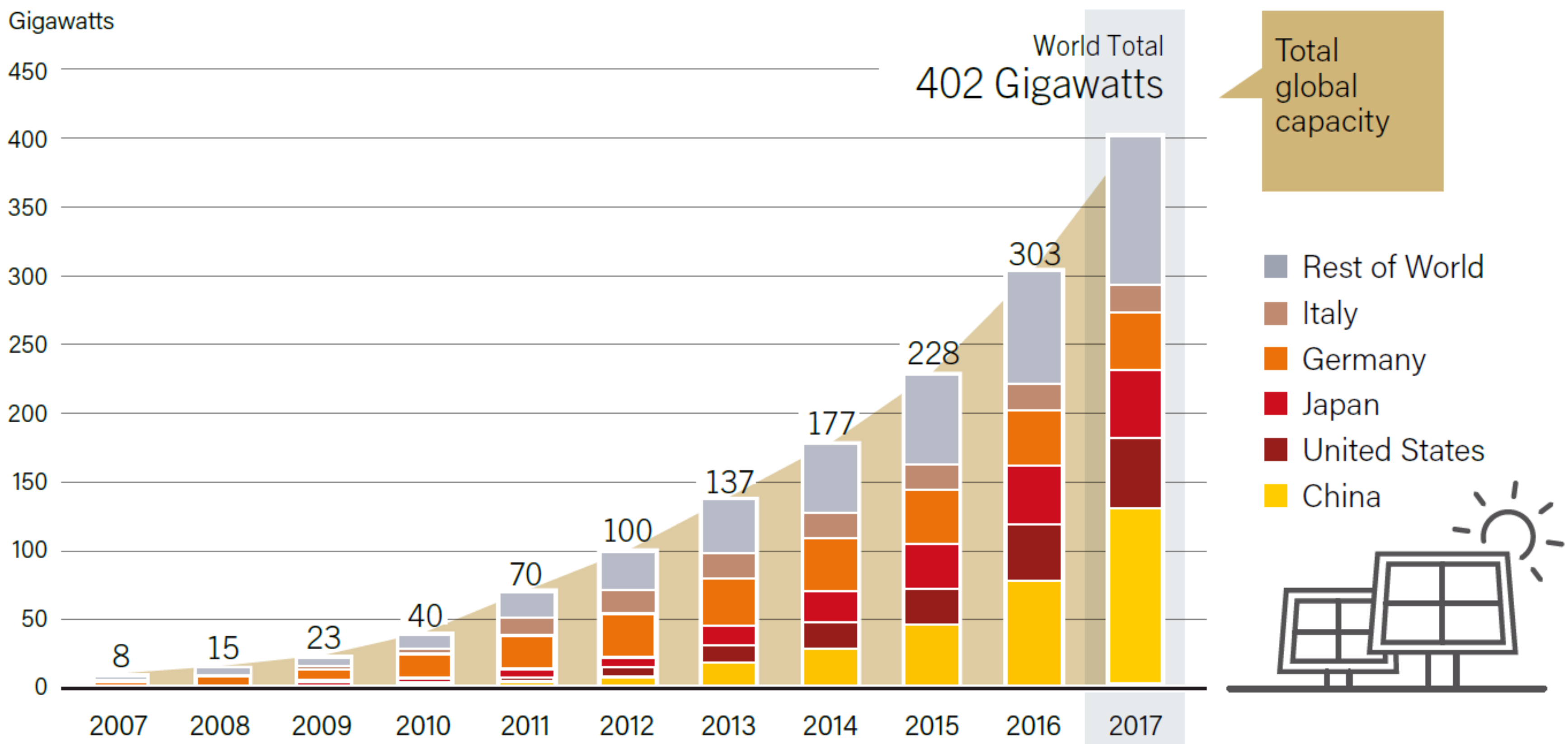




Izvor: Photovoltaics Report Fraunhofer Institute for Solar Energy Systems, 2018

Installed capacity in PV systems [GW] by the end of 2017: 402 GW!

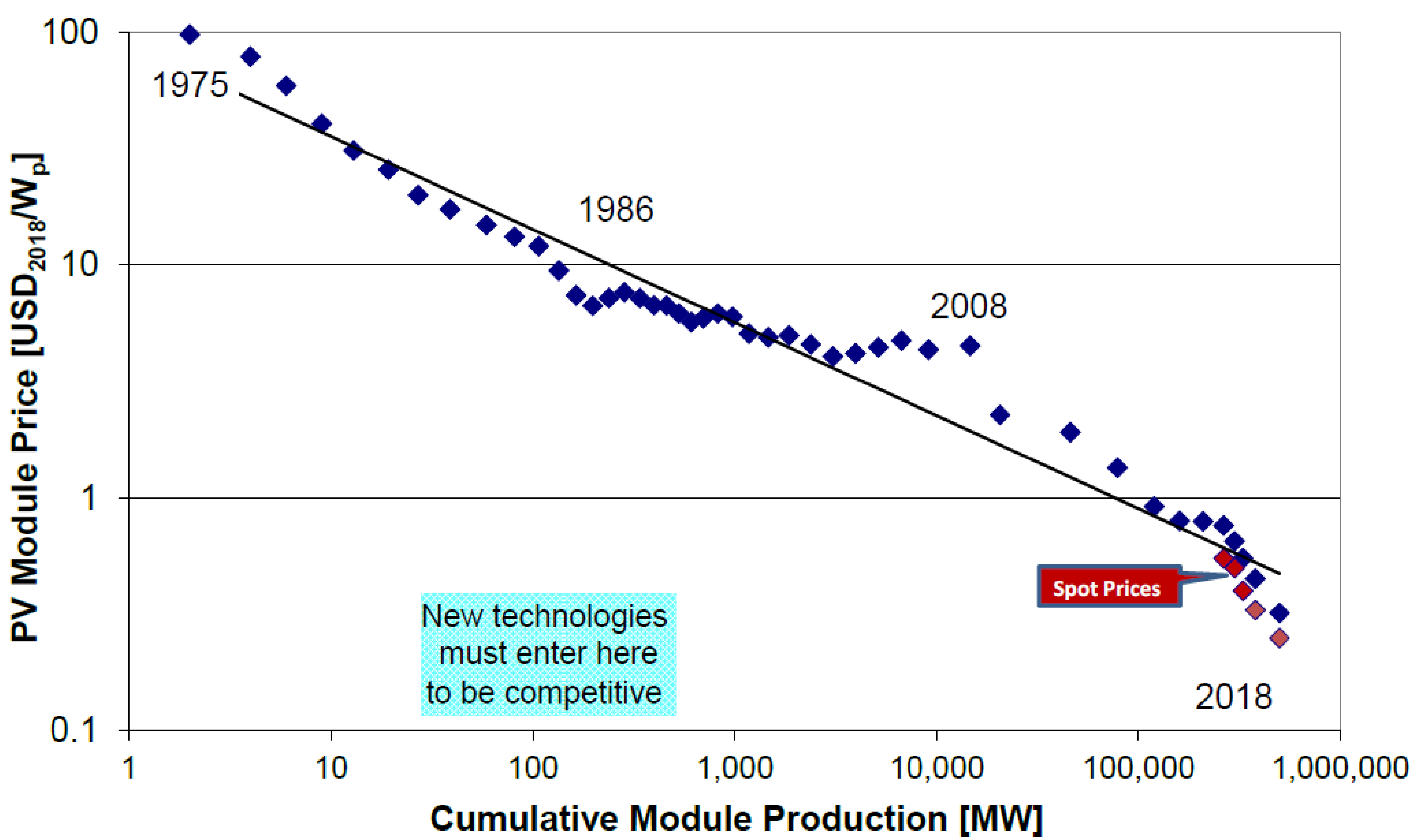
- *In 2017. more than 98 GW (similar to total in 2012!!!), 2016: 75 GW, 2015: 51 GW, a 2014: 40 GW!!! Cumulativly (historcaly) Germany was leading to 2014., China from 2015., followed by Japanu, USA and Italy*



Izvor: REN21 Renewable 2018 Global Status Report

Module prices to 2018

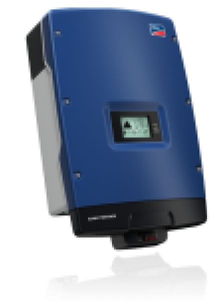
Figure 8: Price-experience curve for solar modules (ASP)



Source: JRC EC PV Status Report 2018

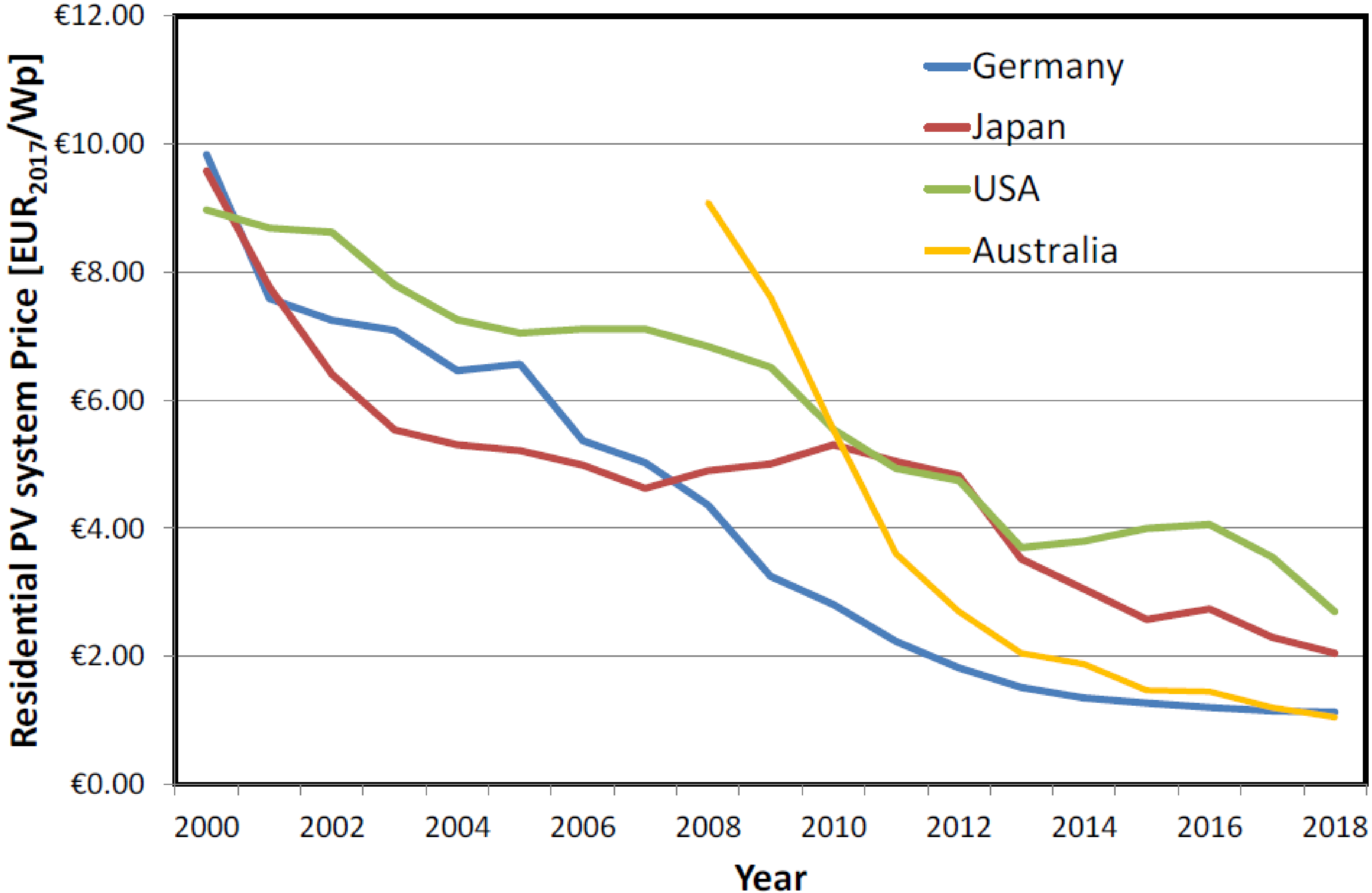
PV inverters on the market 2016

Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	up to 100 kWp	up to 98%	~ 42%	• 7 - 20 €-cents /Wp • Easy to replace
Central Inverters	More than 100 kWp	up to 98.5%	~ 54%	• ~ 6 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-95%	~ 1%	• ~ 33 €-cents /Wp • Ease-of-replacement concerns
DC / DC Converters (Power Optimizer)	Module Power Range	up to 98.8%	~ 3%	• ~ 9 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed • ~ 2 GWp installed in 2016



Izvor: Photovoltaics Report Fraunhofer Institute for Solar Energy Systems, 2017

PV system (small scale, residential) investment costs 2000 to 2018



Izvor: JRC EC PV Status Report 2018

LCOE of small scale PV systems 2016 in EU

Costs at 1000 kWh_e/kW_p (HR Osijek 1160, ST 1380, EGY Cairo 1770), 2% O&M of investements (capital), life-time of 20 years,

WACC (eng. weighted cost of capital/investements) = r (dicount rate)

Selling price of electricity in Croatia for households:
0,51 - 1.05 kn/kWh = 6.8 – 14,0 EURct/kWh

	Price [EUR/kWp]	LCOE Product	LCOE Capital			LCOE O&M	LCOE Total		
WACC		0 %	3 %	5 %	10 %		3 %	5 %	10 %
		[EURct/kWh]							
Hardware	910	4.55	1.39	2.40	5.17	1.82	7.76	8.77	11.54
Eng. and in-stallation	300	1.50	0.46	0.79	1.70	0.60	2.56	2.89	3.80
Other (fees, permits, insur-ances...)	140	0.70	0.21	0.37	0.79	0.28	1.19	1.35	1.77
Total	1 350	6.75	2.06	3.56	7.66	2.70	11.51	13.02	17.12

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where:

LCOE = average lifetime levelised electricity generation cost
I_t = investment expenditures in the year t
M_t = operational and maintenance expenditures in the year t
F_t = fuel expenditures in the year t, which is zero for PV electricity
E_t = electricity generation in the year t
r = discount rate
n = financial lifetime of the calculation

Izvor: JRC EC PV Status Report 2016

LCOE of small scale PV systems 2016 in EU

Costs at 1300 kWh_e/kW_p (HR Osijek 1160, ST 1380, EGY Cairo 1770), 2% O&M of investements (capital), life-time of 20 years,

WACC (eng. weighted cost of capital/investements) = r (dicount rate)

Selling price of electricity in Croatia for households:
0,51 - 1.05 kn/kWh = 6.8 – 14,0 EURct/kWh

	Price [EUR/kWp]	LCOE Product	LCOE Capital			LCOE O&M	LCOE Total		
WACC		0 %	3 %	5 %	10 %		3 %	5 %	10 %
		[EURct/kWh]							
Hardware	910	3.50	1.07	1.85	3.97	1.40	5.97	6.75	8.87
Eng. and installation	300	1.15	0.36	0.61	1.31	0.47	1.97	2.23	2.93
Other (fees, permits, insurances...)	140	0.54	0.16	0.28	0.61	0.22	0.92	1.04	1.37
Total	1 350	5.19	1.59	2.75	5.90	2.08	8.85	10.01	13.17

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where:

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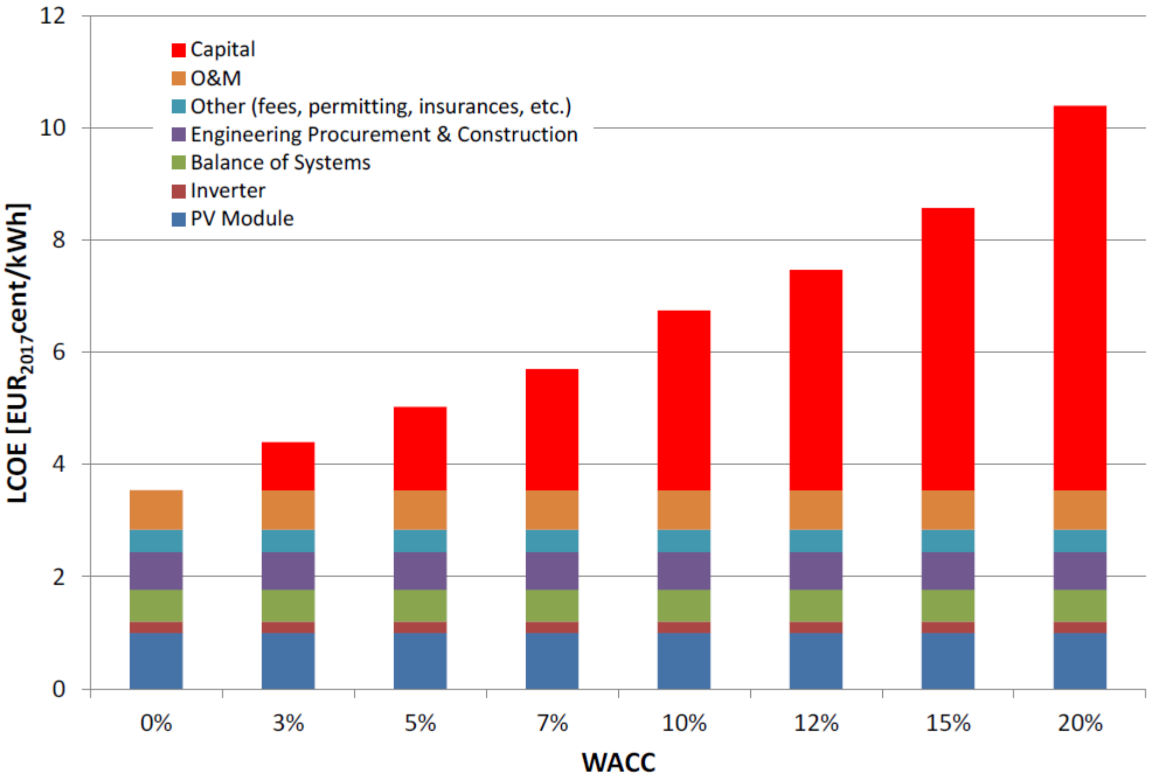
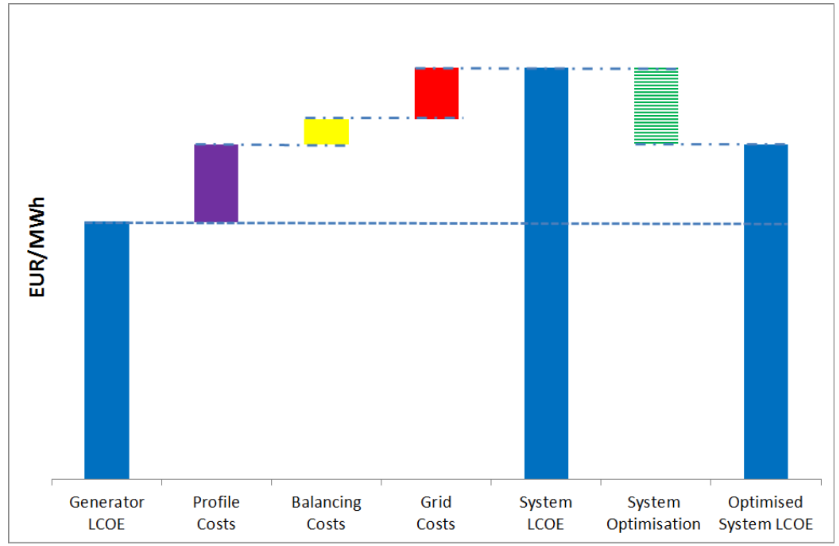
Izvor: JRC EC PV Status Report 2016

LCOE of PV systems 2018



LCOE od small scale PV system depending on WACC-discount rate 2018



Total system LCOE as sum of PV system LCOE, grid connection and balance costs

$$WACC = \frac{E}{V} * Re + \frac{D}{V} * Rd\ (1 - Tc)$$

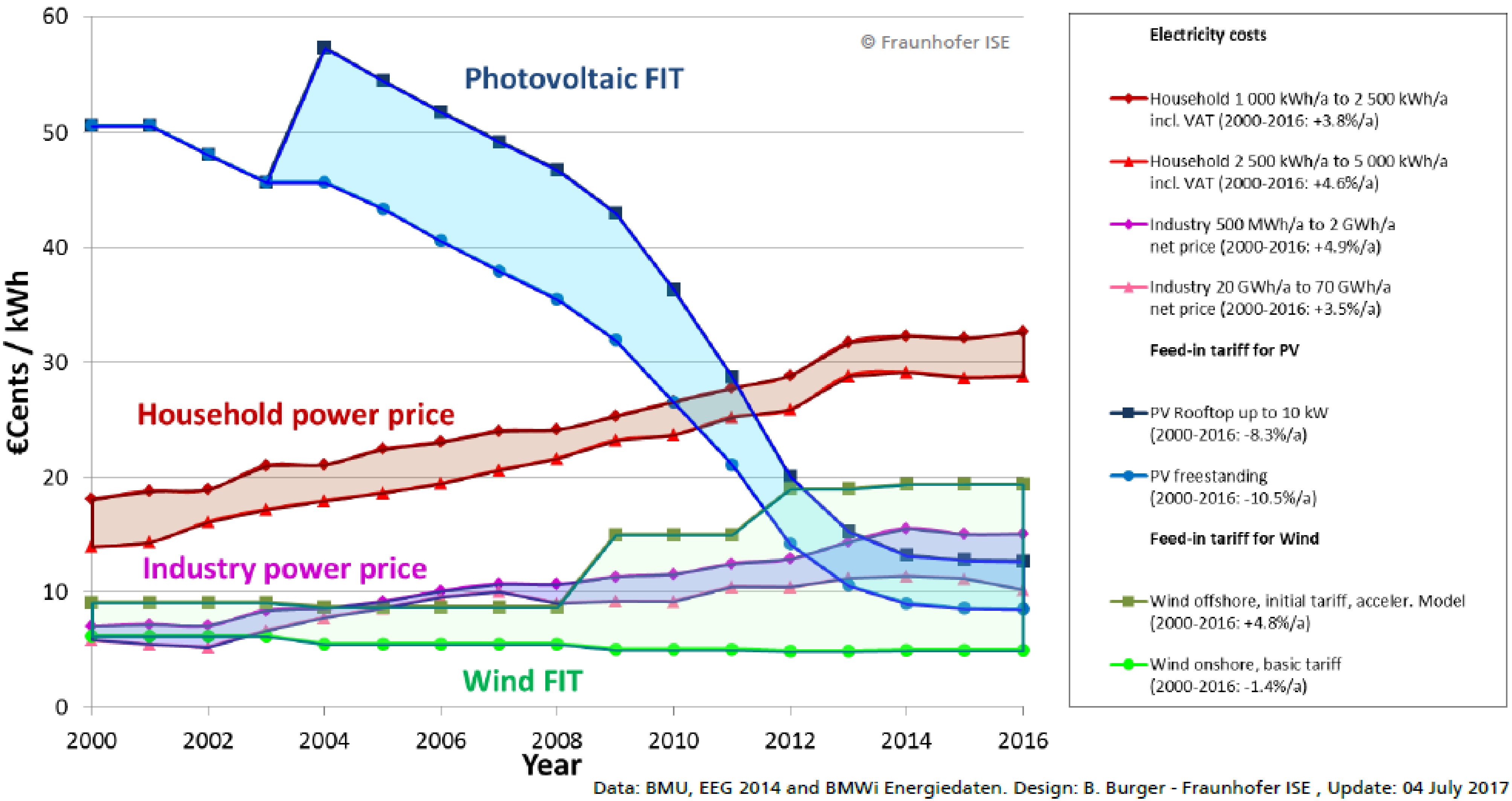
Where:

Re	= cost of equity
Rd	= cost of debt
E	= market value of the firm's equity
D	= market value of the firm's debt
V	= E + D
E/V	= percentage of financing that is equity
D/V	= percentage of financing that is debt
Tc	= corporate tax rate

WACC (eng. weighted cost of capital) - discount rate

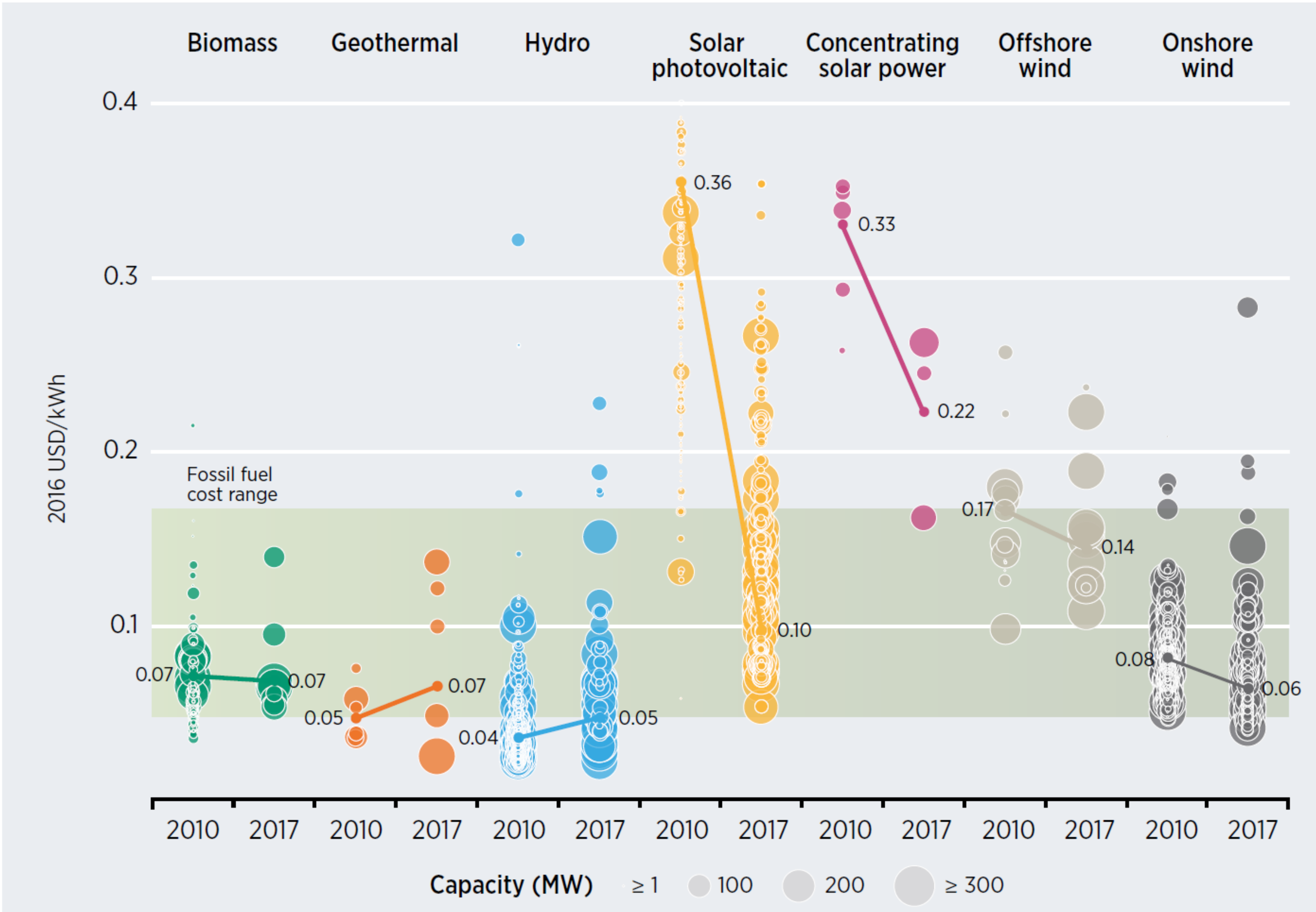
Izvor: JRC EC PV Status Report 2018

LCOE of PV system, feed-in tariffs and selling price of electricity: Germany



Source: Photovoltaics Report Fraunhofer Institute for Solar Energy Systems, 2017

Levelized costs of electricity from RES 2010 - 2017



Source: IRENA Renewable Power Generation Costs 2018

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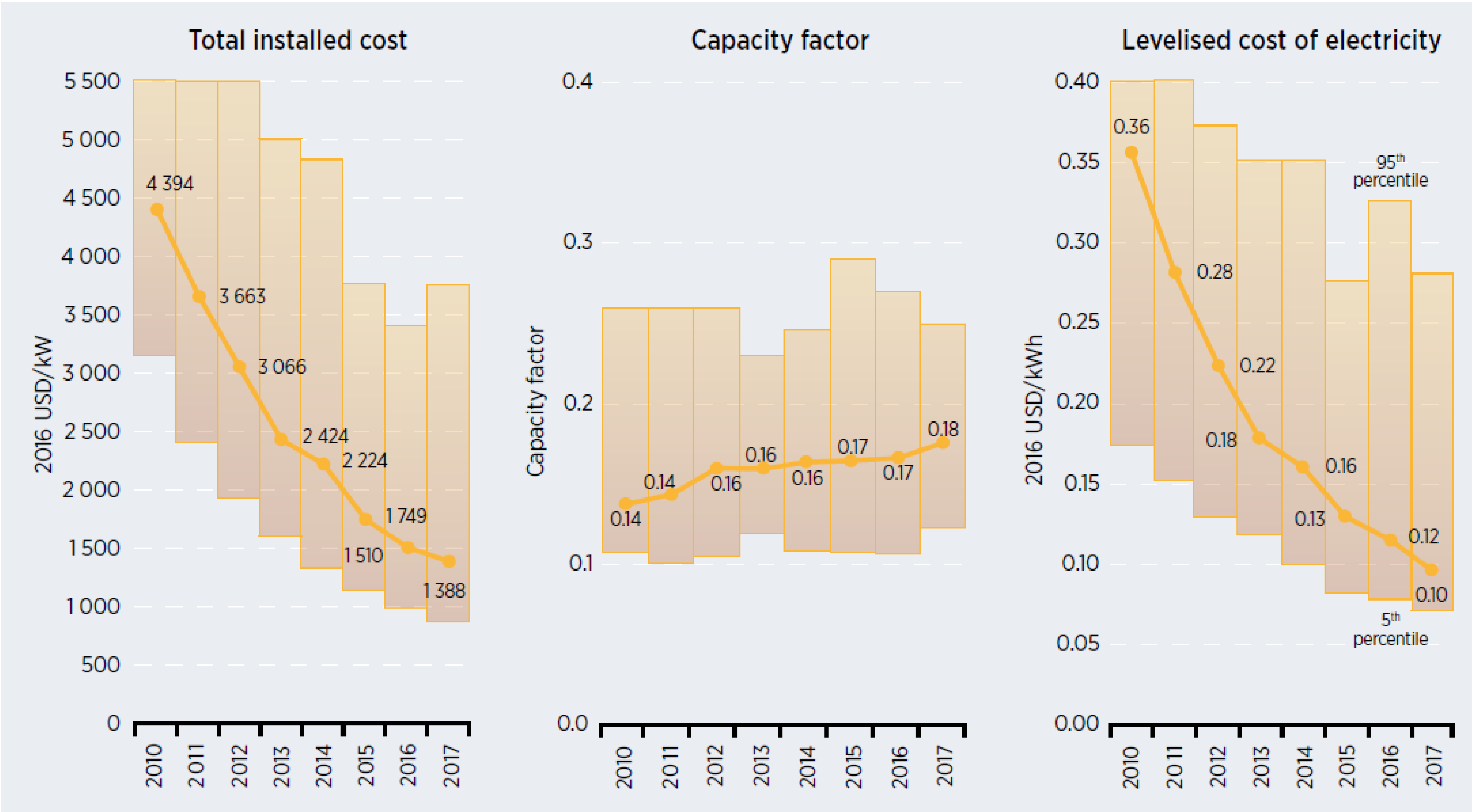
Investment costs, capacity factor and LCOE 2010 - 2017

PV systems



Source: IRENA Renewable Power Generation Costs 2018

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Economic characteristics – influence of RES on employment

Direct and indirect jobs in RES

	World	China	Brazil	United States	India	Japan	Bang-ladesh	European Union[i]		
								Germany	France	Rest of EU
	THOUSAND JOBS									
Solar PV	**3,095**	1,962	4	241.9	121	302	140	31.6	16	67
Liquid biofuels	**1,724**	51	783[c]	283.7[f]	35	3		22.8	22	48
Wind power	**1,155**	509	32.4	102.5	60.5	5	0.33	142.9	22	165
Solar heating/ cooling	**828**	690	43.4[d]	13	13.8	0.7		9.9	5.5	20
Solid biomass[a, g]	**723**	180		79.7[e]	58			45.4	50	238
Biogas	**333**	145		7	85		15	45	4.4	15
Hydropower (small-scale)[b]	**211**	95	11.5	9.3[l]	12		5	6.7	4	35
Geothermal energy[a]	**182**			35		2		17.3	37.5	62
CSP	**23**	11		5.2				0.7		3
Total	**8,305[h]**	**3,643**	**875.9**	**777.3**	**385**	**313**	**162.3**	**334[j]**	**162**	**667[k]**
Hydropower (large-scale)[b]	**1,519**	312	183	28	236	18		6	9	46
Total (including large-scale hydropower)	**9,824**	**3,955**	**1,058**	**806**	**621**	**330**	**162**	**340**	**171**	**714**

Note: Figures provided in the table are the result of a comprehensive review of primary (national entities such as ministries, statistical agencies, etc.) and secondary (regional and global studies) data sources and represent an ongoing effort to update and refine available knowledge. Totals may not add up due to rounding.

[a] Power and heat applications (in the case of geothermal energy in the EU, 110,000 jobs in heat pumps also are included). [b] Although 10 MW is often used as a threshold, definitions are inconsistent across countries. [c] About 238,300 jobs in sugar cane and 174,600 in ethanol processing in 2015; also includes rough estimate of 200,000 indirect jobs in equipment manufacturing in 2015, and 169,900 jobs in biodiesel in 2016. [d] Equipment manufacturing and installation jobs. [e] Based on employment factor calculations for biomass power and CHP. [f] Includes 222,500 jobs for ethanol and about 61,100 jobs for biodiesel in 2016. [g] Traditional biomass is not included. [h] The total for 'World' is calculated by adding the individual totals of the technologies, with 4,870 jobs in ocean energy, 16,400 jobs in renewable municipal and industrial waste and 14,500 jobs in miscellaneous which are not broken down by technology. [i] All EU data are from 2015, except for wind energy jobs data for Finland and Netherlands, which was available for 2016. The two major EU countries are represented individually. [j] Includes 7,700 jobs in publicly funded R&D and administration, not broken down by technology. [k] Includes 13,550 jobs in renewable municipal and industrial waste and 1,000 jobs in ocean energy. [l] Direct jobs only.

Source: REN21 Renewables 2017 Global Status Report

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Usage of PV systems

1. ***Independent source of energy (off-grid):***

   Satelites *(In space – no athmospheric losses).*

   Earth:

   a) industry: technology processes

   b) small consumers: rodd signs, calculators, hand watches, etc.

   c) electrification of ruraln areas (energy access) - alternative to distant grid connection (if possible)

2. ***Additional source of energy (on-grid, grid-connected)***

   a) like bateres: DC for small power supply, e.g.. el. equipment).

   b) grid connected (distributed generation – housholds/buikldings microgrids or centralized – PV plants): used to be non-profitable!!!

   Thanks to incetive schemes – on-grid PV systems or largest and with constant rise!

Comparison of developed and developing countries PV (dis)integration

PV in Europe

grid-connected PV systems → autonomous power supply → autonomous local grid

grid-connected PV systems	autonomous power supply	autonomous local grid
grid-support power quality improvement	PV-only PV + battery PV + CHP supply safety	parallel operation of different sources

Rural Electrification

grid-connected operation ← autonomous local grid ← autonomous power supply

grid-connected operation	autonomous local grid	autonomous power supply
after grid extension	parallel operation of different sources	PV + CHP PV + battery
low- or medium voltage grid	**local grid or village supply**	**individual power supply**

Centralized large scale PV power plants

o | https://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations

Name	Country	Location	Capacity MW_p	Generation GWh p.a.	Size km²	Year	Remarks
Tengger Desert Solar Park	China	37°33′00″N 105°03′14″E	1,547		43	2016	1,547 MW solar power was installed in Zhongwei, Ningxia by 2015.
Datong Solar Power Top Runner Base	China	40°04′25″N 113°08′12″E, 40°00′19″N 112°57′20″E	1,000			2016	1 GW Phase I completed in June 2016. Total capacity will be 3 GW in 3 phases.
Kurnool Ultra Mega Solar Park	India	15.681522°N 78.283749°E	1,000		24	2017	1000 MW operational as of December 2017
Longyangxia Dam Solar Park	China	36°10′54″N 100°34′41″E	850	824[14]	23	2015	320 MW Phase I Completed in December 2013, 530 MW phase II in 2015
Bhadla Solar Park	India	27°32′22.81″N 71°54′54.91″E	745		40	2017	The park is proposed to have a capacity of 2,255 MW with 1920 MW auctioned off in four phases till now[when?] and a tender for additional 750 MW floated in June 2017. A total of 2055 MW installed capacity is expected to be completed by December 2018.
Kamuthi Solar Power Project	India	9°21′16″N 78°23′4″E	648		10.1	2016	Completed on 21 September 2016
Pavagada Solar Park	India	14°05′49″N 77°16′13″E	600		53	2017	In Karnataka state, total planned capacity 2,000 MW
Solar Star (I and II)	United States	34°49′50″N 118°23′53″W	579		13	2015	579 MW_{AC} (747.3 MW_p) connected to the grid on June 19, 2015.[25] Consists of Solar Star I (318 MW_{AC} or 397.8 MW_{DC}) and Solar Star II: 279 MW_{AC} or 349.5 MW_{DC}
Topaz Solar Farm	United States	35°23′N 120°4′W	550	1,301	24.6[28]	2014	Gradually commissioned since February 2013, reached final capacity 550 MW in November 2014
Copper Mountain Solar Facility	United States	35°47′N 114°59′W	552			2015	Phase 1 completed in December 2010. Phase 2 completed in January 2013. Phase 3 completed in early 2015. Construction of 94 MW phase 4 completed in 2016.
Desert Sunlight Solar Farm	United States	33°49′33″N 115°24′08″W	550	1,287	16	2015	Phase I with 300 MW completed in 2013. Construction of phase II to final capacity of 550 MW completed in January 2015
Huanghe Hydropower Golmud Solar Park	China	36°24′00″N 95°07′30″E	500		23	2014	Phase I completed in October 2011, followed by Phase II and III. 60 MW phase IV under construction. Within a group of 1,000 MW of co-located plants
Mesquite Solar project	United States	33°20′N 112°55′W	400			2013	First phase of 150 MW in January 2013. Up to 700 MW when complete.
Quaid-e-Azam Solar Park	Pakistan	29°19′N 71°49′E	400	1000	26.3	2015	First phase of 100 MW completed in April 2015 and inaugurated in May 2015. Approved to be upgraded to 1,500 MW.
Yanchi Solar Park	China	38.1633714°N 106.7611986°E	380	525		2016	First phase of 380 MW completed in June 2016. Up to 2,000 MW when complete.
Charanka Solar Park	India	23°54′N 71°12′E	345		20	2012	Collection of 23 co-located power plants, of which the largest is 51 MW

Izvor: Wikipedija

Primjer: Agua Caliente Solar Project
First Solar, Inc.
290 MW
5.200.000 modula na zemlji (neintegrirano)
220.000 tCO_2-ekv./god (10.000 automobila)
400 radnih mjesta na gradilištu

Izvor: www.firstsolar.com/en/Projects/Agua-Caliente-Solar-Project

Distributed Renewable Energy Systems (DRE) for developing countries

- ***Distributed renewable energy (DRE) systems – power, cooking, heating and cooling systems*** *that generate and distribute services independently or connected to centralised system, in both urban and rural areas of the developing world – already provide energy services to millions of people, and numbers continue to increase annually.*
- *DRE systems can serve as a complement to centralised energy generation systems, or as a substitute. They offer an unprecedented opportunity to accelerate the transition to modern energy services in remote and rural areas,*
- *while also offering co-benefits: improved health (through the displacement of indoor air pollution), a contributons to climate change mitigation, as well as positive effects on income growth, women's empowerment and distributive equity.*
- *They can provide affordable lighting, enhance communications and facilitate greater quality and availability of education.*
- *DRE systems, as well as the hybridisation of existing microgrids, may also reduce dependence on fossil fuel imports.*

Source: REN21 Renewables Global Status Report, 2016

Distributed Renewable Energy Systems (DRE) for developing countries

ENERGY SERVICE	INCOME-GENERATING VALUE	RENEWABLE ENERGY TECHNOLOGIES
Irrigation	Better crop yields, higher-value crops, greater reliability of irrigation systems, enabling of crop growth during periods when market prices are higher	Wind, solar PV, biomass, micro-hydro
Illumination	Reading, extension of operating hours	Wind, solar PV, biomass, micro-hydro, geothermal
Grinding, milling, husking	Creation of value-added products from raw agricultural commodities	Wind, solar PV, biomass, micro-hydro
Drying, smoking (preserving with process heat)	Creation of value-added products, preservation of products that enables sale in higher-value markets	Biomass, solar heat, geothermal
Expelling	Production of refined oil from seeds	Biomass, solar heat
Transport	Reaching new markets	Biomass (biodiesel)
TV, radio, computer, Internet, telephone	Support of entertainment businesses, education, access to market news, co-ordination with suppliers and distributors	Wind, solar PV, biomass, micro-hydro, geothermal
Battery charging	Wide range of services for end-users (e.g., phone charging business)	Wind, solar PV, biomass, micro-hydro, geothermal
Refrigeration	Selling cooled products, increasing the durability of products	Wind, solar PV, biomass, micro-hydro

Source: REN21 Renewables Global Status Report, 2016

Rural RES microgrid (DRE) concept for developing countries

- *Microgrids – distributed systems (DRE) of local energy generation, transmission, and use – are today technologically and operationally ready to provide communities with electricity services, particularly in rural and peri-urban areas of (less) developed countries.*
- *Over 1.2 billion people do not have access to electricity, which includes over 550 million people in Africa and 300 million people in India alone.*
- *The traditional approach to serve these communities is to extend the central grid - this approach is inefficient due to a combination of capital scarcity, insufficient energy service, reduced grid reliability, extended building times and construction challenges to connect remote areas.*
- *Adequately financed and operated microgrids based on renewable and appropriate resources can overcome many of the challenges faced by traditional lighting or electrification strategies.*

Source: UN Foundation Microgrids for Rural Electrification, 2013

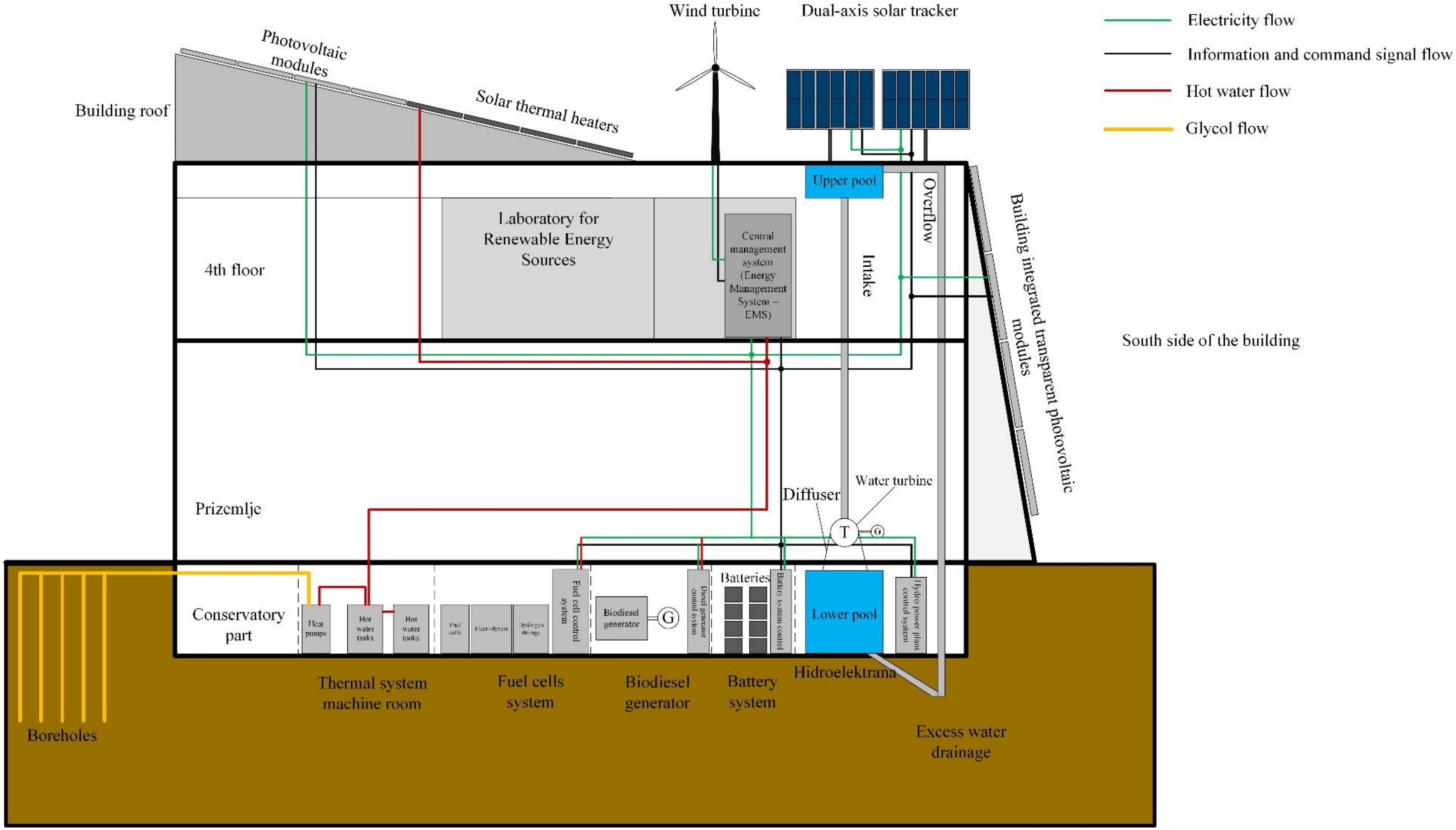
Rural RES microgrid (DRE) concept for developing countries

- **Types of microgids (HOMER Energy):**

1. Large grid-connected microgrids (e.g. military bases or campuses, e.g. FERIT Scientific Research Center, ZICER)
2. Small grid-connected microgrids (e.g. single gensets to back up unreliable central grids)
3. Large remote microgrids (e.g. island utilities)
4. Small rural remote microgrids (e.g. villages, irrigation, etc.)

Source: UN Foundation Microgrids for Rural Electrification, 2013

Microgrid for new FERIT scientific-reserch Institute ZICER buiding in University Campus (after 2025) – EU funding

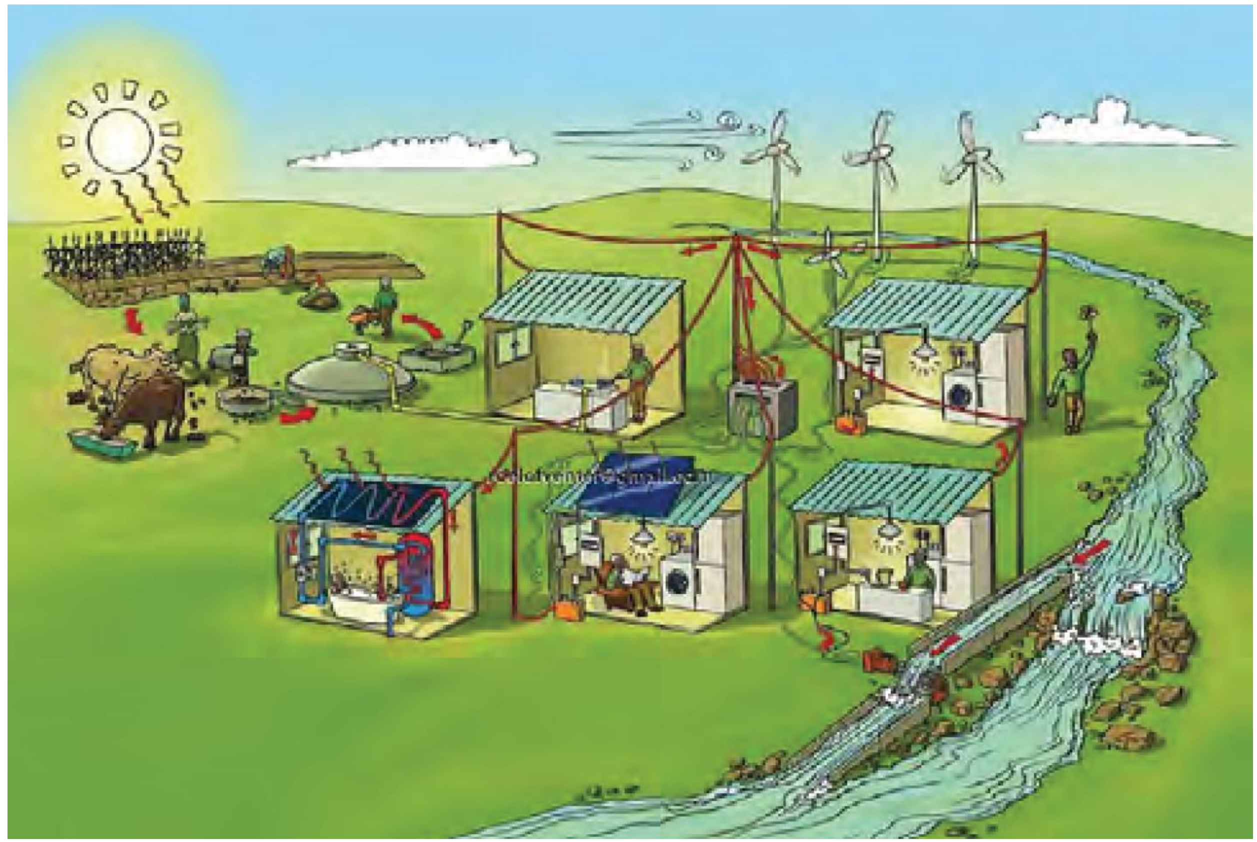


Rural RES microgrid (DRE) concept for developing countries

Rural microgrids ***tend to transmit power*** *over low-voltage* ***distribution networks from interconnected*** *local RES generation* ***such as:***

- *photovoltaics,*
- *micro-hydro,*
- *biomass gasifiers*
- *small wind power*
- *storage (batteries, water...)*
- *back-up generators,* ***etc.***

to a relatively small number of customers.



Source: UN Foundation Microgrids for Rural Electrification, 2013

Renewable microgrids – off-line, flexibility in application

aimed to provide energy access for local population with no acess to power grid.

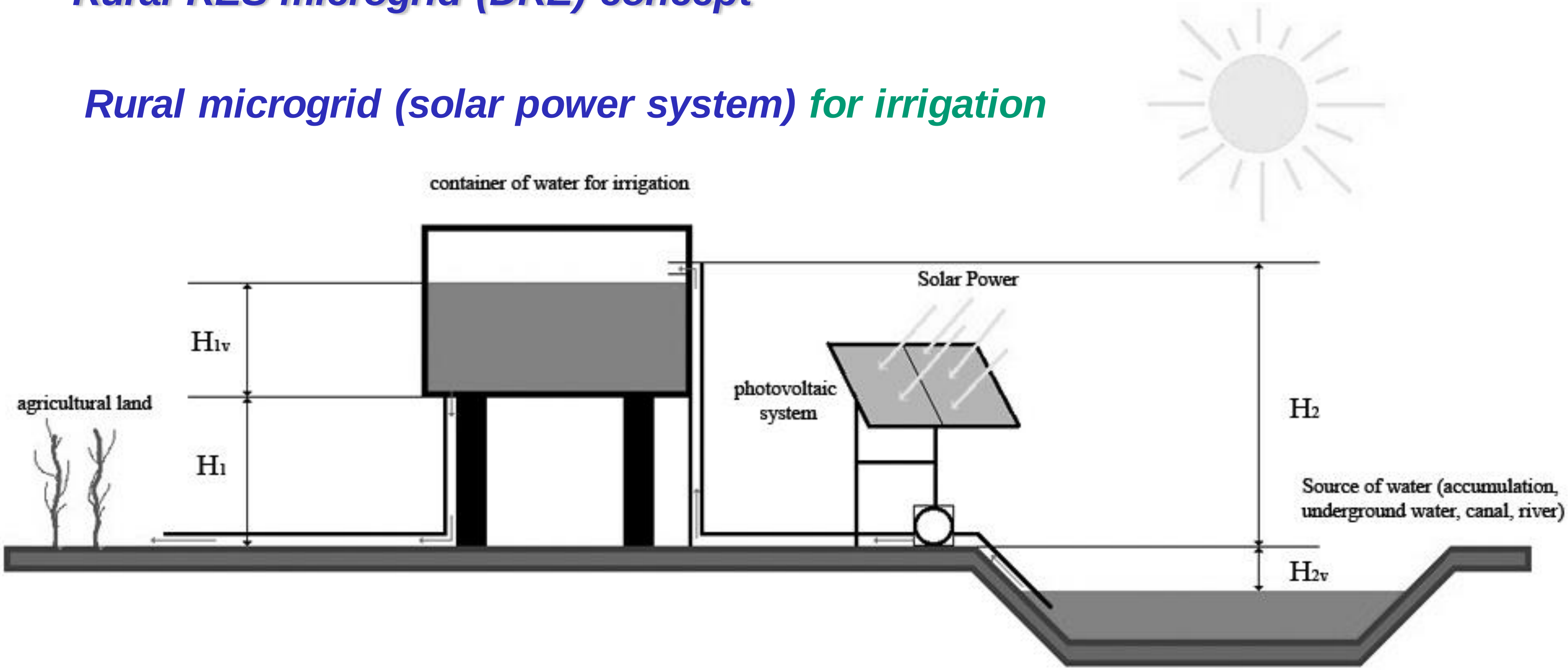
Example:

- *Bancoumanan village, Mali, Africa*
- *Created: 2015 | Village energy committee: 11 members 33 kW solar PV and 68 kW diesel mini-grid*
- *international partners and local community have collaborated on the installation of a hybrid micro-grid providing energy for local population (190 end-users).*
- *Local technicians were trained for operation and maintenance tasks, and the system is managed by a local company. Combining solar energy and diesel, the village of Bancoumanan illustrates the flexibility of community-based renewable energy projects.*

Source: REN21 Renewables Global Status Report, 2016

Rural RES microgrid (DRE) concept

Rural microgrid (solar power system) for irrigation



Source: D. Topić, D. Šljivac, M. Stojkov, 2013

PV SYSTEMS
Modelling, measurement, design

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