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

Photovoltaic systems – theory and practice

Marek Lipiński

Kraków 2020

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

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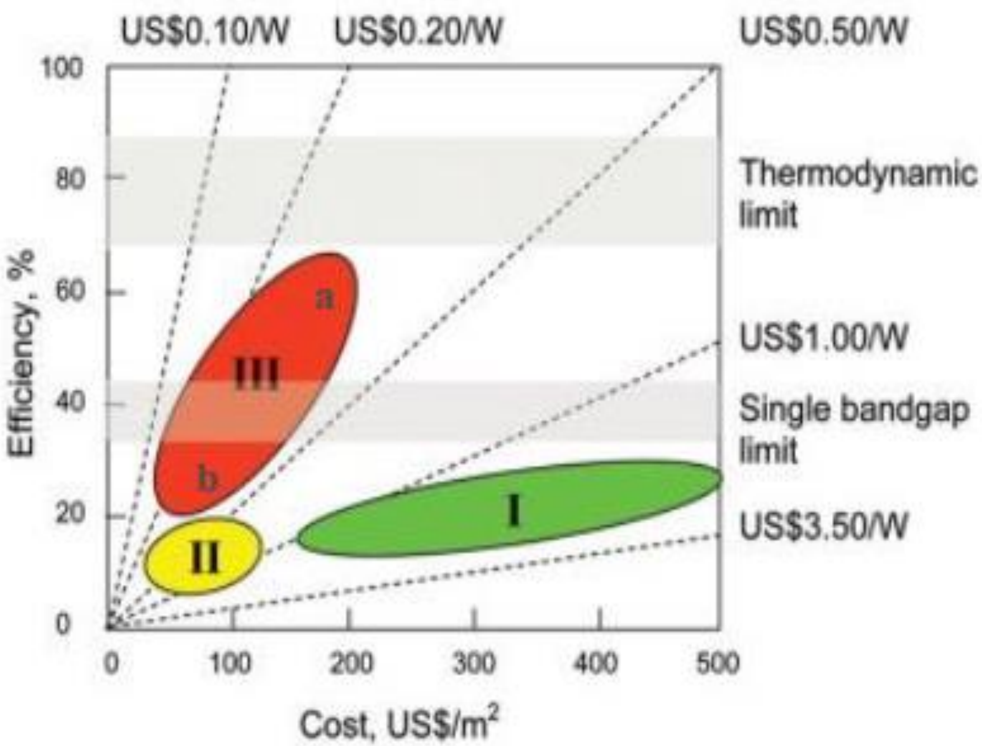
Program Operacyjny Wiedza Edukacja Rozwój 2014-2020, Działanie 3.2 Studia doktoranckie

Three generations of solar cells



Region IIIa: very high –efficiency devices that require novel mechanisms of device operation

Region IIIb: perovskite, DSSC, organic PV with moderate efficiency and very low cost

Average exchange conversion factor for the year 2012: 1US$=0.76 €.

Region IIIb – Emerging PV

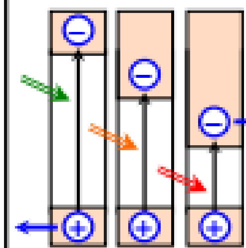
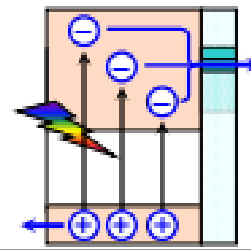
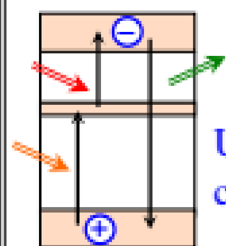
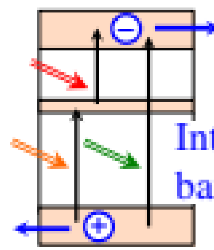
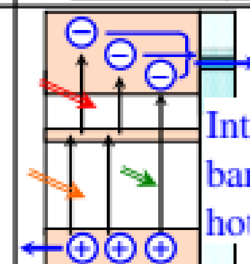
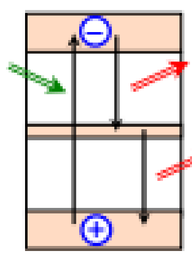
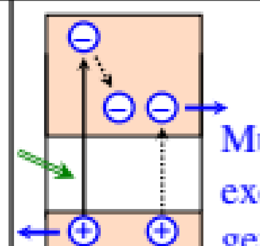
Figure 3: Cost-efficiency analysis for 1st, 2nd and 3rd generation PV technologies (I, II, and III, respectively)

[Adapted from M. Green "Third Generation Photovoltaics", Springer-Verlag, 2003]

Techview: Emerging Photovoltaics (e-PV) 2013

European Business and Technology Centre

Third generataion solar cell - very high efficiency (Region IIIa)

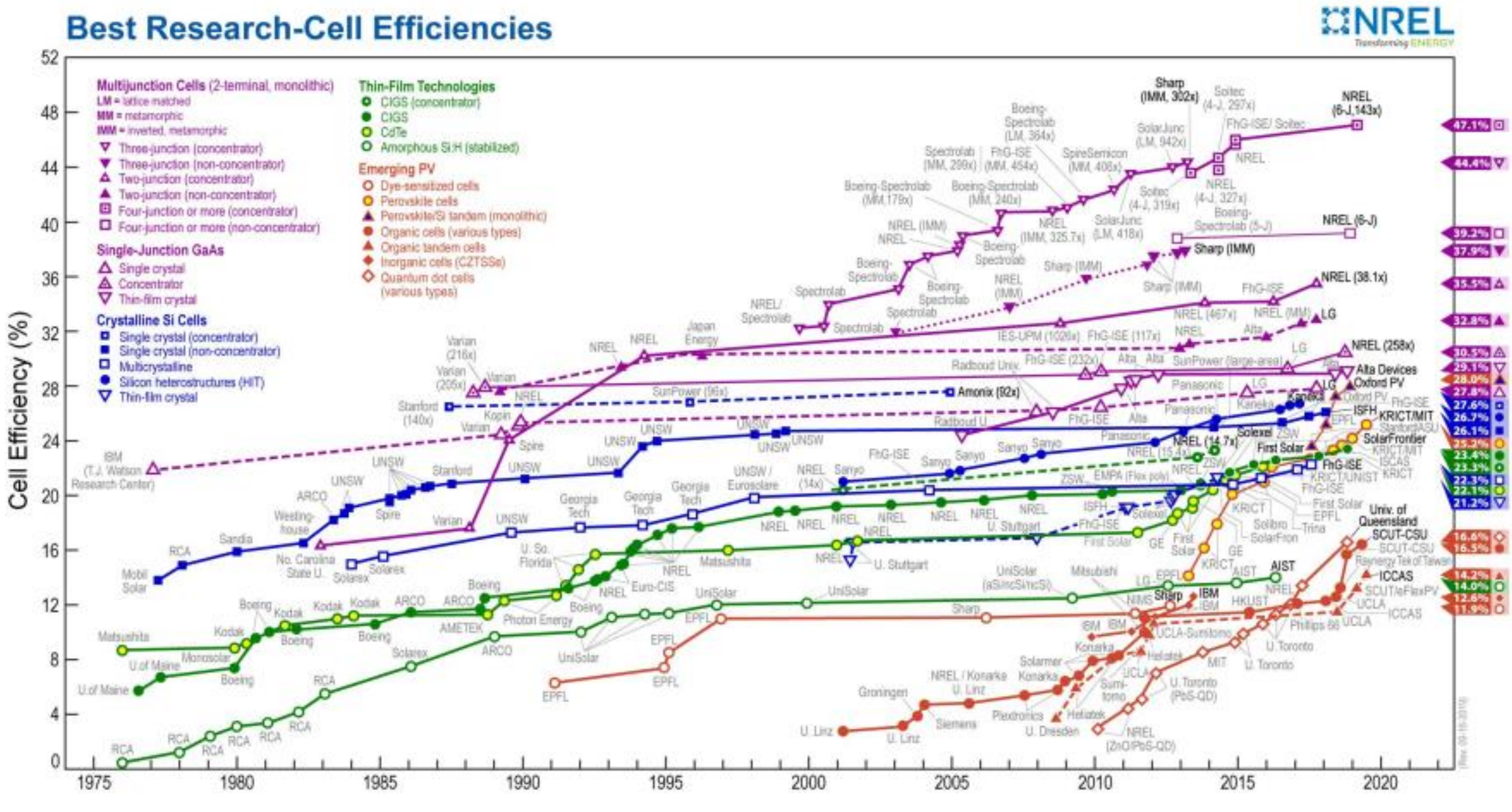
	Spectral conversion	Spectral splitting	Using excess energy
1 photon ↓ 1 electron		 Multi-junction	 Hot-carrier
2 particles (low energy) ↓ 1 particle (high energy)	 Up-conversion	 Intermediate-band	 Intermediate-band-assisted hot-carrier
1 particle (high energy) ↓ 2 particles (low energy)	 Down-conversion		 Multiple-exciton generation

Types of solar cells to exceed the Shockley–Quiseer limit.

Only multijunctions solar cells reached very high effciency!!

Y. Takeda and T. Motohiro , Prog. Photovolt: Res. Appl. 2013; 21:1308–1318

Best research cell efficiensies



Efficiency limits third generation solar cells

Limit	η (max. concentration) %	η (AM1.5) %
Lansberg	93.3	73.7
∞- cells	86.8	69.0
2 - cells	55.7	42.5
3 - cells	63.8	49.3
Hot carrier	85.0	65.0
IBSC	63.2	
MEG		
Down converter DC		36.7 (Si)
Up-converter		48 (Si)
Single junction Si	40.8	31.0

$\mathbf{max.\ concentration\ f_{max} = (d_{zs}/r_s)^2 = 46\ 198\ (2)}$ **for vaccum**
d_{zs} the distance from the Earth to the Sun, and r_s the radius of the Sun.

GREEN M.A., *Third generation photovoltaics: advanced solar electricity conversion*, Springer-Verlag, Berlin Heidelberg, 2006

Multijunction solar cells

	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	PCE [%]	S [cm^2]	suns		year
4-junctions concentration				**46,0**	0,052	**508**	Fraunhofer ISE, Soitec	10. 2014
2-junctions				35,5	0,1	38,1	NREL	10.2017
4-junctions without concenration	8,457	5549	83,5	39,2	0,247	1	NREL	11.2018
2 junction without concenration	14,56	2570	87,7	32,8	1	1	LG Electronics	09.2017
1-junction GaAs, concentration				30,5	0,1004	258	NREL	10.2018

https://spectrum.ieee.org/static/interactive-record-breaking-pv-cells

Multijunction solar cells- high concentration

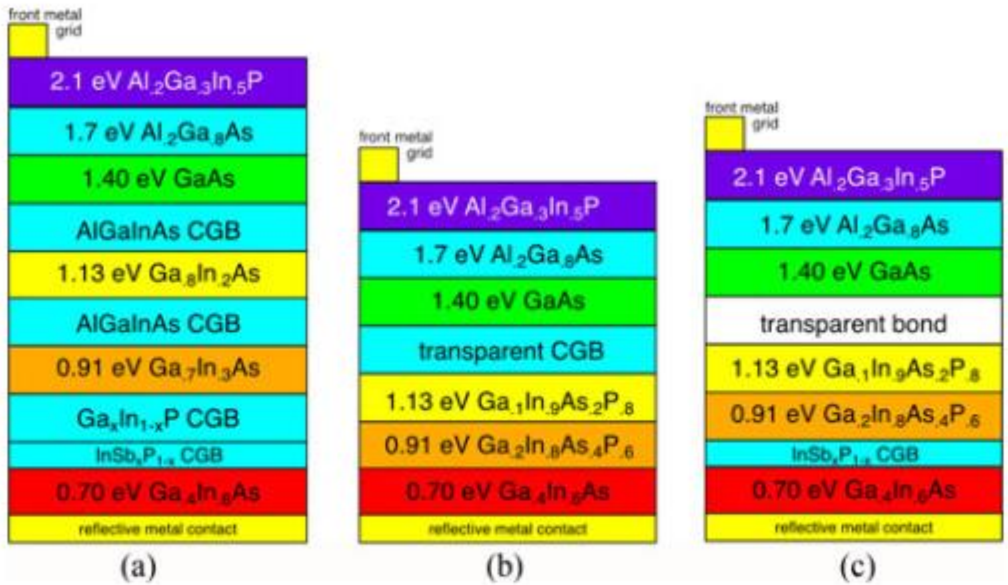


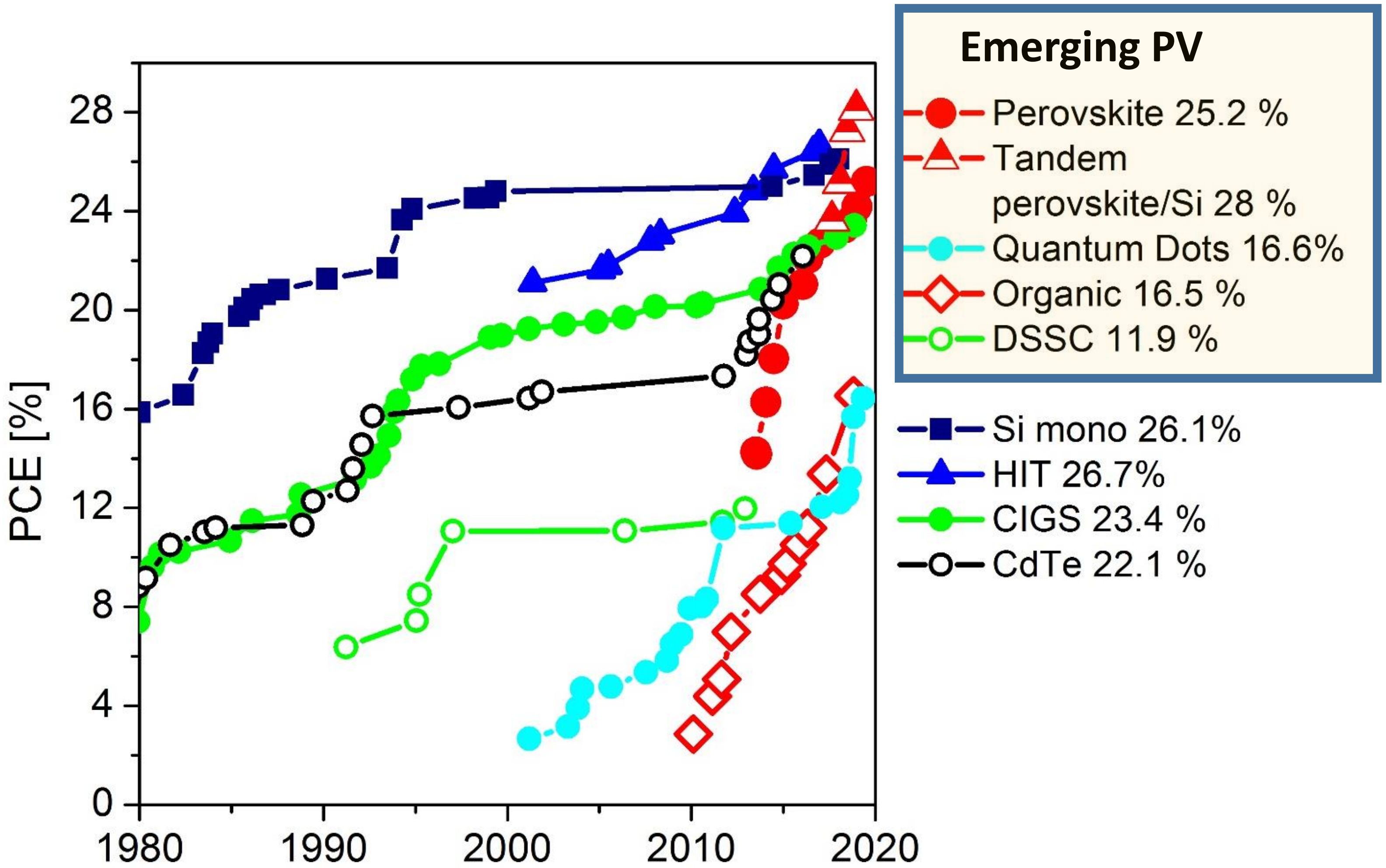
Fig. 1. Schematic for 6J design strategies. The second junction in any of these designs could also be composed of the 1.7-eV quaternary Ga.7 In.3 As.3 P.7 .

HIGH-CONCENTRATION photovoltaics (HCPV) in high direct normal irradiance regions have the potential to become the lowest cost utility-scale solar energy technology. Because of the lower capital investments required to manufacture and install HCPV systems compared with traditional flat-plate photovoltaics (PV), this technology also has the potential to rapidly scale up.

Efficiency 47.1 % was reached.

John F. Geisz et al., Building a Six-Junction Inverted Metamorphic Concentrator Solar Cell , IEEE JOURNAL OF PHOTOVOLTAICS, 8(2) (2018) 626-632.

Emerging PV



PCE [%]
0
4
8
12
16
20
24
28
1980
1990
2000
2010
2020
Emerging PV
Perovskite 25.2 %
Tandem perovskite/Si 28 %
Quantum Dots 16.6%
Organic 16.5 %
DSSC 11.9 %
Si mono 26.1%
HIT 26.7%
CIGS 23.4 %
CdTe 22.1 %

QD solar cells

nature energy

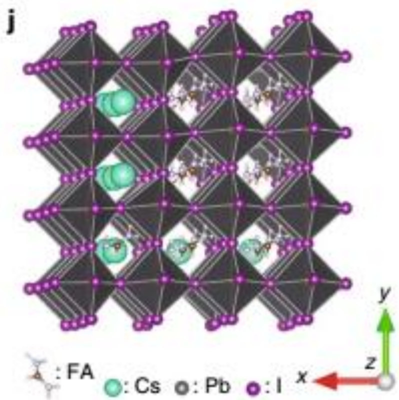
ARTICLES

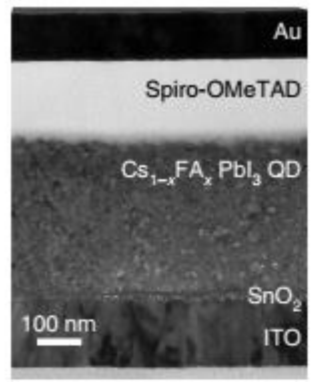
https://doi.org/10.1038/s41560-019-0535-7

Ligand-assisted cation-exchange engineering for high-efficiency colloidal $Cs_{1-x}FA_xPbI_3$ quantum dot solar cells with reduced phase segregation

Mengmeng Hao[1], Yang Bai[1*], Stefan Zeiske[2], Long Ren[3], Junxian Liu[4], Yongbo Yuan[5], Nasim Zarrabi[2], Ningyan Cheng[3], Mehri Ghasemi[1], Peng Chen[1], Miaoqiang Lyu[1], Dongxu He[1], Jung-Ho Yun[1], Yi Du[3], Yun Wang[4], Shanshan Ding[1], Ardalan Armin[2], Paul Meredith[2], Gang Liu[6] Hui-Ming Cheng[6,8,9] and Lianzhou Wang[1*]

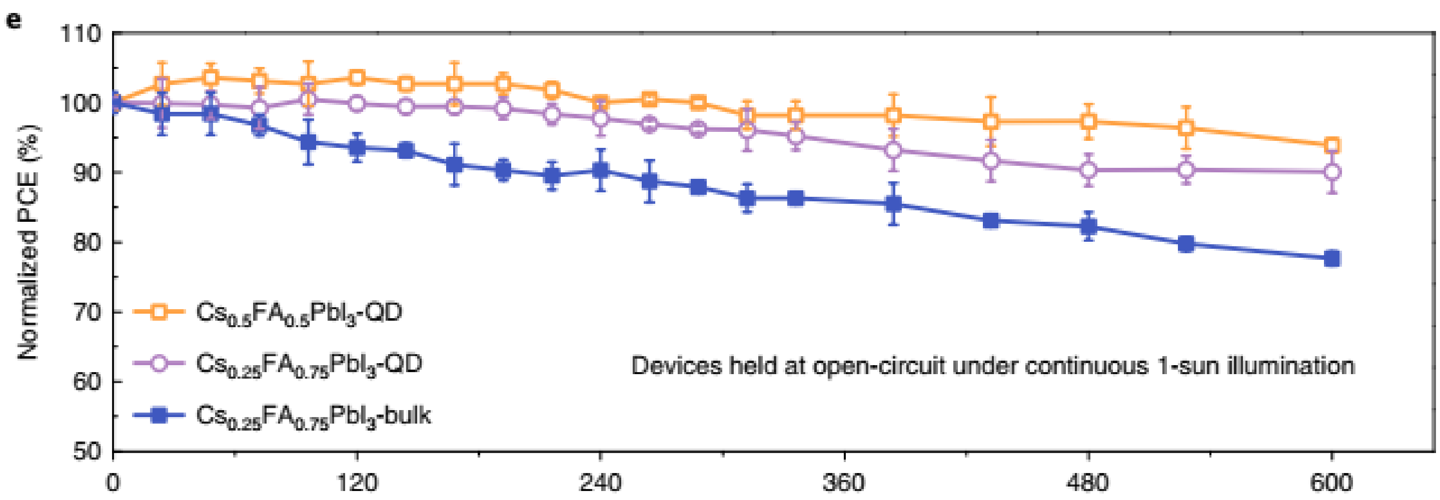
j





The best $Cs_{0.5}FA_{0.5}PbI_3$
PCE = QDS 16.6 % (certified record)

e

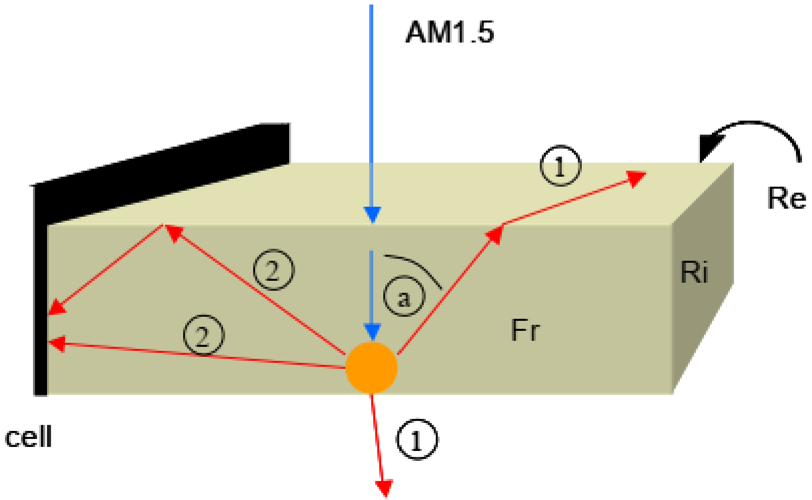


94 % of the original PCE under continuous 1-sun illumination for 600 h

Luminescent Solar Concentrators (LSC's)

THE LUMINESCENT CONCENTRATOR: A BRIGHT IDEA FOR SPECTRUM CONVERSION?

L.H. Slooff,[1] R. Kinderman,[1] A. R. Burgers,[1] J.A.M. van Roosmalen,[1] A. Büchtemann[2], R. Danz,[2] M. Schleusener,[2]
A. J. Chatten,[3] D. Farrell,[3] K. W. J. Barnham[3]
[1] Energy research Centre of the Netherlands, P.O.Box 1, 1755 ZG Petten, The Netherlands, email: slooff@ecn.nl
[2] Fraunhofer-Institute for Applied Polymer Research, Geiselbergstr.69, D-14476 Golm, Germany
[3] Physics Department, Imperial College London, SW7 2BW, U.K.



Presented at the 20th European Photovoltaic Solar Energy Conference and Exhibition,
Barcelona, Spain, 6-10 June 2005

The LSC has an important advantage over geometric concentrators. Both direct and diffuse sunlight is collected, making solar tracking unnecessary.

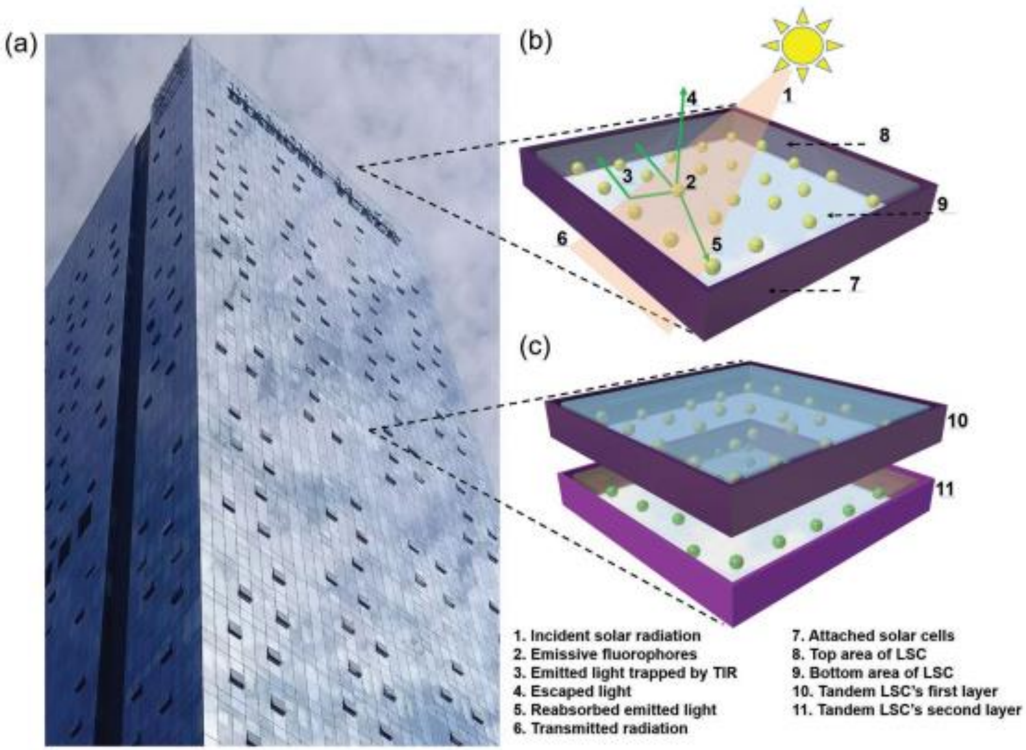
In an LSC **fluorescent dyes** or **Qdots** absorb and re-emit light isotropically, and due to total internal reflection the reemitted light is highly concentrated on the small edges of the collector.

Eco-Friendly Colloidal Quantum Dot-Based Luminescent Solar Concentrators

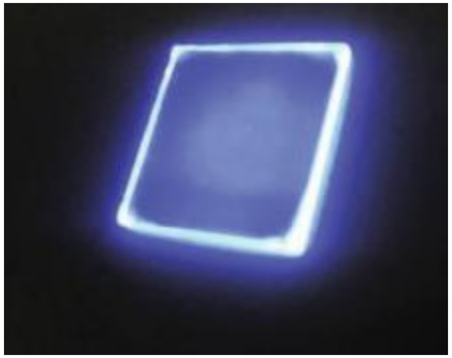
Yimin You, Xin Tong, Wenhao Wang, Jiachen Sun, Peng Yu, Haining Ji, Xiaobin Niu, and Zhiming M. Wang**

Adv. Sci. 2019, 6, 1801967

DOI: 10.1002/advs.201801967



LSC for building integrated photovoltaic (PV) systems



N-doped carbon QDots based LSC under UV illumination

Eco-Friendly Colloidal Quantum Dot-Based Luminescent Solar Concentrators

Yimin You, Xin Tong, Wenhao Wang, Jiachen Sun, Peng Yu, Haining Ji, Xiaobin Niu, and Zhiming M. Wang**

Table 1. Comparison of the parameters of various eco-friendly CQD/nanocrystal-based LSCs.

Fluorophore	QY [%]	Absorption range [nm]	Emission range [nm]	Stokes shift	LSC size [cm^3]	Optical efficiency [%]	PCE [%]
N-doped carbon QDs	–	300–550	400–650	–	2.5 × 1.6 × 0.1	4.75	3.94
N-doped carbon QDs	–	UV to 420	400–500	–	1.8 × 1.8 × 0.11	5.02	4.97
Carbon QDs[a]	40	UV to 550	450–600	–	10 × 10 × 0.2	1.1	–
Si QDs	55	UV to 600	600–1000	400 meV	12 × 12 × 0.26	2.85	–
InP/ZnO QDs	–	UV to 550	550–700	–	9 × 1.5 × 0.3	1.45	–
$CuInS_2$/ZnS QDs	91	UV to 830	620–1240	> 550 meV	10 × 10 × –	8.1	2.94
$CuInS_2$/ZnS QDs	56	UV to 500	450–750	> 150 nm	2.2 × 2.2 × 0.3	26.5	8.71
$CuInS_2$/ZnS QDs	65	UV to 500	450–700	–	2 × 2 × 0.8	–	4.20
Zn and Al co-doped $CuInS_2$ QDs	–	UV to 800	600–900	–	1.8 × 1.8 × 0.11	6.97	3.18
$CuInSe_2$/ZnS QDs[a]	72	UV to 800	650–1000	–	15.2 × 15.2 × 0.16	6.4	3.1
$CuInSe_xS_{2-x}$ QDs	40	UV to 900	800–1250	530 meV	12 × 12 × 0.3	3.2	–
$AgInS_2$/ZnS QDs	60	UV to 800	500–1240	–	5 × 5 × 3	3.94	–
GSH-AuNCs	–	UV to 500	500–800	–	2 × 2 × 0.2	–	–
Zn-AuNCs	53	UV to 500	350–550	–	2 × 2 × 0.2	–	–

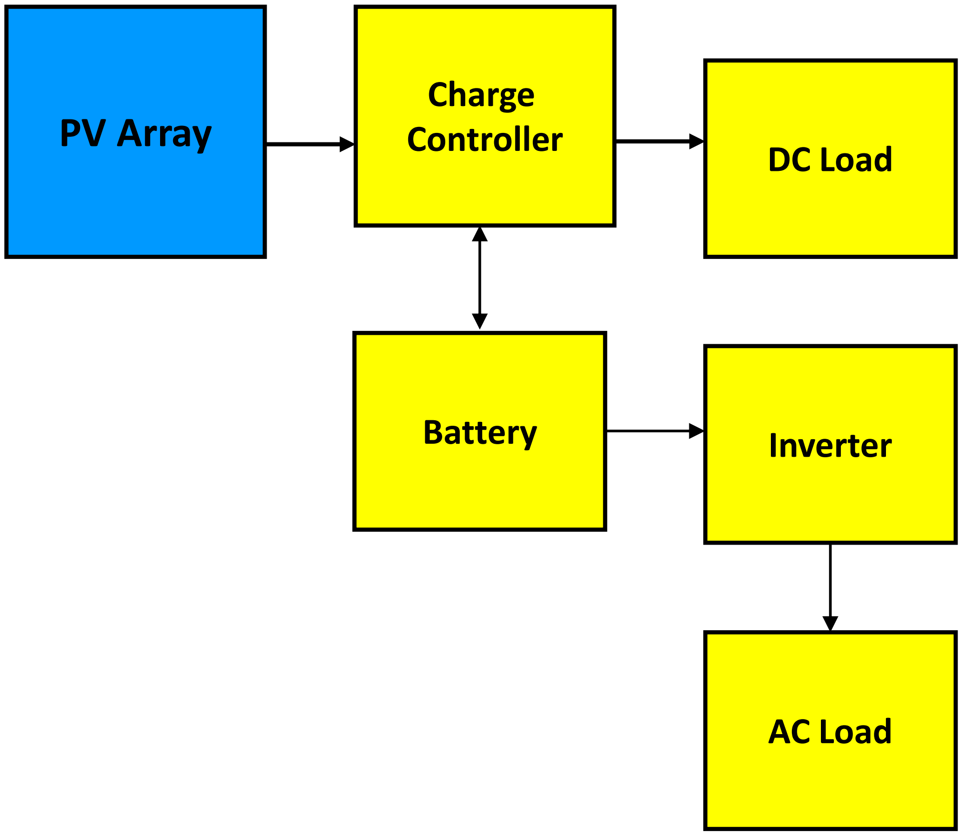
[a] Tandem LSC.

Further optimization is needed.
Application: net-zero power consumption of future urban buildings.

Photovoltaic Power System Types

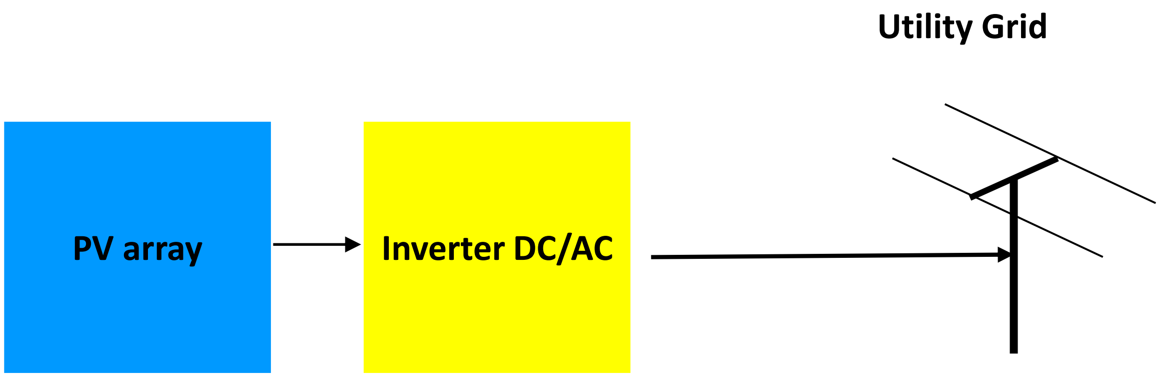
- Stand-alone
- Grid-connected
- Hybrid

Stand-alone

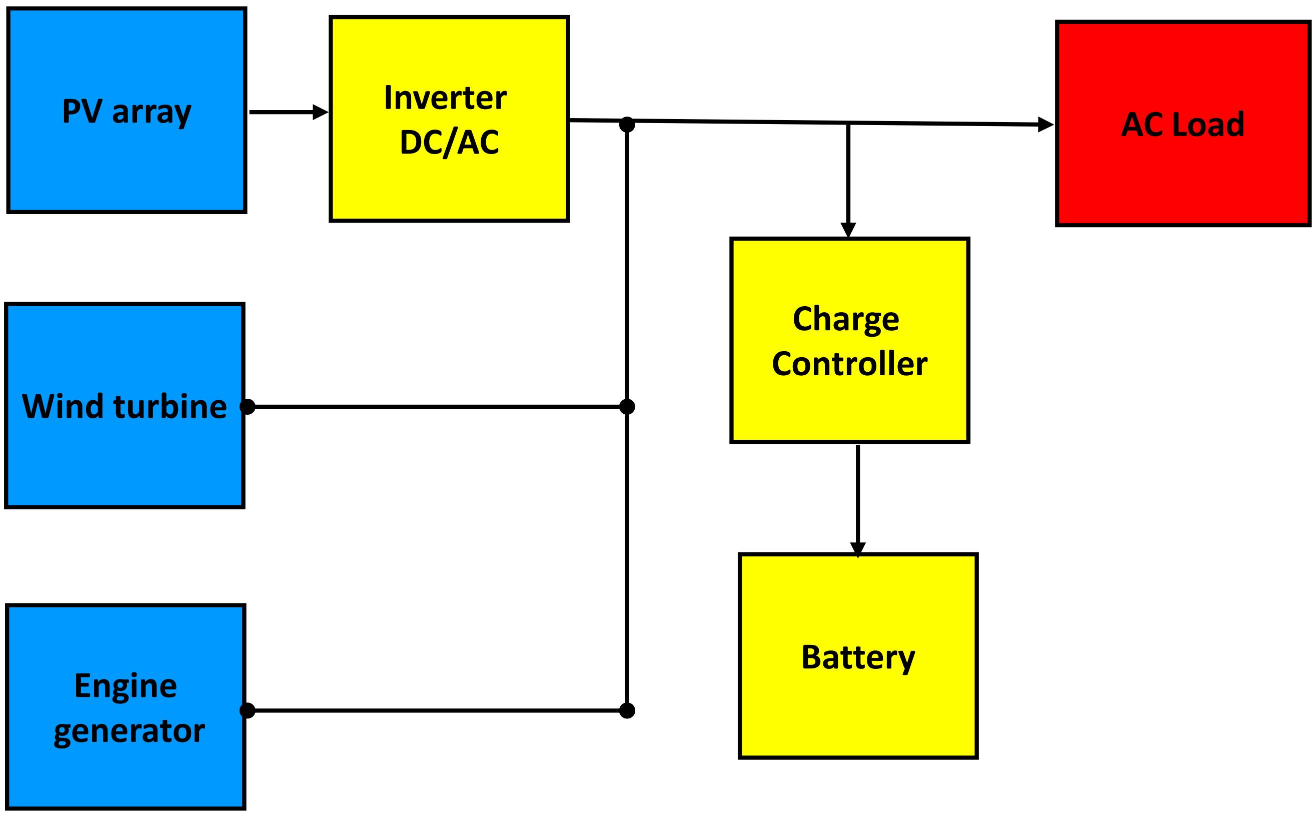


Scheme of stand-alone (off grid) PV system

Grid-connected without battery



Hybride system (PV/Auxiliary Generators)



Scheme of Hybride System (PV/Auxiliary Generators)

Photovoltaic Power System Types

Stand-alone system (autonomus) – off grid

Grid conected

Free standing system

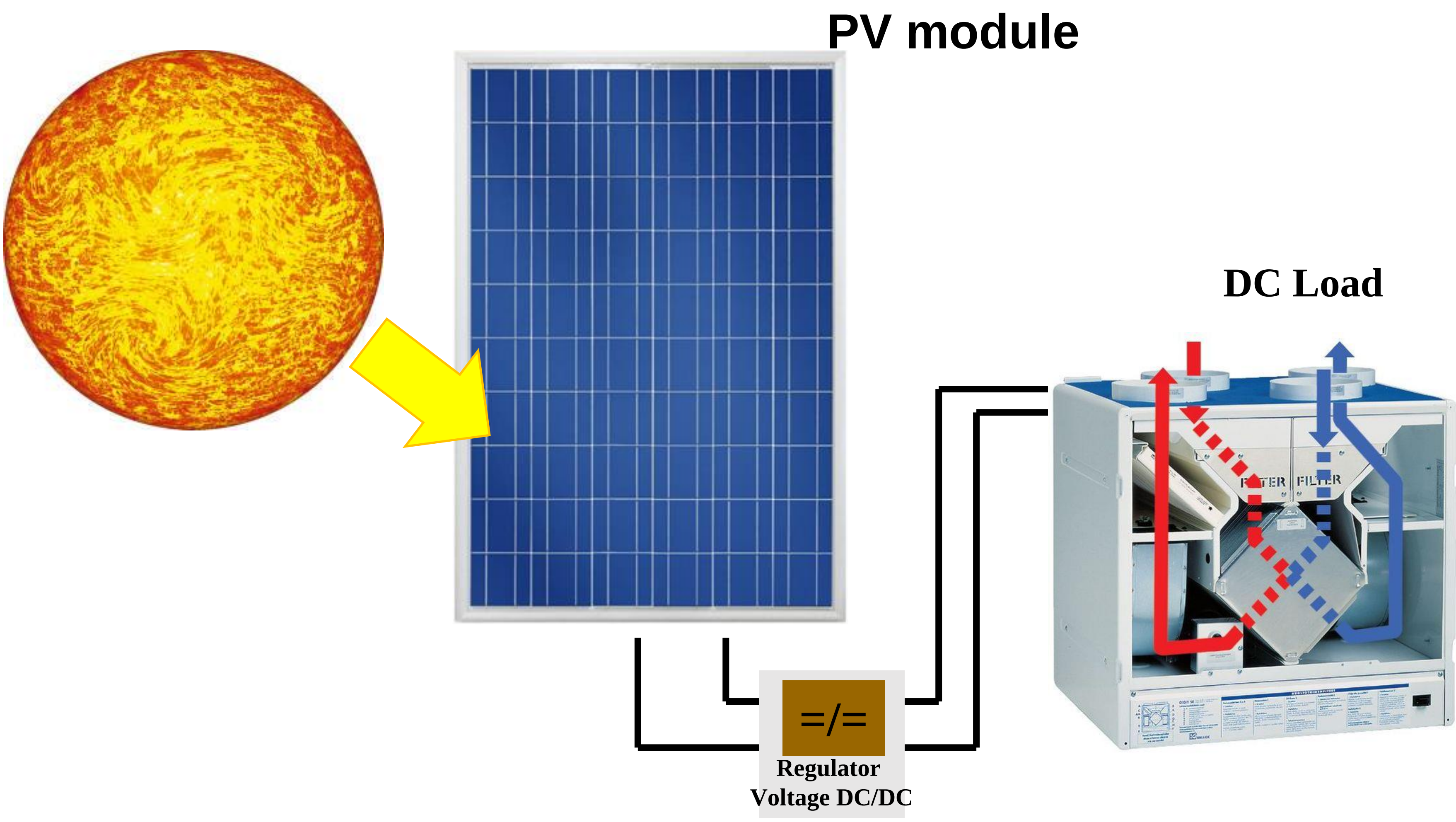
Roof system

integrated with the building BIPS

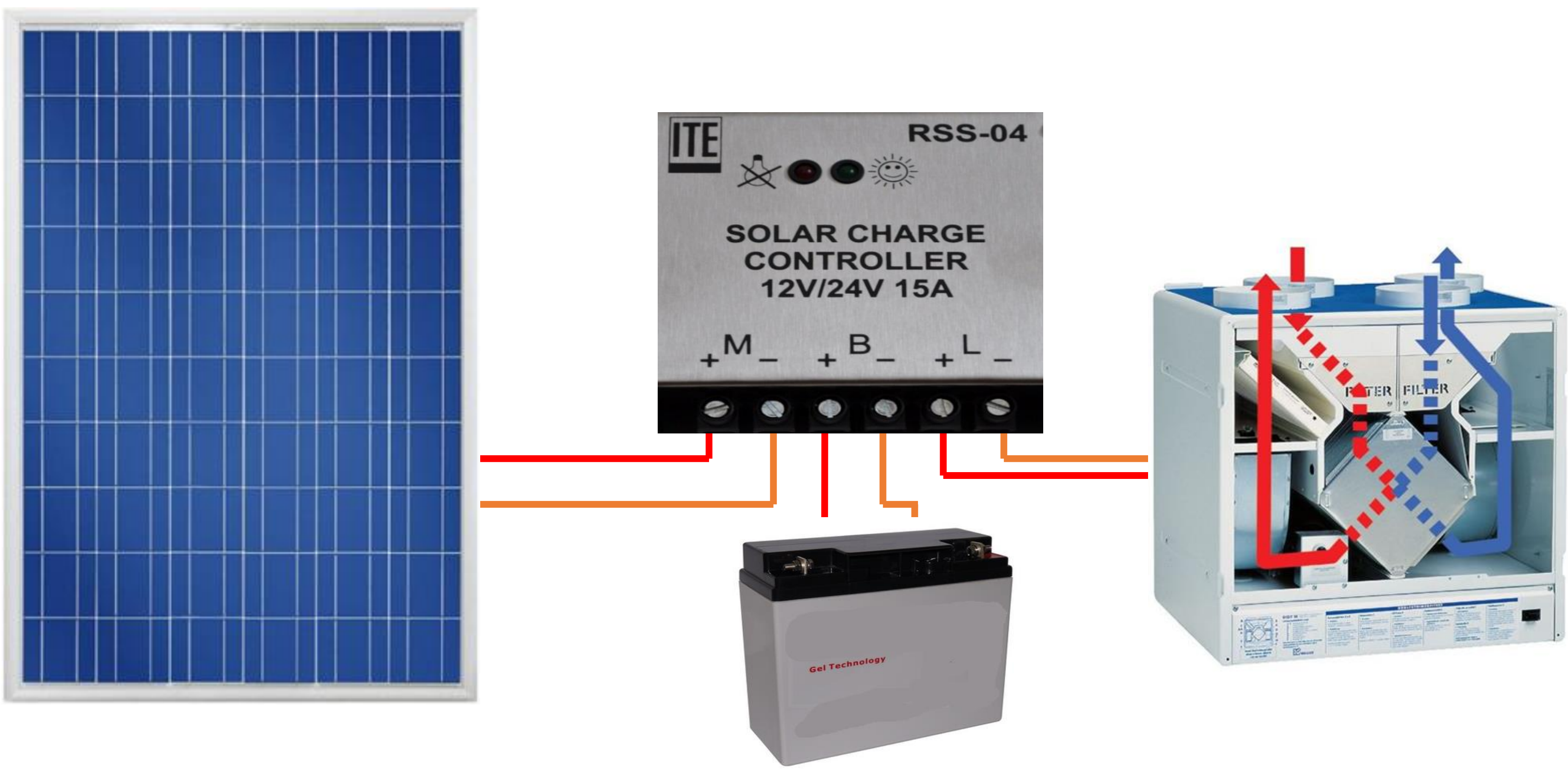
without tracking system

with tracking system

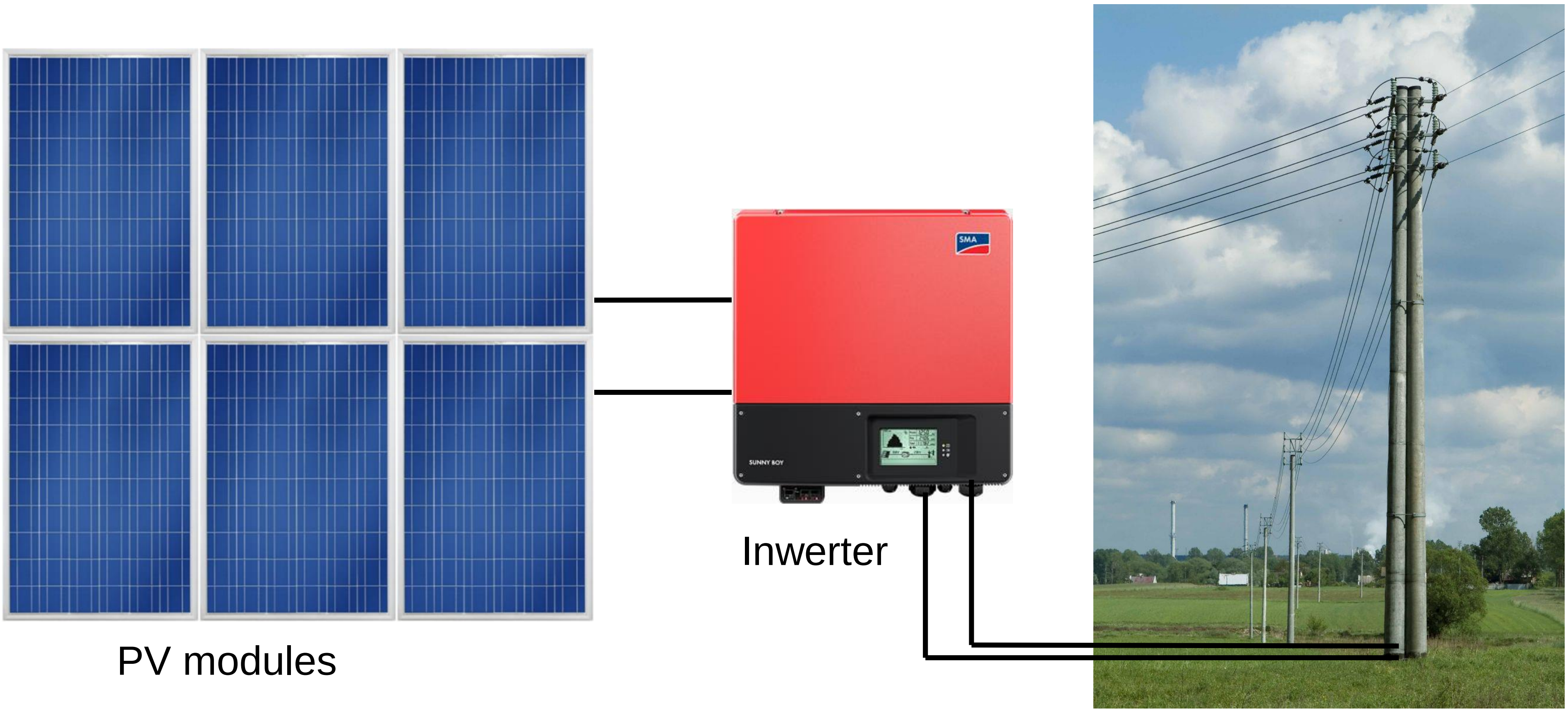
System PV without storage



Stand-alone system DC

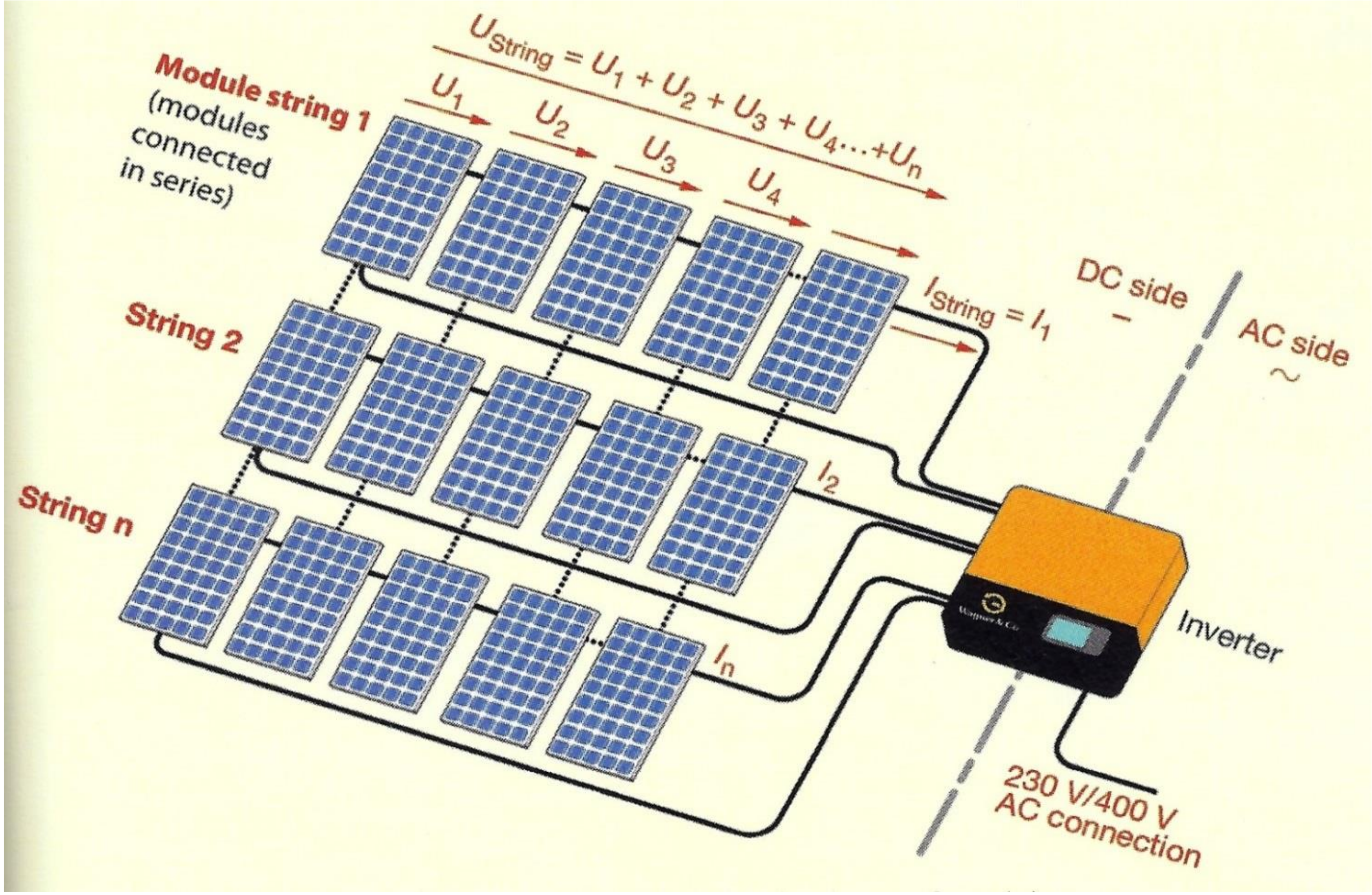


Grid conected PV system



Źródło: www.sma.de, wirbet.com.pl, georyt-solar

PV array

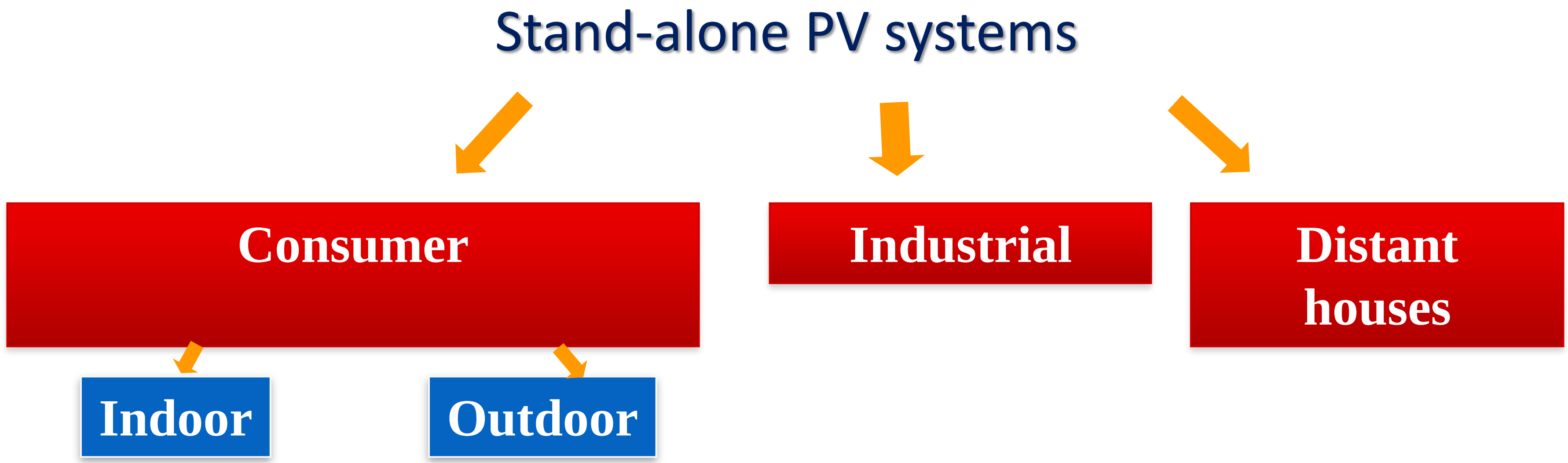


$U_{String} = U_1 + U_2 + U_3 + U_4 ... + U_n$
Module string 1
(modules connected in series)
U_1
U_2
U_3
U_4
String 2
String n
$I_{String} = I_1$
I_2
I_n
DC side
–
AC side
~
Inverter
230 V/400 V
AC connection

PV system grid-connected

Źródło: Polskie Centrum Solarne

Types of stand-alone (autonomous systems)



Types of grid connected PV systems

Grid connected PV systems

Decentralized

- Roofs
- School
- Facades
- Parking
- Transport routes

Centralized

- PV plant

Hybrid PV systems

Box 11. HYBRID RENEWABLES DEVELOPMENTS

Reflecting the many benefits available from combining renewables power generation sources with storage, projects have been initiated in various countries.

HYBRID RENEWABLES DEVELOPMENTS IN COUNTRIES	
Europe	Vestas and EDP completed Spain's first hybrid 3.3 MW wind-solar project in 2018.
India	In 2016, India introduced a national wind-solar hybrid policy to resolve grid integration issues, with a proposed target of 10 GW of hybrid projects to be installed by 2022 (Zion Market Research, 2019). Just prior to approval of this policy, Hero Future Energies completed India's first hybrid project, combining a 50 MW wind farm with a 28.8 MW solar PV site in Raichur district in April 2018. This project is aimed to be retrofitted with lithium-ion battery storage technology to combat curtailment during times of strong wind resource availability. The Solar Energy Corporation of India recent issued tenders for 2.5 GW of hybrid wind and solar projects to be connected to the country's Interstate Transmission System.
Unites States	GE Renewable Energy aims to develop the country's first commercial integrated 4.6 MW hybrid wind and solar project, in the state of Minnesota. NextEra and the US utility Portland General Electric will build a 380 MW wind-solar plus storage hybrid project in eastern Oregon.

Hybrid PV systems

The Danish wind specialist and the renewable energy unit of the Portuguese utility have installed the 3.3 MW power facility near Cadiz, in the Spanish region of Andalucia.

https://www.pv-magazine.com/2018/03/27/vestas-and-edp-completes-hybrid-wind-solar-project-in-southern-spain/

Lack of sites with transmission infrastructure, technical issues such as grid balancing and tariffs pose challenges to hybrid project roll-out in India.

www.pv-magazine.com/2020/06/11/india-set-to-add-15-gw-of-wind-solar-hybrid-capacity-in-five-years/

Image: hpgruesen/Pixabay

Agrophotovoltaics

Int. J. Solar Energy, 1982, Vol. 1, pp. 55–69
0142–5919/82/0101–0055$06.50/0

On the Coexistence of Solar-Energy Conversion and Plant Cultivation

A. GOETZBERGER and A. ZASTROW

Fraunhofer-Institut für Solare Energiesysteme Oltmannsstrasse 22, D-7800 Freiburg, West Germany

(Received February 15, 1981)

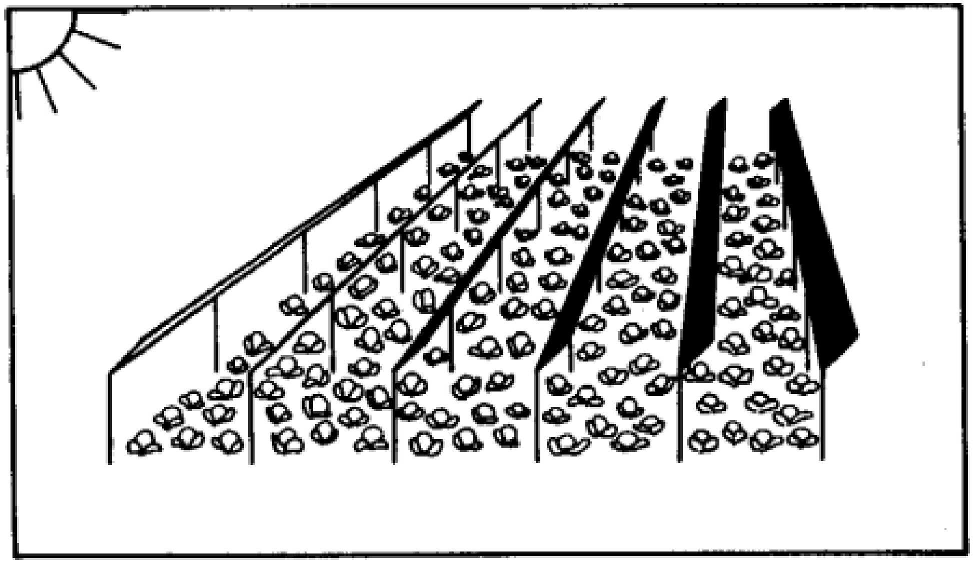


FIGURE 1 Model sketch of elevated collector field.

Agrophotovoltaics

Image by Fraunhofer ISE (www.ise.fraunhofer.de).

April 15 (Renewables Now) - A project in Germany testing the agrophotovoltaic (APV) concept has shown a land use efficiency of 160 % in 2017 and as much as 186 % in 2018, the Fraunhofer Institute for Solar Energy Systems ISE said Friday.

https://renewablesnow.com/news/german-agro-pv-trial-shows-up-to-186-land-use-efficiency-650768/

Agrophotovoltaics

The “Agrophotovoltaics – Resource Efficient Land Use (APV-RESOLA)” project evaluated the benefits of producing both solar power and crops on arable land near Lake Constance. The partners in the project installed a solar system of 194 kW on a five-meter-high structure on land used to grow winter wheat, potatoes, clover and celery.

https://renewablesnow.com/news/german-agro-pv-trial-shows-up-to-186-land-use-efficiency-650768

Elements of solar installation

Electrical parameters of the photovoltaic module

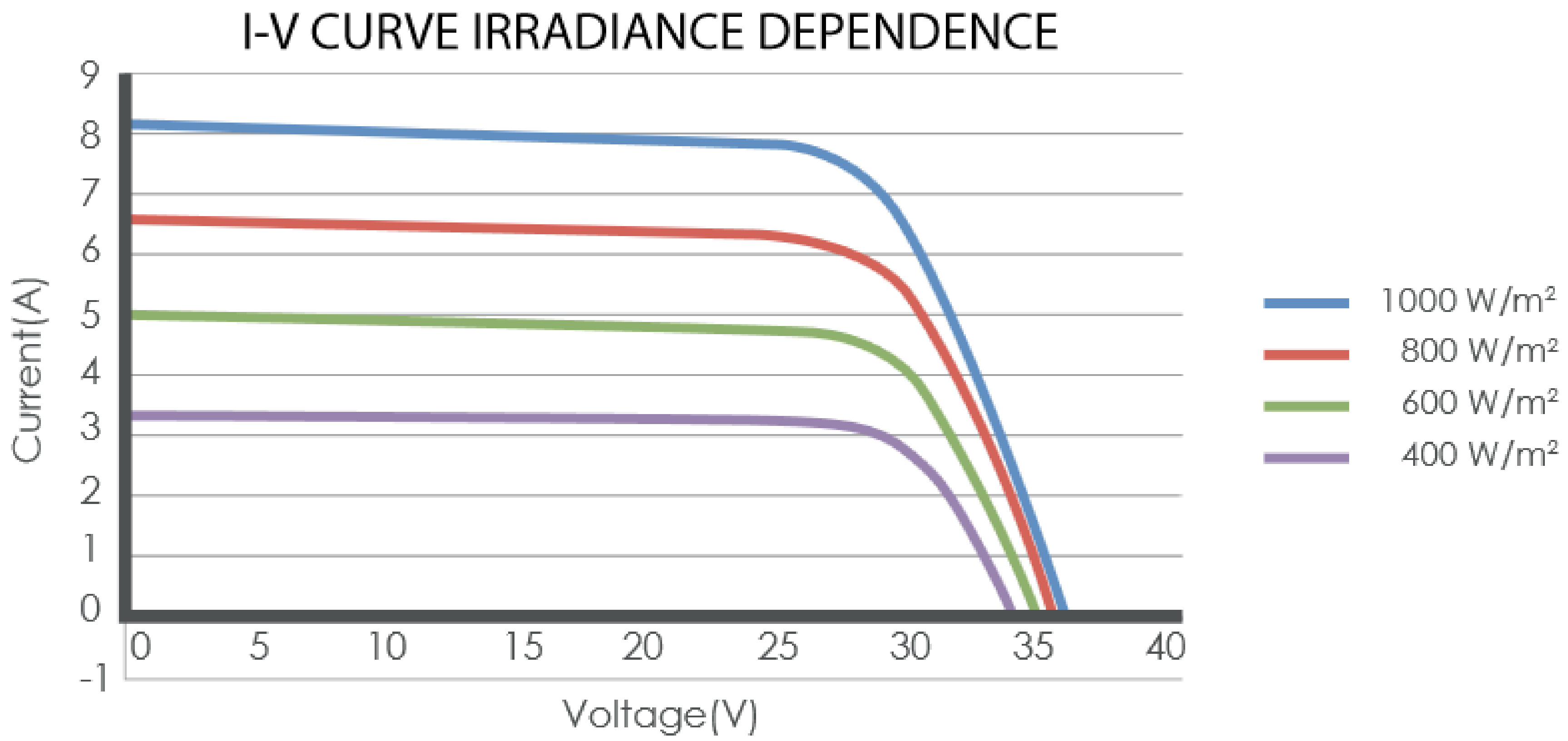
ELECTRICAL SPECIFICATIONS	
STC rated output (P_{mpp})*	250 Wp
PTC rated output (P_{mpp})**	223.0 Wp
Standard sorted output	
Warranted power output STC ($P_{mpp\,min}$)	250 Wp
Rated voltage (V_{mpp}) at STC	30.48 V
Rated current (I_{mpp}) at STC	8.23 A
Open circuit voltage (V_{oc}) at STC	38.09 V
Short circuit current (I_{sc}) at STC	8.64 A
Module efficiency	15.2%

PTC: “Photovoltaics for Utility Scale Applications Test Conditions” or PVUSA Test Conditions

Mechanical parameters

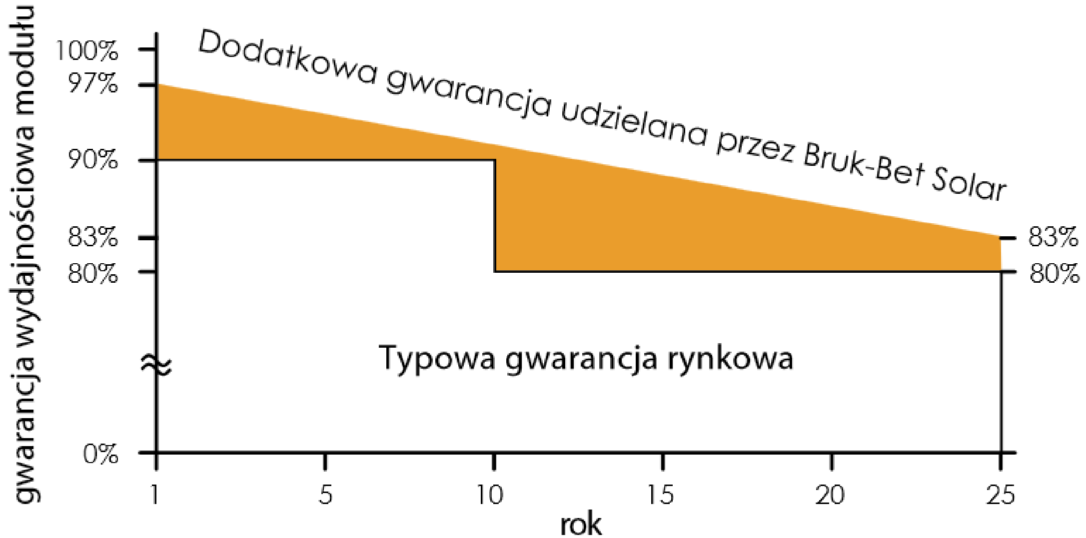
MECHANICAL SPECIFICATIONS	
Outer dimensions (L x W x H)	1652 x 994 x 45 mm 65.04 x 39.13 x 1.77 in
Frame technology	Aluminum, silver anodized
Module composition	Glass / EVA / Backsheet (white)
Weight (module only)	20 kg / 44.0 lbs
Front glass thickness	3.2 mm / 0.13 in
Junction box IP rating	IP 65
Cable length / diameter (UL)	1000 mm / 39.37 in / 12 AWG
Cable length / diameter (IEC)	1000 mm / 39.37 in / 4 mm^2
Maximum load capacity	5400 Pa
Fire class	C
Connector type (UL)	Multi Contact type 4
Connector type (TUV)	MC type 4 compatible

Electrical parameters of the photovoltaic module



Tests in the module certification process

- ✓ *Visual inspection*
- ✓ *UV preconditioning*
- ✓ *Damp heat test, DH*
- ✓ *Humidity-freeze, HF*
- ✓ *Mechanical Load test*
- ✓ *Thermal cycling, TC*
- ✓ *Hail impact test*



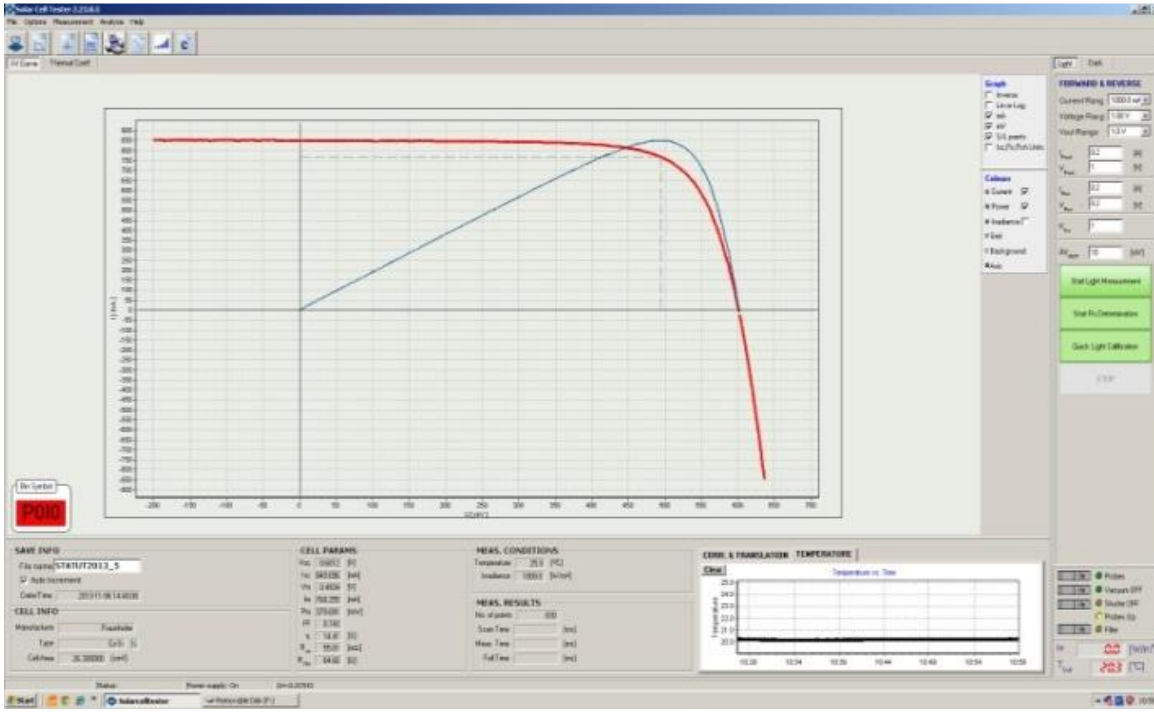
DH : temperature 85± 2°C , relative humidity: (85 ± 5)% test duration 1000 h

HF: Humidity Freeze - PV modules are exposed to cycles ranging between temperatures of 85°C with relative humidity of nearly 85 % and negative temperature reaching - 40°C. PV modules are subjected to a total of 10 complete cycles in a closed climatic chamber.

TC thermal cycling test (200 cycles at -40°C to 85°C)

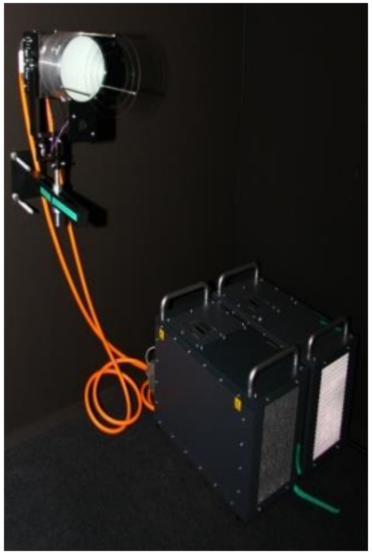
Certified measurements in the Photovoltaic Laboratory

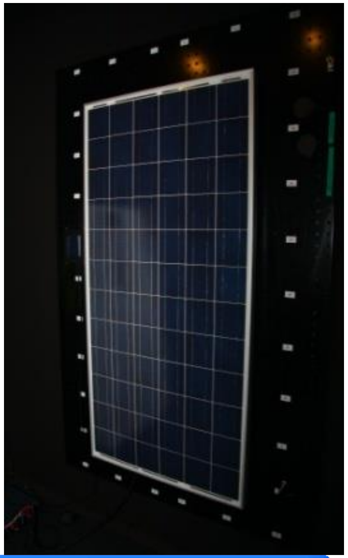
I-V characteristic solar cell

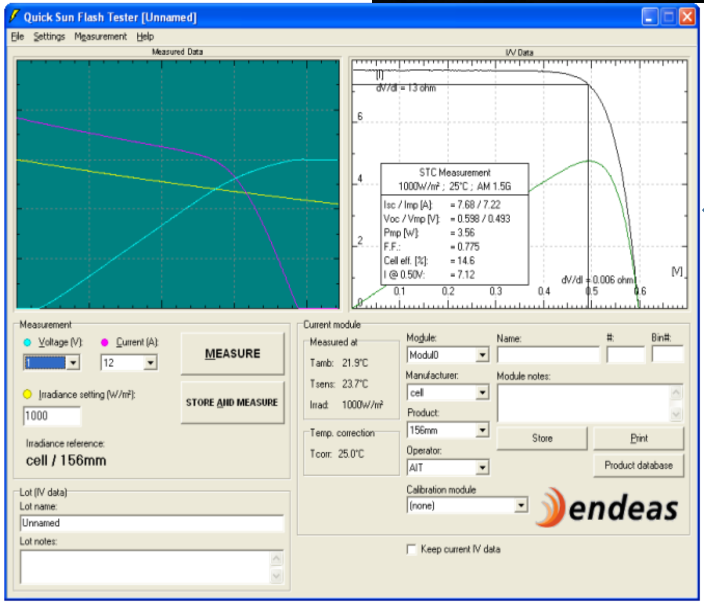


AB 120

Certified measurements in the Photovoltaic Laboratory







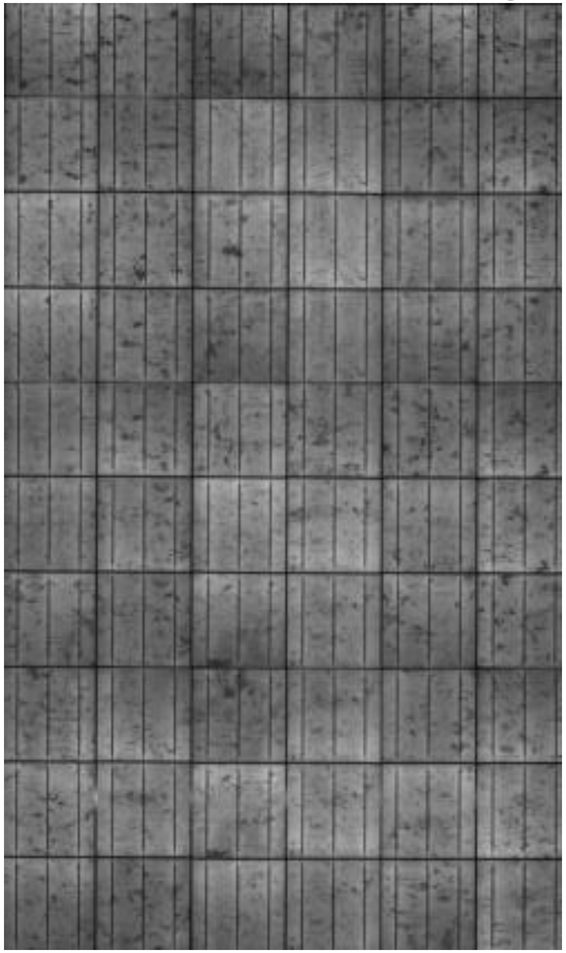
AB 120

I-V characteristic solar cell

Electrical parameters:
Isc
Voc
Impp
Vmpp
FF
Eff
Pmax

For STC

Electroluminescence image



Solar system - actual implementation

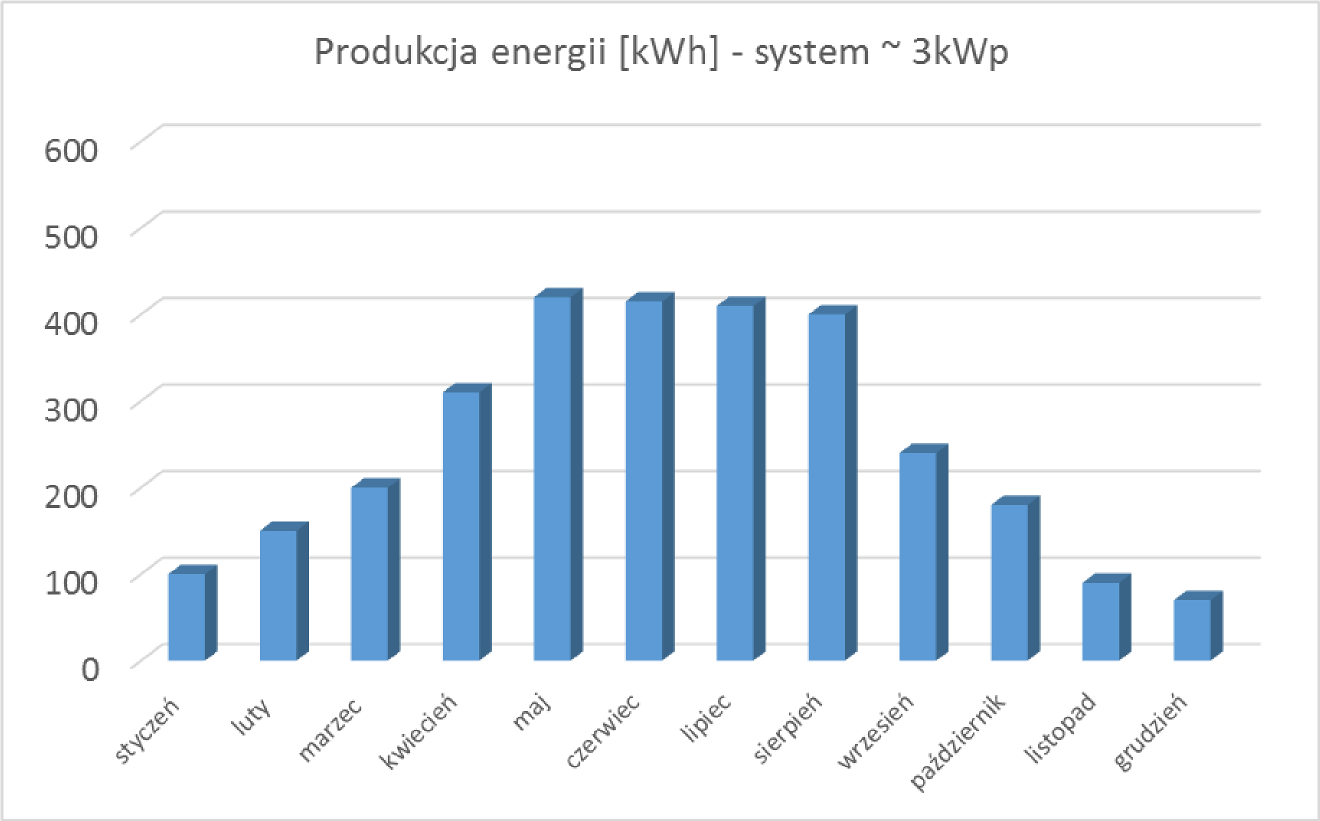
Maximal Power for STC : 2.35 kWp
Number of PV modules: 10
PV modules: SFE 235 Wp
Total area of PV modules: 16.32 m^2
Number of inverter: 1
Tilt angle: 35º
Azimut: 0º
Projected energy production: **2399** kWh

Źródło: Polskie Centrum Solarne

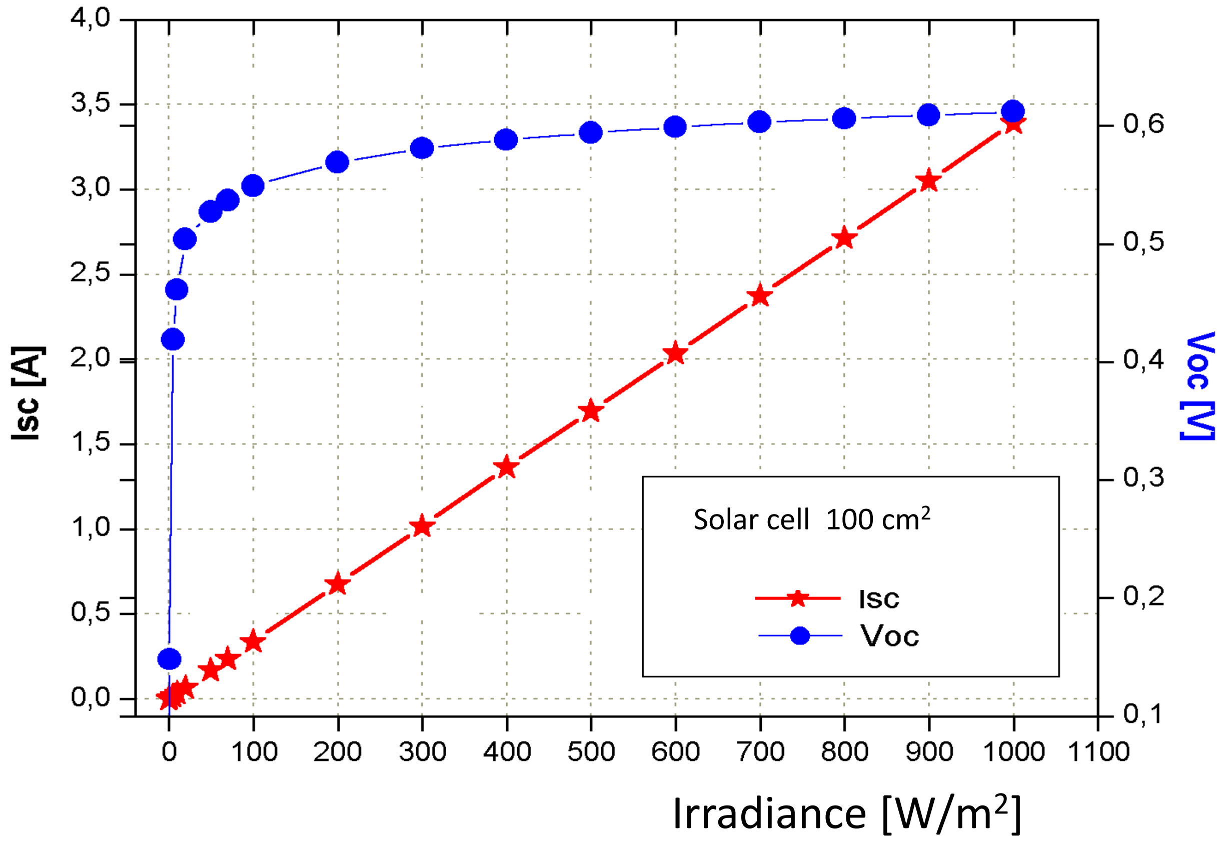
http://2kw.krdglobalgroup.com/

Solar system - actual implementation

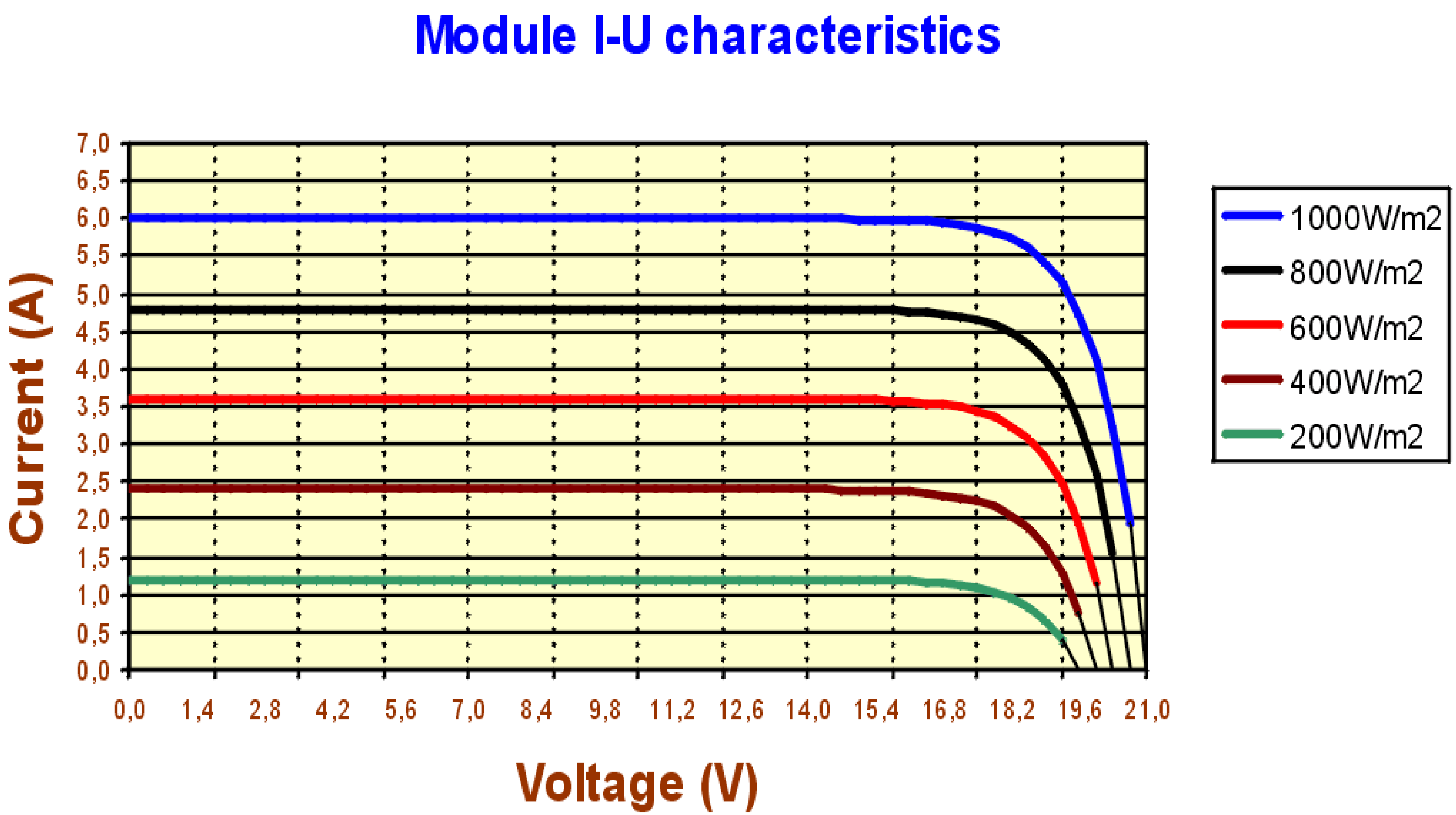
Maximal Power for STC : **3,1 kWp**, Number of PV modules: **12**, ModulesL: Selfa **260 Wp**
Total area: **20,4 m^{2}**, Tilt angle: **32º**, Azimut: **0º**
Projected energy production: ~**3000** kWh



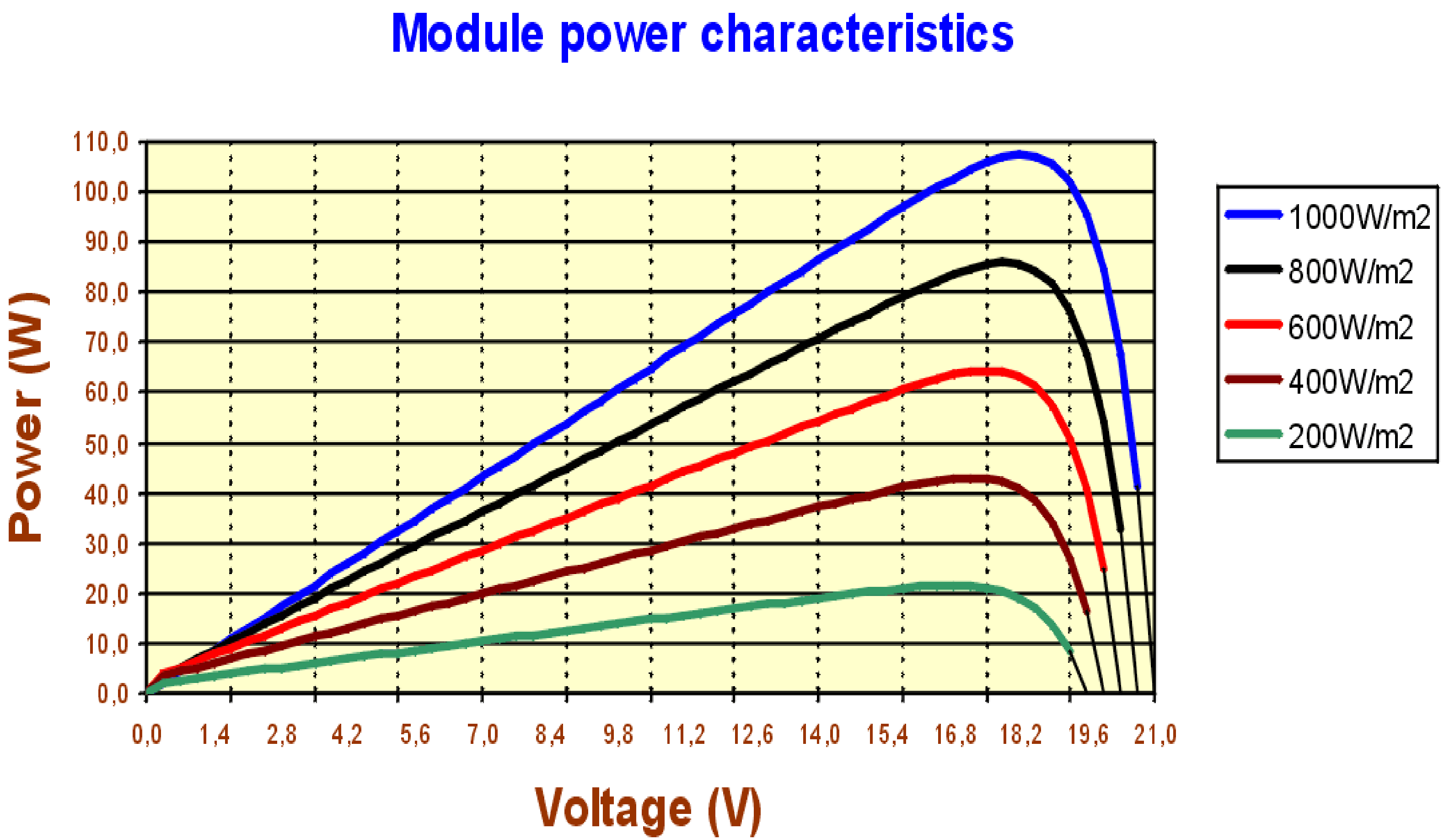
Dependence of basic solar cell parameters on the value of radiation intensity



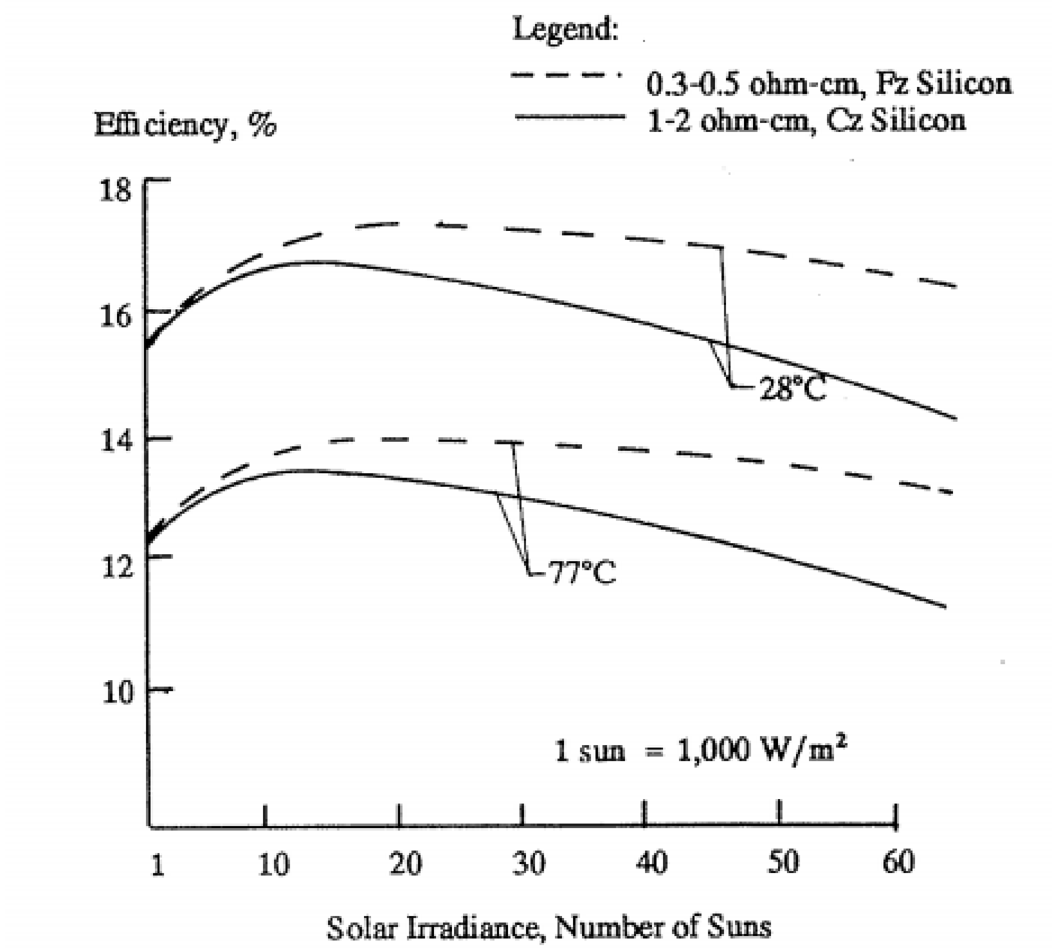
Dependence of basic solar cell parameters on the value of radiation intensity



Dependence of basic solar cell parameters on the value of radiation intensity

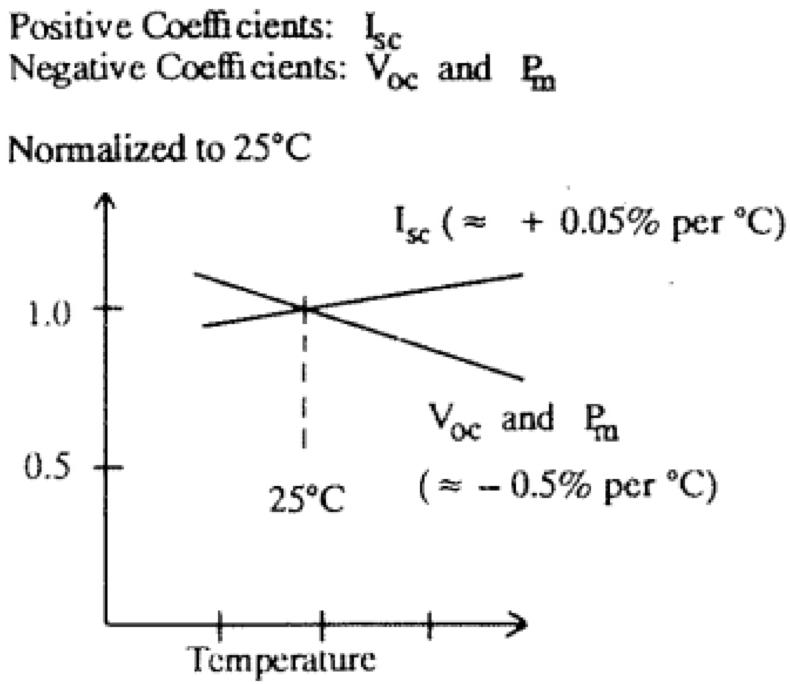


Dependence of basic solar cell parameters on the value of radiation intensity

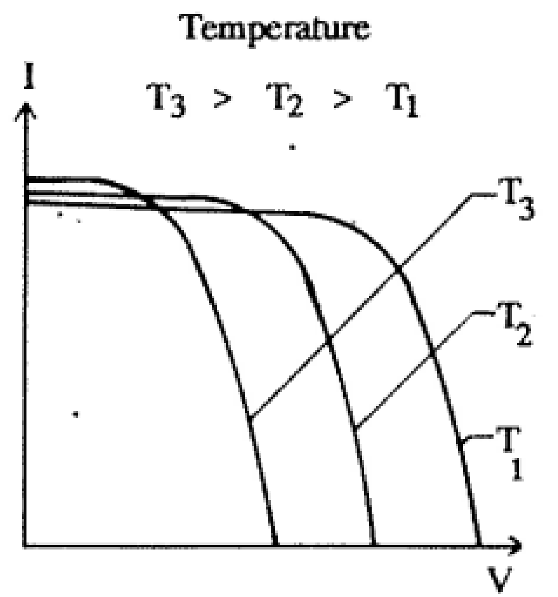


M.S.Imamura, P.Helm,and W.Palz, Photovoltaic system technology, A European Handbook 1992.

Dependence of basic solar cell parameters on the value of temperature



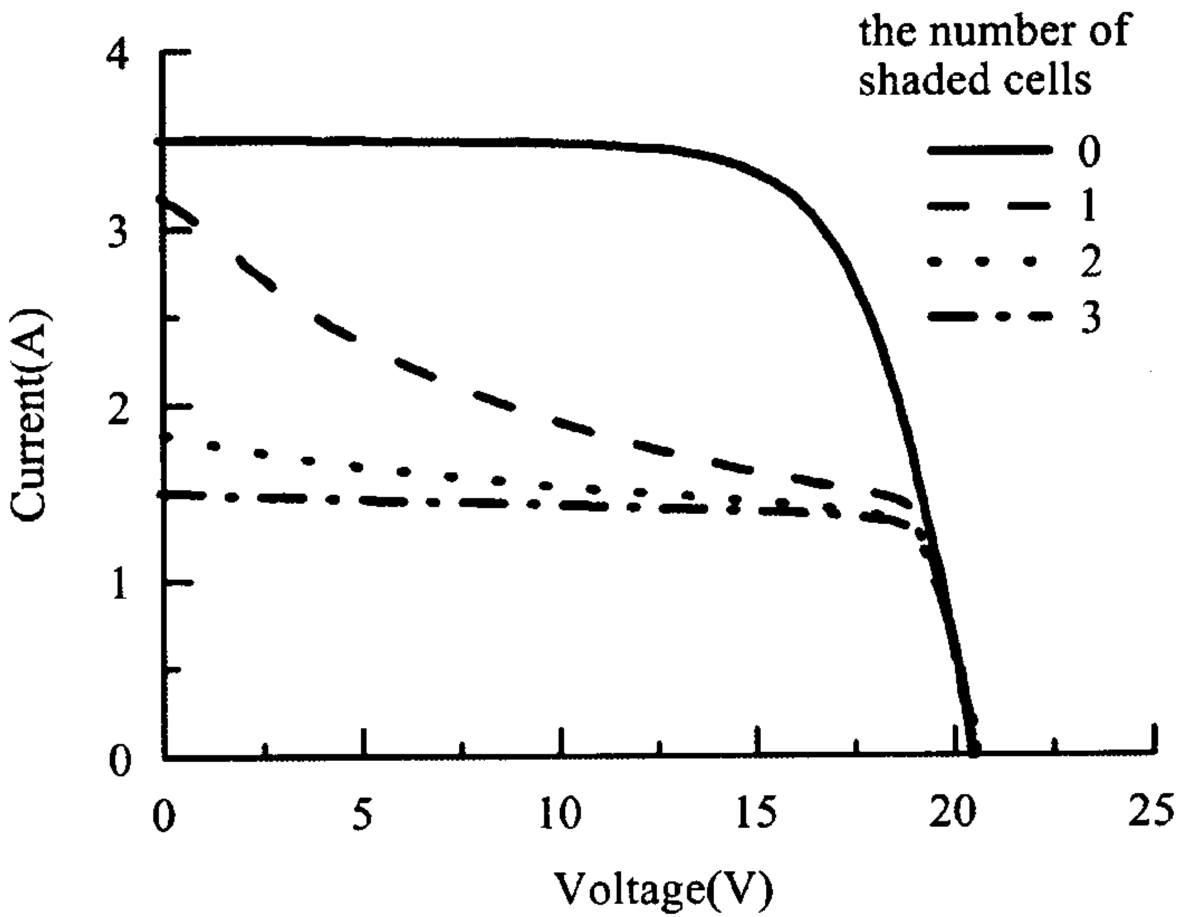
Temperature Coefficients



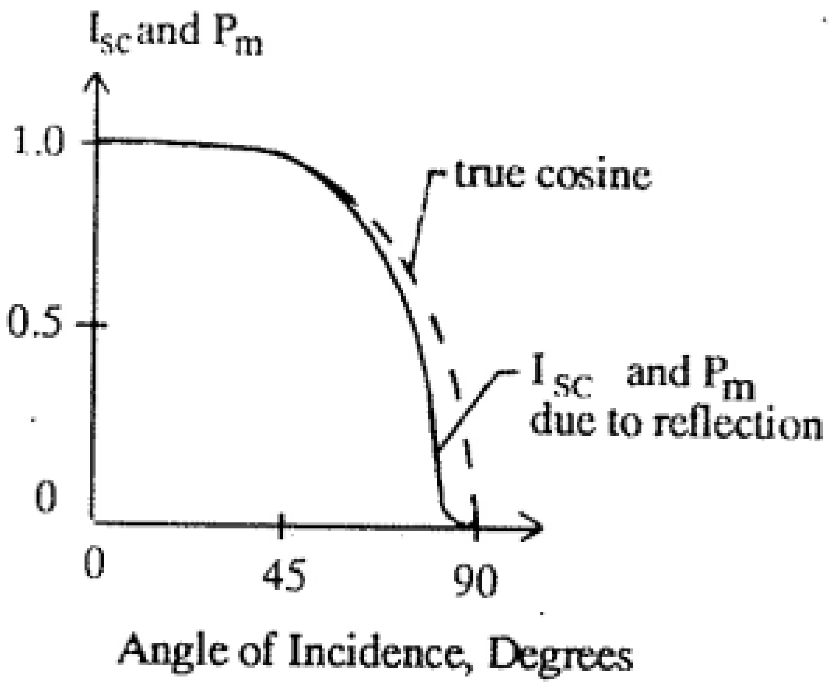
Temperature Effects on I-V Output

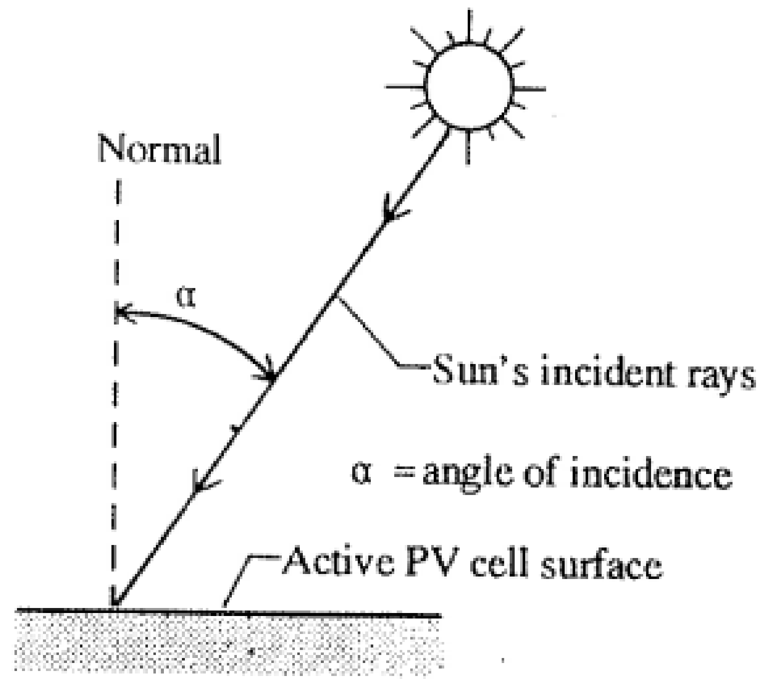
M.S.Imamura, P.Helm,and W.Palz, Photovoltaic system technology, A European Handbook 1992.

The effect of shading one link on the characteristics of the PV module



Dependence of I_{SC} on the value of angle of incidence





Effects of PV Module Orientation

M.S.Imamura, P.Helm,and W.Palz, Photovoltaic system technology, A European Handbook 1992.

Thank you for your attention