Univerza v Ljubljani
Fakulteta za strojništvo

LOTZ

IDES-EDU

INTELLIGENT ENERGY EUROPE

FOR A SUSTAINABLE FUTURE

IDES-EDU modul **Energy production**

Lecture #9 **Photovoltaics (PV)**

Coordinator: Sašo Medved, UL

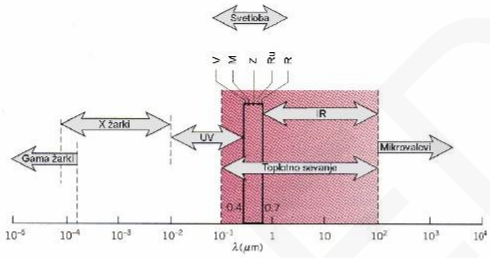
Contributor: Sašo Medved, UL

Univerza v Ljubljani
Fakulteta za strojništvo
LOTZ
IDES-EDU
INTELLIGENT ENERGY EUROPE

- EU directive on "Green electricity" established in 2003, provides legal basis and targets for electricity production from RES for all EU member states.
- It looks like that one technology, called photovoltaics, benefit mostly from this directive.
- Photovoltaic systems consist of large number of solar cells gathered in solar panels or modules, convert solar energy directly into electricity
- There are several types of solar cells, but they are mostly made from silicon, very common element on Earth and have similar, but low efficiency in the range between 10 and 18%.
- Despite low efficiency of photovoltaic systems, areas of facades and roofs in buildings are in most cases large enough for independent electricity supply. In addition to that, building owners could sell electricity to the public grid and benefit from so called "feed-in-tariff" subsidies or other state benefits.

Solar energy

- Solar radiation a form of electromagnetic radiation.
- Electromagnetic radiation covers a wide range phenomena from radio waves to x-rays and gamma rays. The sources of those radiation are different.
- The source as in case of solar radiation, is body with temperature above absolute zero (0K). This is so called thermal radiation.
- All electromagnetic radiation travel in vacuum with speed of light, but differs by wavelength and amount of energy they transfer.



Solar energy

- Wavelengths λ of thermal radiation are between 100 to 10.000 nm (0,1 to 100 μm).
- Most of the solar radiation has wavelengths between 0,3 and 3 μm. This range is divided between ultraviolet (UV) radiation, visible light (0,38 μm to 0,76 μm) and infrared (IR) radiation. This correspond to radiation emitted by body with surface temperature about 5700 K.
- The solar radiation can be represent with energy carrier particles called photons. The energy transferred by photon can be calculated using Plank's law:

$$E = h.c/\lambda$$

(h is Planck constant [6,63 10^{-34} Js], c velocity of light in vacuum [3 10^{8} m/s] and λ is wavelength of radiation [m])

- or can be expressed by electonvolts (eV). 1 eV corresponds to 1,60 10^{-19}J

Solar energy

EXAMPLE:

- Photon having wavelength λ 0,55 μm (this corresponds to the mid wavelength of visible light) has energy of:

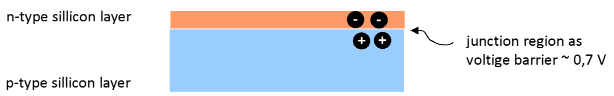
$$E = h.c/ \lambda = 6{,}63\ 10^{-34}\ .\ 3\ 10^{8} / 0{,}55\ 10^{-6} = 3{,}6\ 10^{-19}\ J$$

or

- $$E = 3{,}6\ 10^{-19}\ J / 1{,}60\ 10^{-19}\ J = 2{,}26\ eV$$

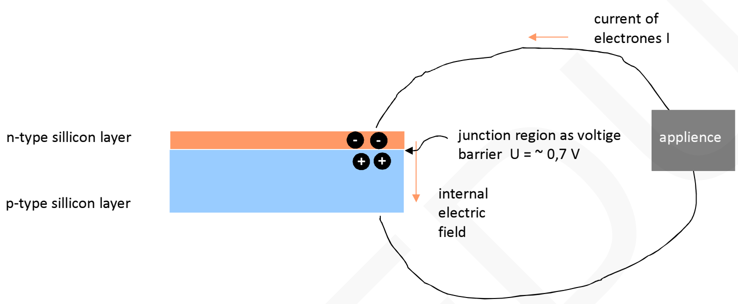
Photovoltaic cell (PV cell)

- Most common PV cells are made from silicon.
- The cell has two thin layers – bottom one, where small amount of boron is added to silicon (so called p-type layer with free positive charged holes) and few μm thick upper layer, where phosphorus is added to silicon (so called n-type layer because with free negative charged electrons).
- Putting those layers together voltage barrier (~ 0,7 V) rising in PV cell.



PV cell – how electricity is generated

- Photons with sufficient energy can produced new electrons and holes. This results in internal electric field
- If resistant load -appliance like bulb or motor - is connected with PV cell electrons lives the PV cell and travel thought appliance and return to PV cell where bond together with "waiting" hole. The life of new electron-hole pair is ended, but appliance produce work in meantime.

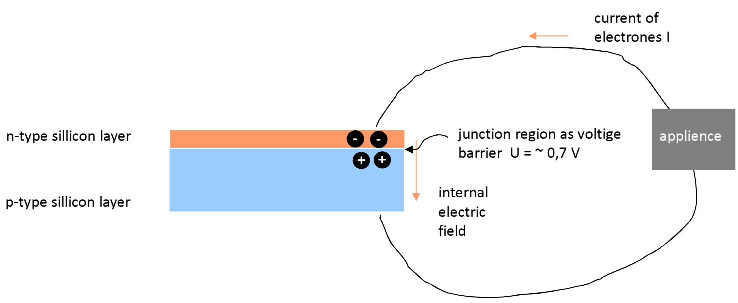


PV cell – how electricity is generated

- Electrical power of PV cell is equal to

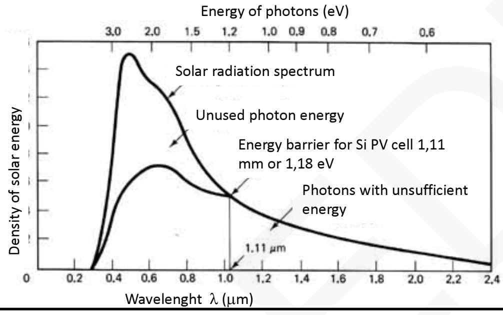
$$P_e = U . I$$

where U is approximately constant and depends on base material (mostly silicon) and added atoms (beside P, B also Cd, As,..), meanwhile electricity current is proportional to the density of solar radiation.



PV cell – efficiency

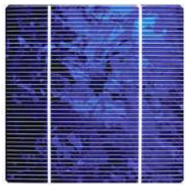
- The reason why conversion of solar energy into electricity by PV cell is relatively low (between 15 to 20%) is that only limited amount of photons of solar radiation has adequate energy to produce new electron-hole pairs.
- For silicon PV cell these are photons with wavelength less that 1,11 μm or having energy greater then 1,18 eV.
- Unfortunately entire energy of most photons with adequate energy can't be convert into electricity !



PV cell – types and efficiency

- Mostly used today are silicon PV cell produced from only one crystal of Si (this type is called monocristalline "mc-Si" PV cell) of several crystals of Si (this type is called polycrystalline "p-Si" PV-cell). This PV cells have highest efficiency: mc-Si 15 -18% and p-Si 12-16%
- Production of Si crystals are expensive and could be decreased if amorphous Si is used; this is another form of Si in environment; efficiency of "a-Si" cells are much lower – up to 8%
- Polycrystalline cell can be made from other materials and could be very thin; this are so called thin-film PV cell made from cadmium telluride (CdTe), gallium arsenide (GaAn) or copper indium deselenide (CIS); they are less efficient (12 – 14 %) but production is cheaper

mc-Si

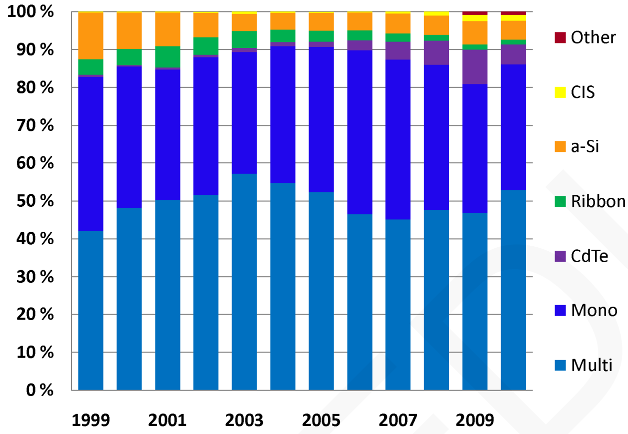


p-Si

CIS

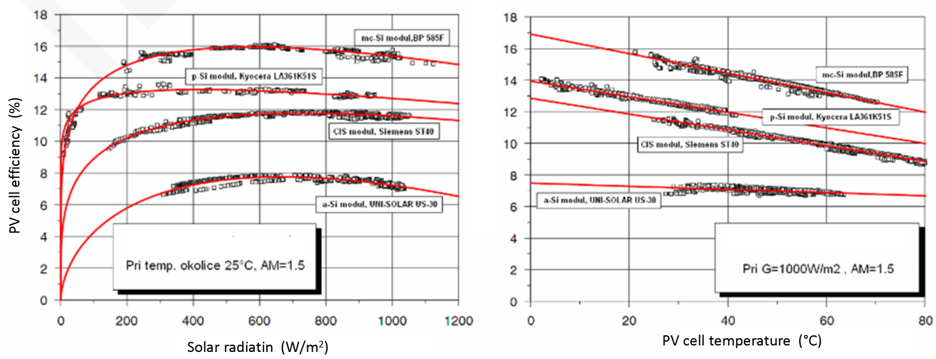
PV cell – types and efficiency

- Market share of different PV cell technologies



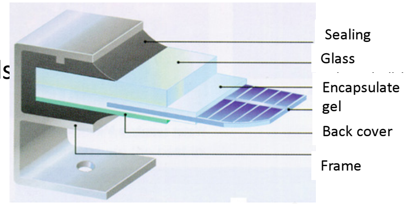
PV cell – types and efficiency

- Efficiency of PV cell is independent on solar radiation density (if >100 W/m^2), but decrease with cell temperature; that's why researchers try to combine solar heating (cooling of PV) and electricity production !



Photovoltaic modules

- For practical reasons PV cell are encapsulated in PV modules. Modules are in different size from some hundreds of cm^2 to several m^2. Most often modules in size of 1 m . 1,6 m are used in buildings. 40 to 50 PV cell are normally grouped together to produce 20 to 25 V of direct current (DC).



- Each producer declare “peak electrical power (Wp)” for their PV modules. This is the electrical power when solar radiation is 1000 W/m2 and cell temperature is 25°C. This are ideal conditions and in hour-to-hour operation the power is lower (of course 0 W during the night)
- Each producer declare “durability factor” for their modules. This is the guaranteed efficiency after 20 to 30 years of operation. Typically this is only 5 to 15% -> module having 100 W_p will have power of 90 to 95 W after 30 years of operation! PV technology is very durable !

PV systems

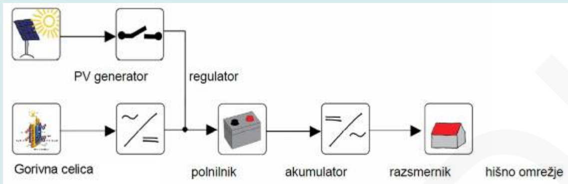
Two types of PV system are most common:

- off-grid systems or island operation stand alone systems
- grid connected system

- Off-grid system could be low-voltage direct current (DC) (mostly 24 V) storing electricity in batteries. Between the batteries and users inverter could be installed to produce high voltage (220 V) alternating current (AC). This allows common appliance to be supplied with electricity and reduce the size of wires and reduce system cost.

PV systems

EXAMPLE:



Grid Stand alone PV system with PV modules area of, inverter and batteries (capacity of 600 Ah). As backup methanol fuel cell is used.

PV systems

- Grid connected system are so called PV solar power plants. They produce and send electricity to the public grid. In many countries investors in PV power plant are encourage with state incentives.
- This could be in form of “CO_2 coupons” or as “feed-in-tariff”. Feed-in-tariff is price of electricity offered to investor in long them contract. Feed-in-tariffs for PV systems are normally 2 to 4 time greater then regular price of electricity (between 0,02 to 0,06 €/kWh depending of country).
- Such supporting schemes origin from EU RES-e Directive published in 1998 bust PV market in last decade.

Largest Slovenian 107 kW_p and EU PV power plant in Spain (23 MW_p) (2008)

Increasing of PV system efficiency

- Despite huge volume production increase of PV systems, the technological break-through is not happen yet. Nevertheless there are ways how to increase annually produced amount of electricity.
- PV modules can be mount on Sun tracking device. This way annually production of electricity can increase up to 60%.
- Mirrors with low concentration ration can be added to PV modules for increasing the solar irradiation. PV system electricity production can be increased by 30% or more.

Integration into the buildings

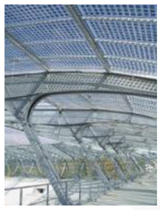
- Mounting the PV modules into the building skin in most cases reduce electricity production because modules are not installed in optimal position.

  That's why financial support for such PV systems is higher !

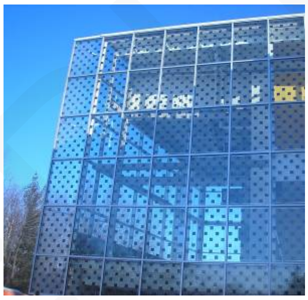
- Building integrated PV modules offer many advantages such as:
- Modules can replace facade and roof construction and decrease the cost of building
- Modules are weather durable therefore maintenance of buildings can be cheaper
- Modules can improve building envelopment properties – reduce heat transfer coefficient (U) and provide shading of large glass areas
- Guarantee long term income for the owner
- Emphases the "green view" of the building
- And reduce the use of land for installing PV system

ntegration into the buildings

- PV modules producers developed solutions to atract architects and investors. Some examples:
- PV modules can be opaque or semi transparent



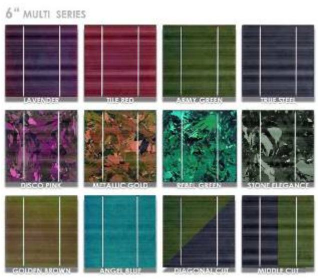
- Density of the solar cell in PV modules can be custom made adjusted to desired visual effect, natural lighting, shading.



Source: http://www.dansksolenergi.dk; http://www.concerto-sesac.eu; http://www.solarpv.co.uk; http://photovoltaic-shingles.com; http://drexelcorp.wordpress.com

ntegration into the buildings

- Solar cells can be in different colours to emphases appearance of the building



- PV modules can be integrated in standardized solutions of building constructions

Source: http://www.dansksolenergi.dk; http://www.concerto-sesac.eu; http://www.solarpv.co.uk; http://photovoltaic-shingles.com; http://drexelcorp.wordpress.com

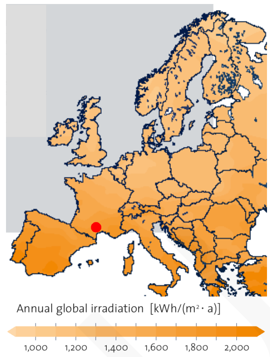
Electricity production – calculation methods

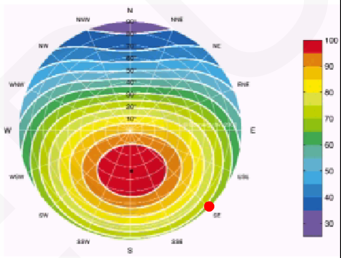
Rule of thumb

- Yearly production of PV system having size of 1 m^2 installed in the area with annual global solar irradiation 1100 kWh/m2 and optimal orientated position is:

  120 – 140 kWh/m^2 (for pc-Si modules)

- Very often PV modules integrated into the buildings are not orientated optimal, therefore reduction factor, shown on the figure, must be taken into account.
- From figure optimal slope and orientation of PV modules can be seen as well – representing with red area on the chart ! (Attention: chart is valid for latitudes between 30°and 50°)





Electricity production – calculation methods

EXAMPLE:

PV system will be installed in city having annual global solar irradiation 1800 kWh/m^2. PV modules will be installed on southeast vertical facade. What will be yearly electivity production with 100 m^2 of mc-Si modules? What will be pre-tax income if “feed-in” tariff is 0,4 €/kWh and what will be simple return rate if installed kW of PV system cost 3500 € ?

- Orientation factor (presented by red dot on previous figure) is 0,65
- Annually produced electricity will be:

  E ~ 120 kWh/m^2 . 1800 kWh/m^2a / 1100 kWh/m^2a . 0,65 . 100 m^2 =

  E ~ 12,8 10^3 kWh/a

- Annual income will be: 12,8 103 kWh/a . 0,4 €/kWh = 5120 E
- 1m^2 of PV modules have power of 120 W. Therefore total power of PV system is 12 kW. Simple rate of return is 12 kW . 3500 € / 5120 E/a = 8,2 years

- Public available computer tool

- Site and PV modules orientation

RETScreen® Solar Resource and System Load Calculation - Photovoltaic Project

Site Latitude and PV Array Orientation		Estimate	Notes/Range
Nearest location for weather data		Ljubljana/Bezigrad	See Weather Database
Latitude of project location	°N	46,1	-90.0 to 90.0
PV array tracking mode	-	Fixed	
Slope of PV array	°	30,0	0.0 to 90.0
Azimuth of PV array	°	0,0	0.0 to 180.0

Load Characteristics		Estimate
Application type	-	Off-grid
Use detailed load calculator?	yes/no	Yes

Description	AC/DC	Solar-load correlation	Load (kW)	Hours of use per day (h/d)	Days of use per week (d/wk)
Radios	DC	Zero	0,015	2,00	7
PC	AC	Zero	0,250	10,00	7
TV	AC	Zero	0,200	4,00	7
Lights	DC	Zero	0,020	4,00	7
Fridge	AC	Zero	0,040	5,00	7

- Load definition

- Operation principle
- PV module selection
- Follow recommendations
- Iterative optimization

System Characteristics		Estimate	Notes/Range
Application type	-	**Off-grid**	
PV system configuration	-	PV/battery	
Base Case Power System			
Source	-	Grid extension	
Power Conditioning			
Suggested inverter (DC to AC) capacity	kW (AC)	0,49	
Inverter capacity	kW (AC)	0,5	
Average inverter efficiency	%	90%	80% to 95%
Miscellaneous power conditioning losses	%	0%	0% to 10%
Battery			
Days of autonomy required	d	2,0	1.0 to 15.0
Nominal battery voltage	V	24,0	12.0 to 120.0
Battery efficiency	%	85%	50% to 85%
Maximum depth of discharge	%	70%	20% to 85%
Charge controller (DC to DC) efficiency	%	95%	85% to 95%
Battery temperature control	-	Minimum	
Minimum battery temperature	°C	15,0	0.0 to 15.0
Average battery temperature derating	%	4%	0% to 50%
Suggested nominal battery capacity	Ah	499	
Nominal battery capacity	Ah	500	
PV Array			
PV module type	-	mono-Si	
PV module manufacturer / model #		BP Solar/ BP 140	See Product Database
Nominal PV module efficiency	%	9,6%	4.0% to 15.0%
NOCT	°C	45	40 to 55
PV temperature coefficient	% / °C	0,40%	0.10% to 0.50%
PV array controller	-	MPPT	
Miscellaneous PV array losses	%	5,0%	0.0% to 20.0%
Suggested nominal PV array power	kWp	4,52	
Nominal PV array power	kWp	**4,52**	
PV array area	m²	47,1	

Annual Energy Production (12,00 months analysed)		Estimate	Notes/Range
Equivalent DC energy demand	MWh	**1,460**	
Equivalent DC demand not met	MWh	0,008	
Specific yield	kWh/m²	30,8	
Overall PV system efficiency	%	2,6%	
PV system capacity factor	%	3,7%	
Renewable energy delivered	MWh	**1,452**	
	kWh	1.452	
			Complete Cost Analysis sheet

- real self sufficient production (buy nothing principle) time dependent supply vs. demand balance problem -> batteries (costly, large) must be integrated
- virtual self sufficient production (energy balanced principle) PV system is connected to the public grid and produced electricity could be “stored” into public grid and used in cloudy days and during the nights.
- economical balanced production (pay zero principle) EU RES-e directive dictate that electricity produced by RES must be bought by distributors by higher price. In Slovenia (similar in D and S) the ratio is 1:4; therefore only ¼ of electricity must be produced and put into the public grid. Smaller PV system is needed, investment is smaller.

Self sufficient electricity production/supply - principles

EXAMPLE: electricity supply for small coutage

	buy nothing	energy balanced	pay zero
all year 24/7 use	**PV modules area 42 m^2 usefull produced 32.3 kWh$_e$ /m^2 a** **Battery capacity 450 Ah**	**13.5 m^2** 107 kWh$_e$ /m^2 a	**3.4 m^2** 107 kWh$_e$ /m^2 a
summer use only May-Sept.	**13 m^2** 44.4 kWh$_e$/m^2 a 200 Ah		

Environmental issues of PV

Several principles can be used for justify PV systems regarding to their environmental impact. Here are some examples !

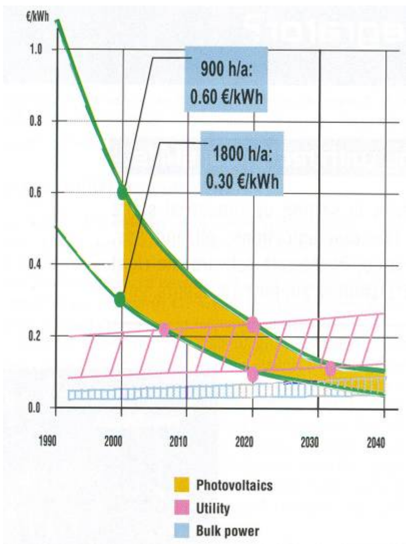
- Embodied energy – ratio between produced electricity to energy needed for production of PV modules versus ; Si cells produce in life time (in general 30 years) 10 to 20 times more energy that it is needed for production
- Reduce emissions of greenhouse gases and other air pollutants – emissions can be reduced between 60 to 90% regarding to energy grid mix
- Recycling – not commercial, it is proposed that recycling of Si will reduce energy consumption to 1/3

More complex method are available – for example PI – pollution index method (http://envimpact.org) suggested following relations for electricity production (less is better):

from coal PI = 885; PV PI = 52 , from wind PI = 9 ; from hydro PI = 0,5

The future of PV

- The price of electricity produced by PV system will decrease in next 20 years to the level equal to fossil and nuclear electricity. This will be achieved even with today known technologies.
- New development in PV cell producing will further decrease price of PV systems



Source: SunWorld

The future of PV

- PV will be leading technology in the cities of tomorrow

BUILT ON BLACK GOLD

Masdar: Oil wealth fuels construction of an ecological city in the Arabian desert.

A sheikhdom whose wealth rests on black gold is building a city that will not rely on any of it. Subterranean electric cars—dubbed Personalized Rapid Transit—will ferry passengers from point to point because the city of Masdar, whose name translates as "the source," will be off-limits to automobiles. Solar power plants in the surrounding sand, already in early construction, will provide electricity for lighting and air-conditioning and for desalinating ocean water. Wind farms will contribute, along with efforts to tap geothermal energy buried deep underneath the earth. The municipality, which will ultimately aim to be zero carbon and zero waste, will boast a plant to produce hydrogen as well as fuel from the residents' sewage, according to planners Foster + Partners. Perhaps most important for the desert city, all water will be recycled; even residents' wastewater will be used to grow crops in enclosed, self-sustaining farms that will further recycle their own water. "We must fundamentally rethink how cities can conserve energy and other resources," said Sultan Al Jaber, Masdar Initiative CEO, this past June in an address to a U.S. congressional committee. "We must heavily employ new technologies and even create new urban models."

David Biello is an associate editor reporting on the environment for ScientificAmerican.com.

Masdar at a Glance

Location: Abu Dhabi, United Arab Emirates

Size: 1,600 acres

Schedule: Completion by 2016

Future population: 30,000 people from the wealthy emirate

Cost: At least $22 billion (amount committed by the U.A.E. government)

Green features: Zero waste, zero carbon emissions and zero energy from fossil fuels are the goals of this community, one of the first major eco-cities to break ground. Desalination, drawing on large amounts of electricity from solar, wind and geothermal sources, will be key to sustaining this desert city. Creative but traditional architecture, including wind towers, will aid in cooling inhabitants.

Artist's conception, 2016

Personalized Rapid Transit vehicles on fixed paths (to be installed underground) will replace automobiles.

Source: SunWorld

Self evaluation

- Briefly explain how PV cell produce electricity from solar radiation !
- Describe types of solar cells and their efficiency !
- Draw U-I curve of photo cell and explain how is dependent on temperature and density of solar radiation !
- What are PV modules ?
- What you know about sizing of the PV systems ?
- Describe procedure of sizing of the PV systems !
- Explain how environment can benefit from PV systems !

Literature/References

M. J. Moran, H. N. Shapiro: Fundamentals of Engineering Thermodinamics; John Wiley & Sons, USA, 1998

Hsieh J.; Solar Energy Engineering, Prentice Press, 1986

Johanson et. All.; Renewable Energy; Sources for Fuels and Electicity, Island Press; 1993

B. Lenz, J. Schreiber, T. Stark; Sustainable building services, Detail Green Books; Germany, 2011

Daniels K., Hammann R.; Energy Design for Tomorrow, Axel Menges, 2008

RETSCreen simulation tool

SunWorld Magazine

SunandWind Magazine

Source: http://www.dansksolenergi.dk; http://www.concerto-sesac.eu; http://www.solarpv.co.uk; http://photovoltaic-shingles.com; http://drexelcorp.wordpress.com