

TSTE26 Powergrid and technology for renewable  
production

Lecture 1  
Introduction / Overview  
PV-theory

Lars Eriksson  
Professor  
FS/ISY

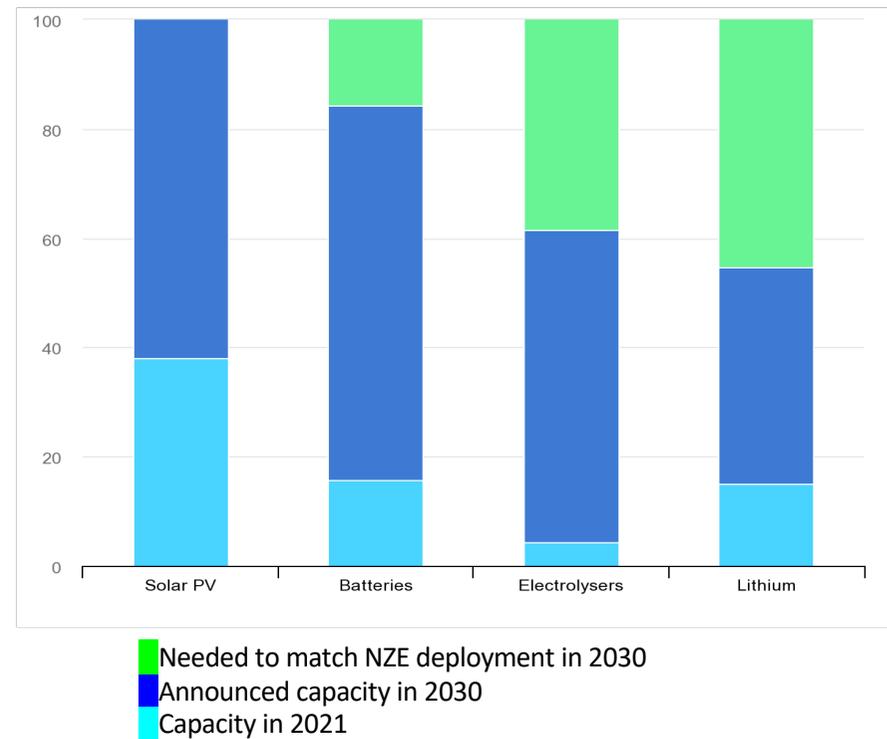
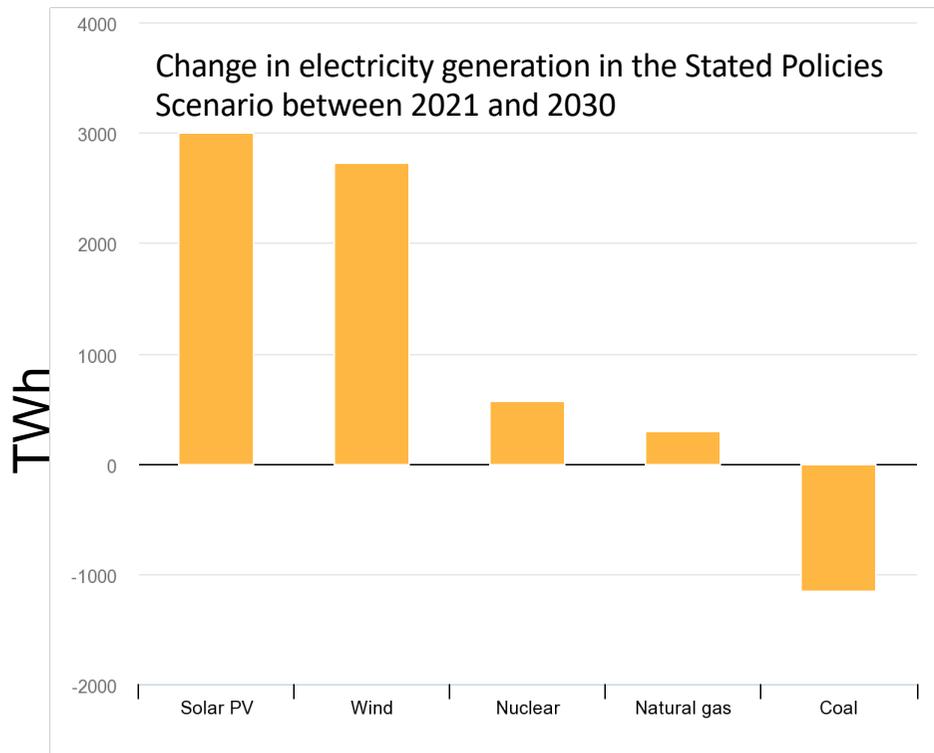
# Solar power introduction

- Motivation
- Course overview
- Solar irradiation
- PV-characteristics
- Cell technologies

# TSTE26 Powergrid and technology for renewable production

Elkraftnät och teknik för förnyelsebar elproduktion

[Executive summary – World Energy Outlook 2023 – Analysis - IEA](#)



# Course staff

## Lectures

- Lars Eriksson
- [lars.eriksson@liu.se](mailto:lars.eriksson@liu.se)
- Office B-building Fordonssystem Behind Café Java

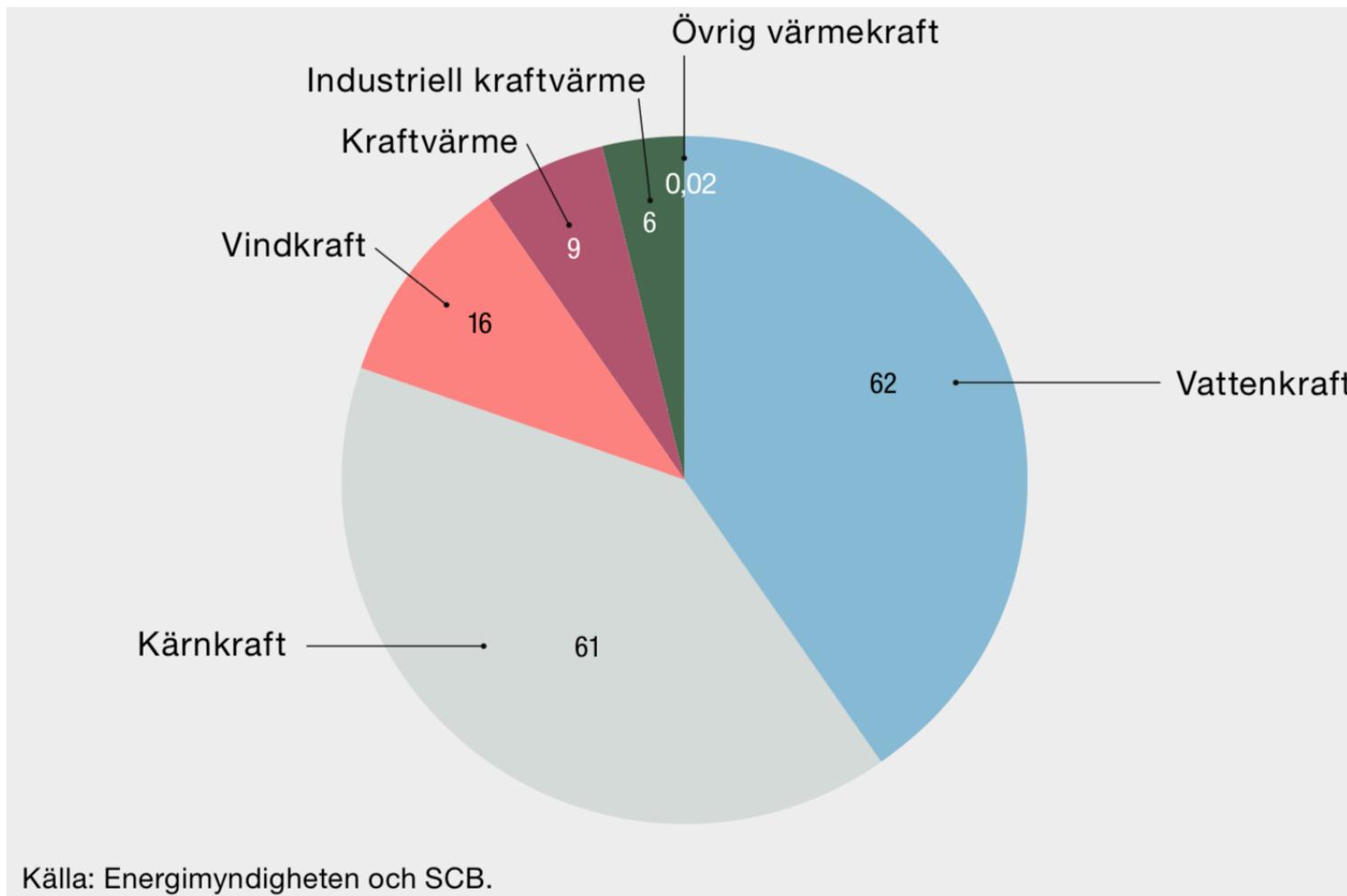
## Assistant for labs & tutorials:

- Arvind Balachandran ([arvind.Balachandran@liu.se](mailto:arvind.Balachandran@liu.se))
- Office L-Building

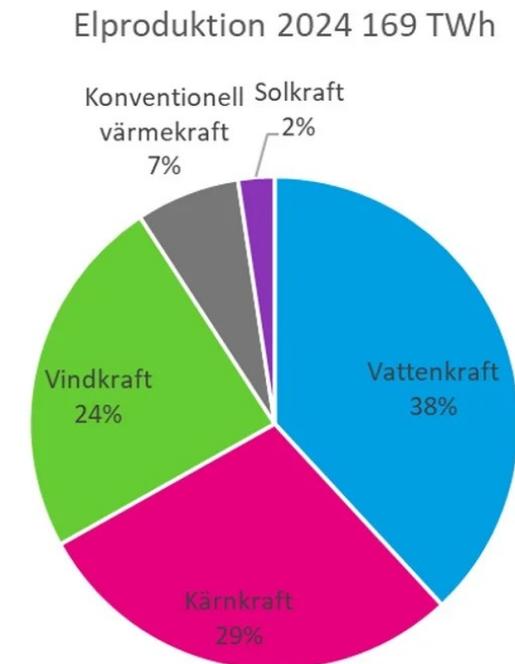
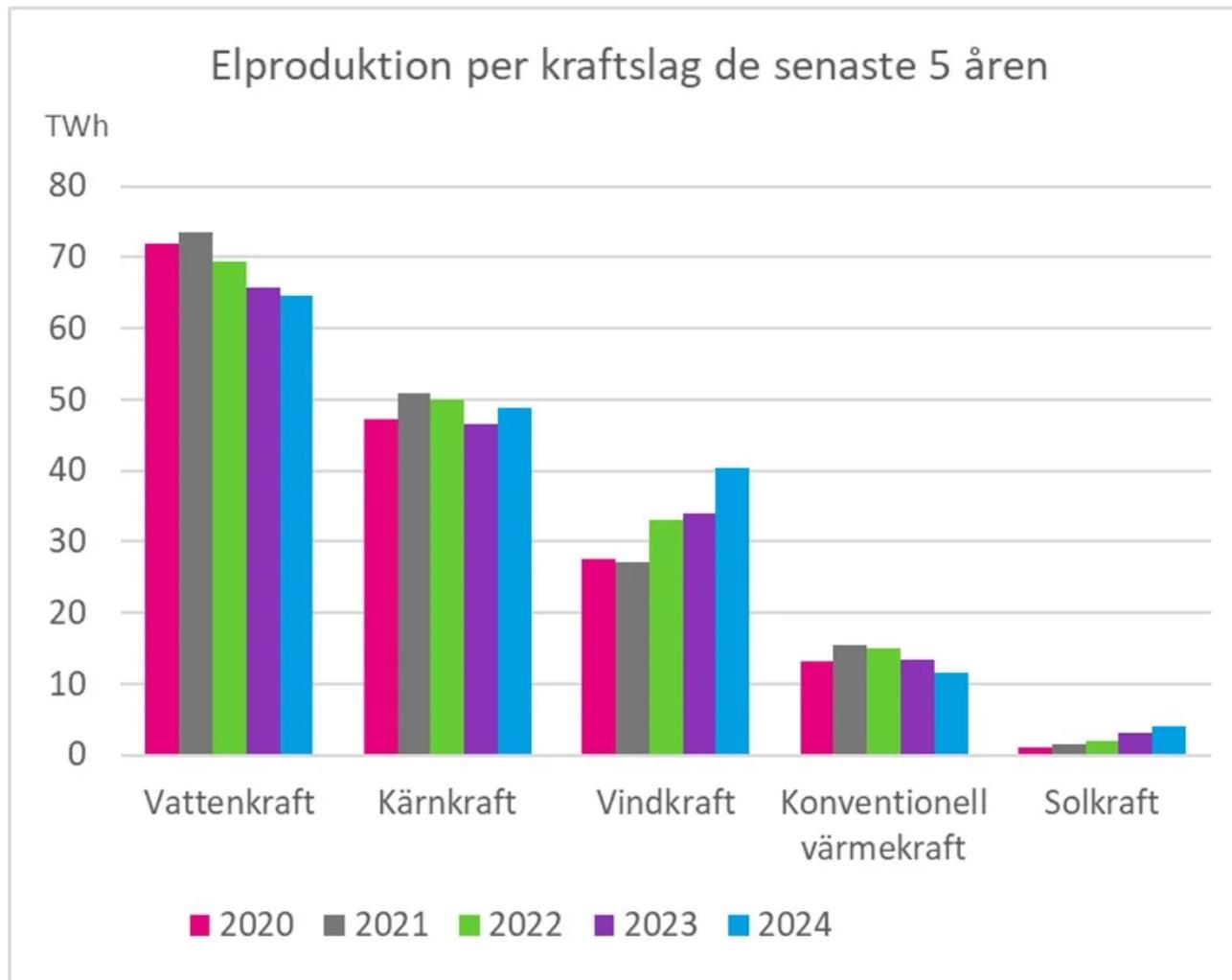
## Course web pages

- Lisam examination booking
- The Open Page

# Electricity production in Sweden 2016



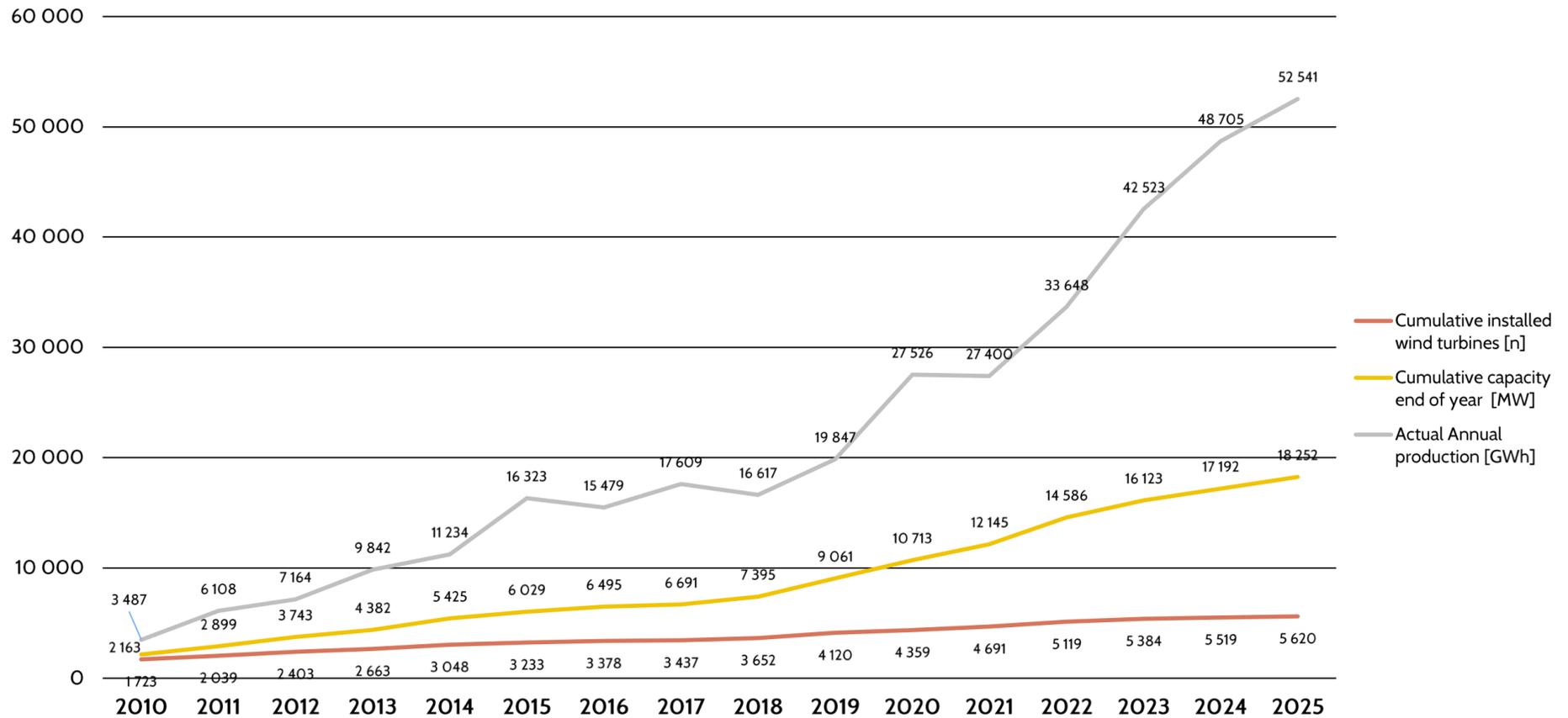
# Electricity production in Sweden 2020-2024



Source: Energiföretagen

# Wind power prediktion 22-10-29

## (Svensk vindenergi)



# Solar power introduction

- Motivation
- Course overview
- Solar irradiation
- PV-characteristics
- Cell technologies

# Understanding PV

- Semiconductor fundamentals and basic characteristics of PV cells
- PV cell technologies
- Solar module configuration, shading
- PV systems
  - Converter configurations
  - Grid connection
  - Stand alone operation

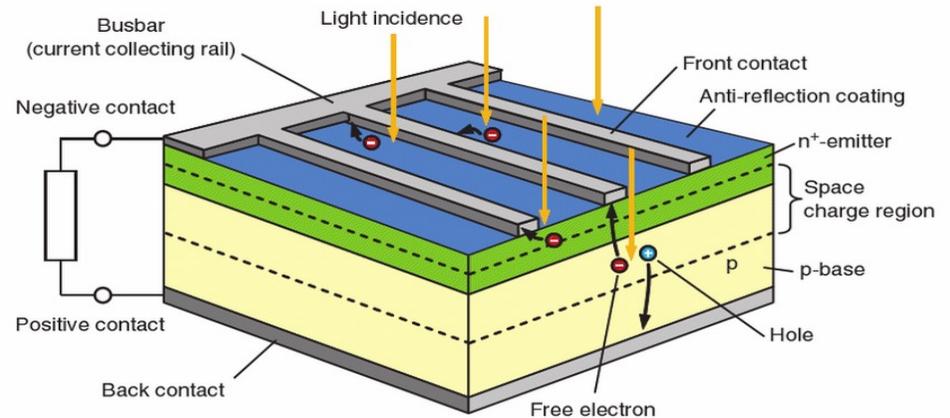
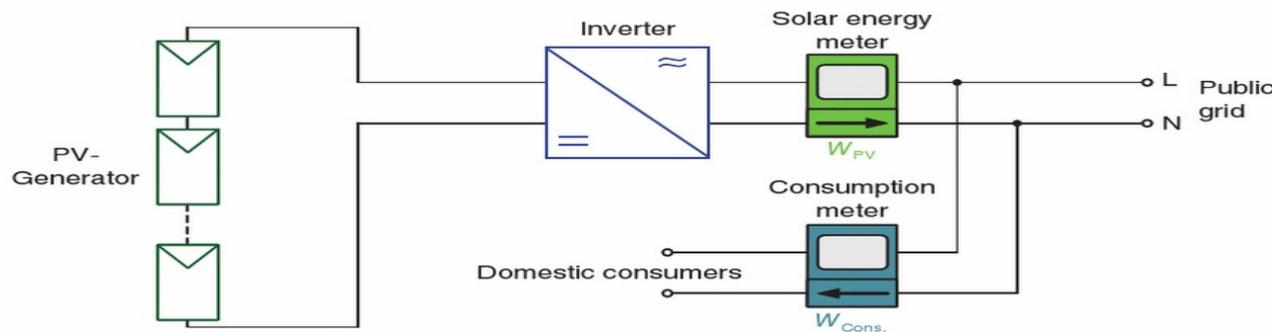
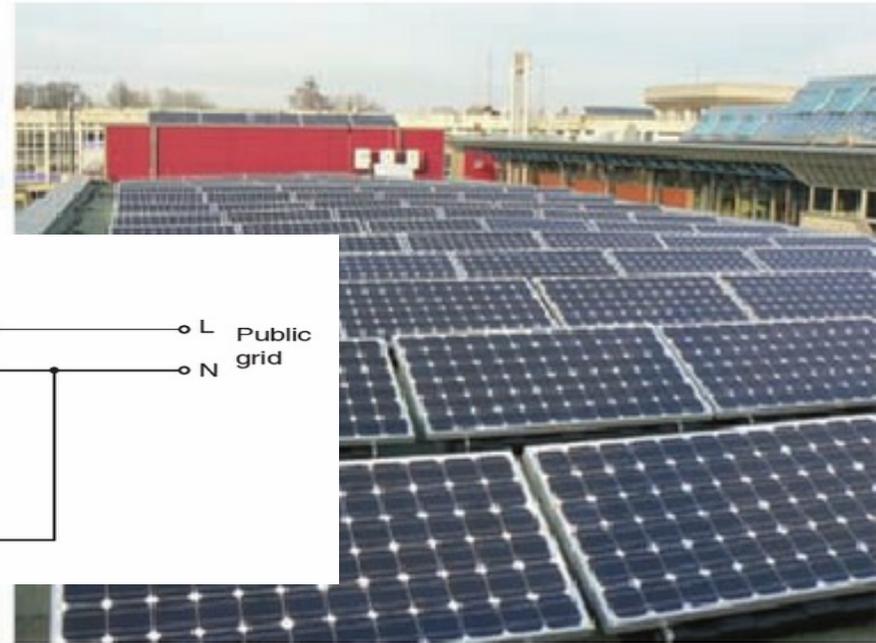


Figure 4.4 Typical silicon solar cell



# Power System Theory

- 1) PU-system, phasor representation, active/reactive power, 3-phase system
- 2) Transmission lines & cables
- 3) Power flow in power system networks
- 4) Circuit simulation using Simscape for MATLAB
- 5) Voltage control & stability
- 6) Transient stability & frequency control

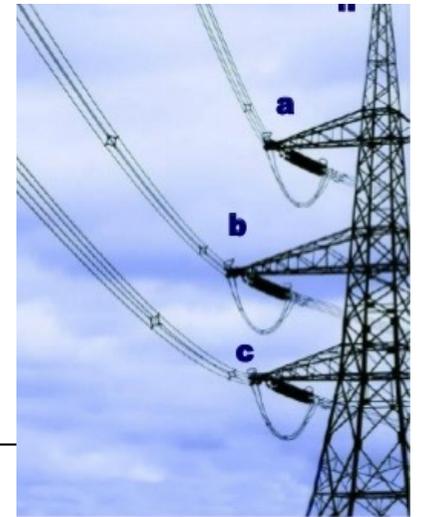
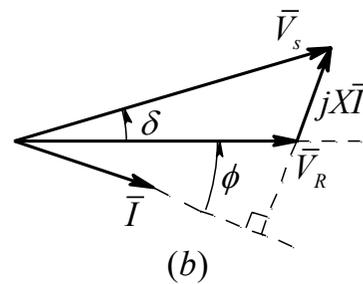
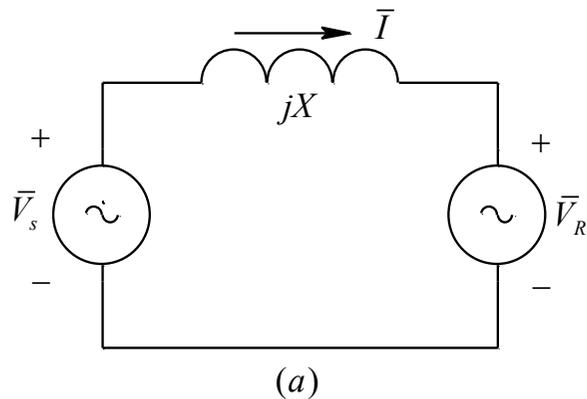
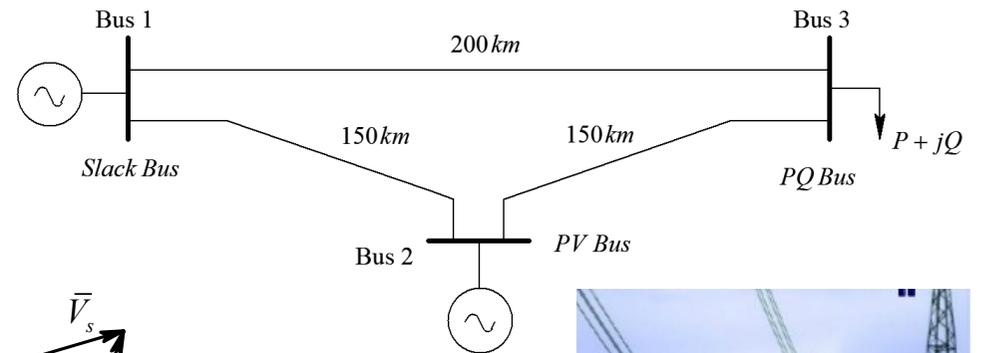
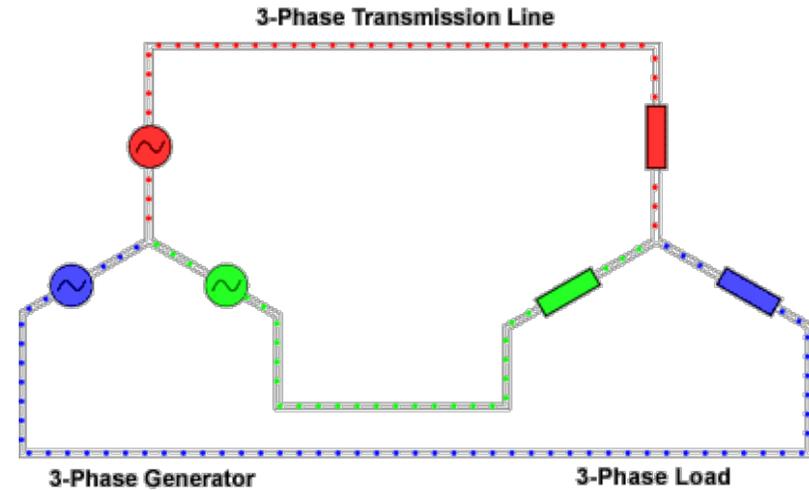
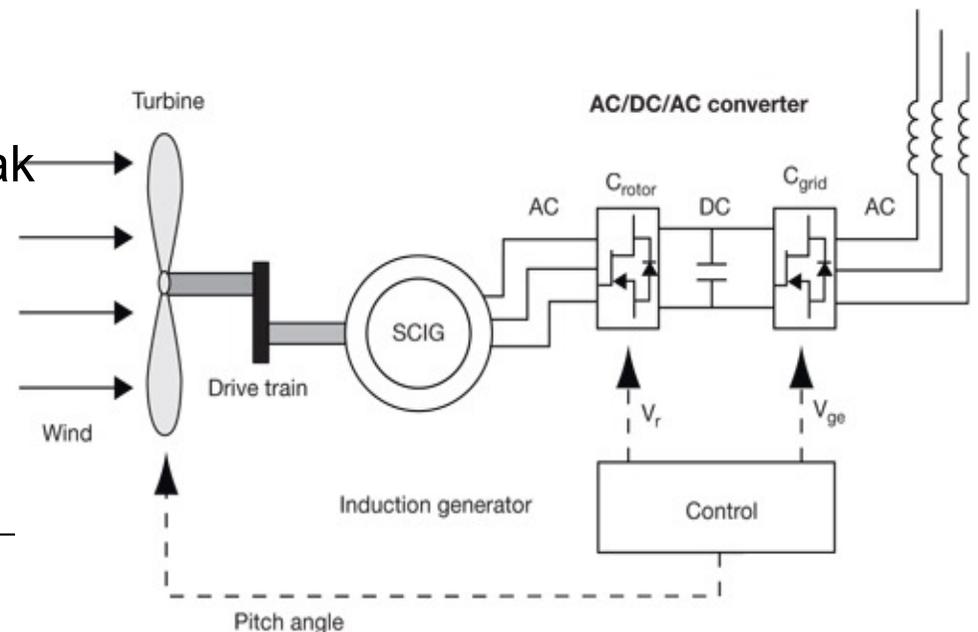
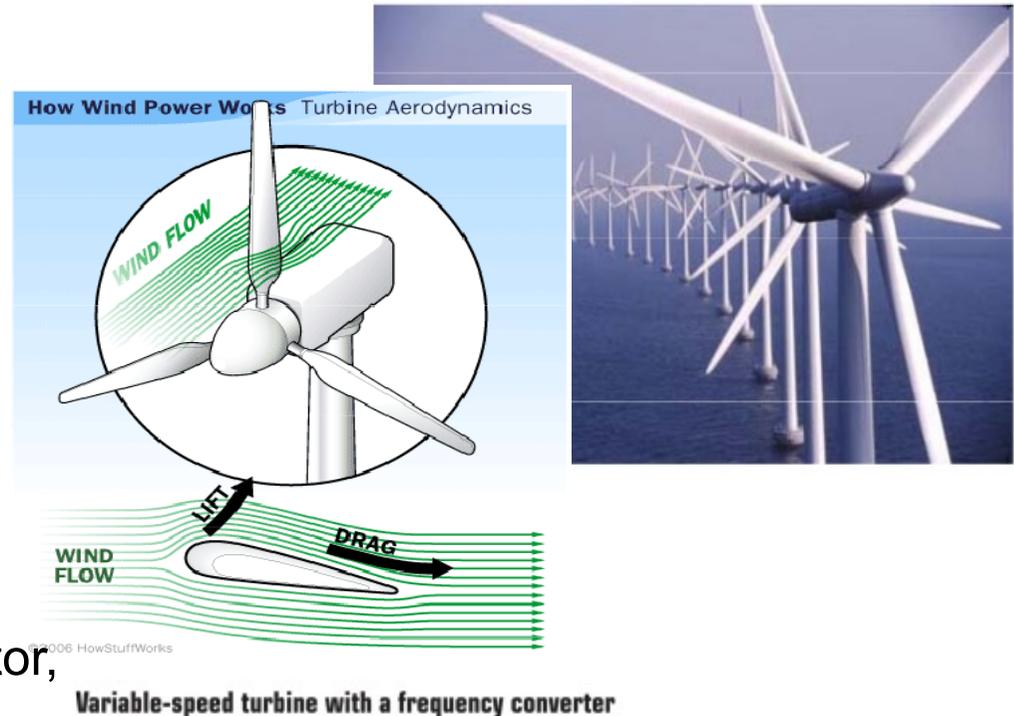


Fig. 2-17 Power transfer between two ac systems.

# Understanding wind power

- Wind fundamentals
  - Power vs wind equations
  - Basic turbine aerodynamics
- The wind power plant
  - Basic equipment
    - Generator. Synchronous generator, Induction generator
    - Gear-box
    - Transformer
    - Converter
  - Mechanical control: Pitch, Yaw, Break
  - Variable speed
  - Grid connection



# Goals

- describe the main principles of the powergrid and how to control the voltage and frequency through connected generation units and power converters
- describe the functional blocks of a wind turbine system and the associated properties for control
- describe the properties of a pv-system and how to connect to the powergrid
- describe how battery energy storage is dimensioned
- describe the function and control of power converters for integration of a generation unit to the power grid
- understand and use models for the main components of a powergrid in system simulation of a power system for energy production.

# Course Contents

- 9 Lectures given in 4 blocks:
  - PV-technology, lecture 1-2
  - Power system theory, lecture 3-4.
  - Wind-power technology, lecture 5-6
  - Power converter control, energy storage, lecture 7-9
- 7 Tutorials
  - PV-exercises
  - Power system basics
  - Load flow solution MATLAB Simscape/Simulink
  - Wind-turbines and voltage stability
  - Converter control
  - Transient stability, frequency control
  - Exam preparation
- 3 Labs
  - Lab 1: PV-module measurements (2x4 Hardware, sign-up needed)
  - Lab 2: Power grid and wind-turbine simulation
  - Lab 3: Power converter control

# Literature

## Main books

1. [Electric Power Systems a first course, Ned Mohan, Wiley 2012](#)  
Not available any more, but extract available in Lisam
2. [Photovoltaics: Fundamentals, Technology and Practice, Mertens, Konrad, Hanser, Karl Friedrich, Wiley 2013 \(Available as eBook at Liu library\)](#)
3. [Wind Power Integration: Connection and System Operational Aspects 2<sup>nd</sup> ed, Brendan Fox et al, IET 2014 \(Available as eBook at Liu library\)](#)

Reading guidelines in course information in Lisam.

## Other books

- Grid Converters for Photovoltaic and Wind Power Systems, Remus Teodorescu, Marco Liserre, Pedro Rodriguez, Wiley 2010 (eBook)
- [Wind Energy Explained: Theory, Design and Application, J.F. Manwell, J.G. McGowan, A.L. Rogers, Wiley 2002 \(eBook, Online Access\)](#)

# Examination

- 3 Labs completed
  - Results presented in written report
- Written exam 14<sup>th</sup> January 2023. Computer aided examination.
  - Allowed to bring one own designed A4 to the exam.

# Solar power introduction

- Solar irradiation
- PV-characteristics
- Cell technologies

# Solar power

## Solar thermal energy

- Water heating

## Concentrated solar thermal

- Steam turbine driving electric generator

## Photovoltaic solar energy



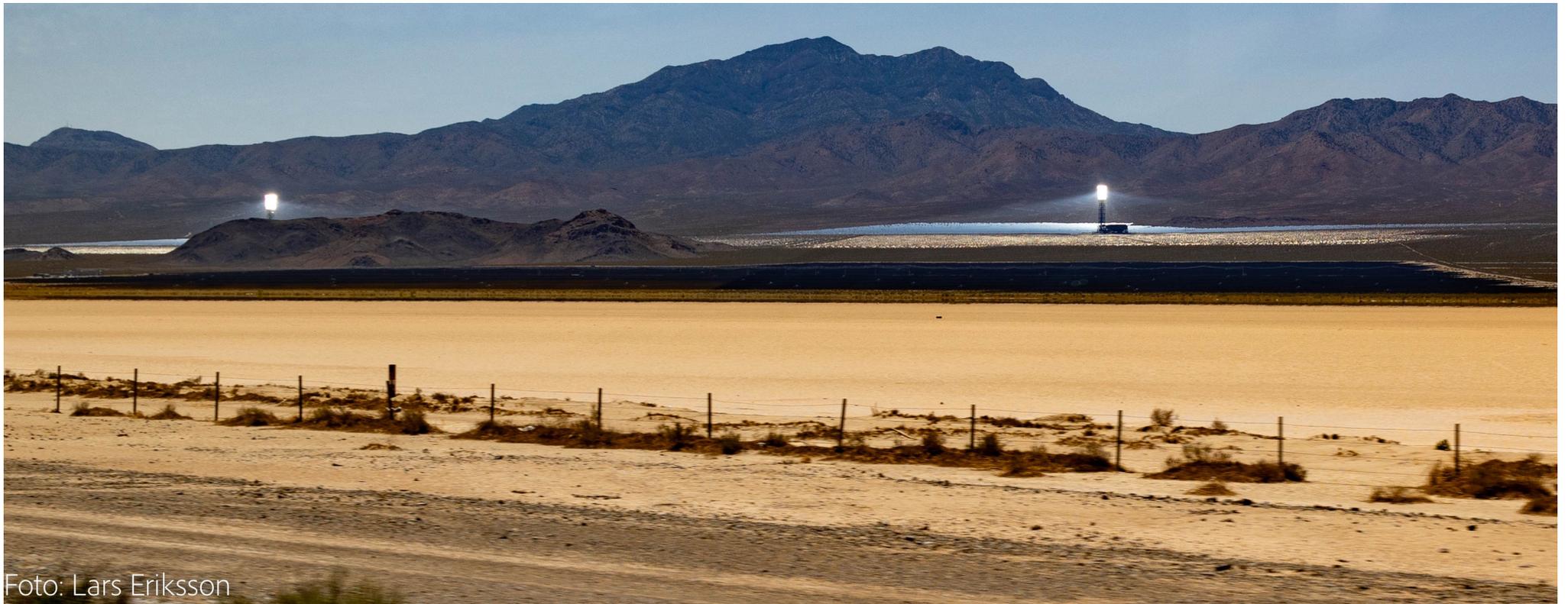
# Solar power – Ivanpah Solar Power Facility (Mojave Desert)

- Concentrate sun to heat to electricity
  - Steam turbine drives electric generator

Three 140 m boilers in towers. Total 392 MW.

173.500 heliostats (2 mirrors each)

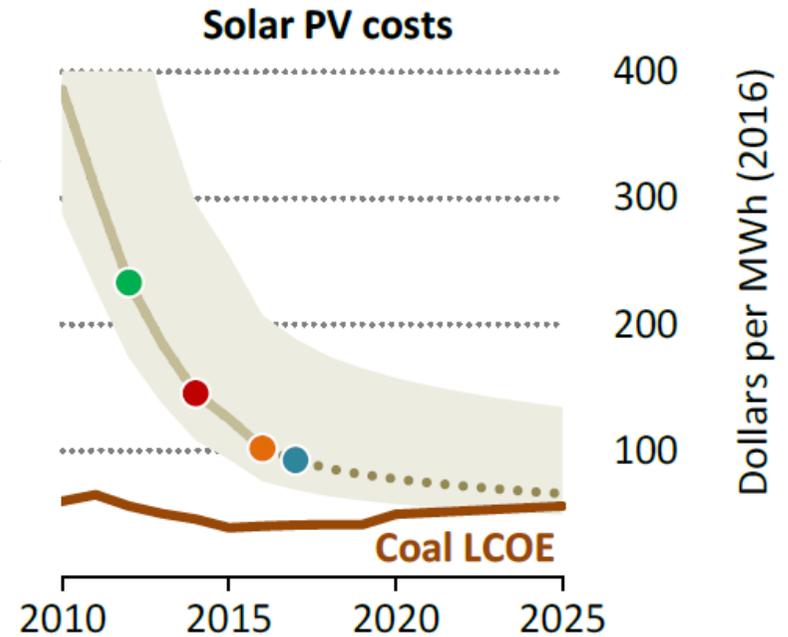
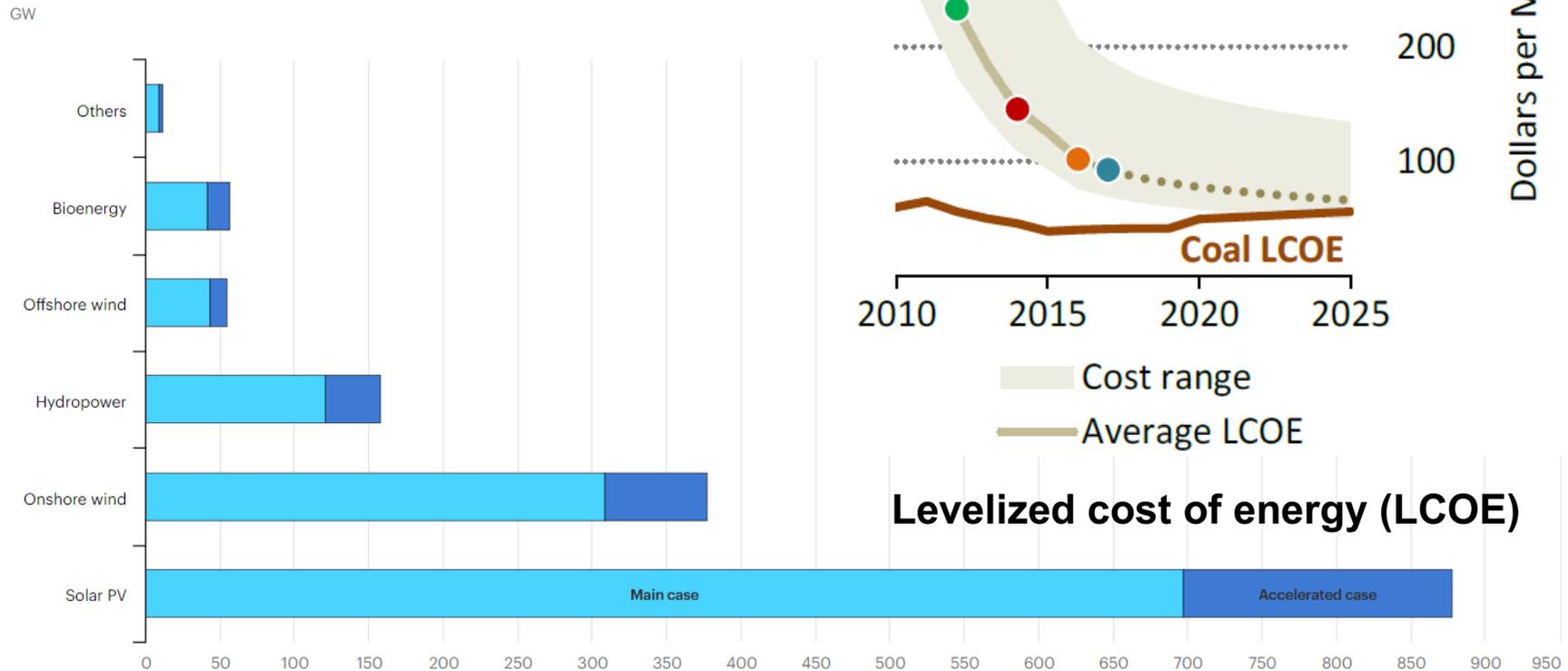
Cost of photovoltaic elements is sinking, more economic presently.



# Global PV expansion

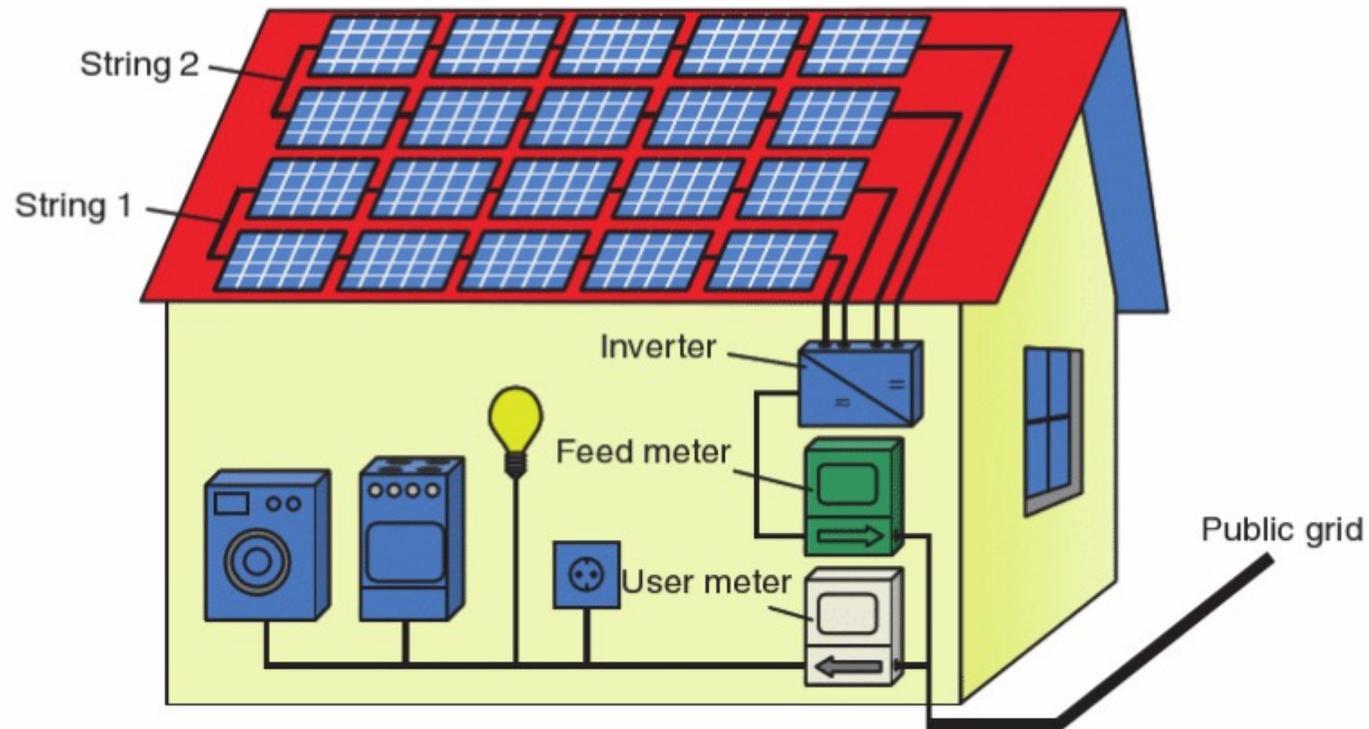
[IEA – International Energy Agency](#)

Renewable capacity growth between 2019 and 2024 by technology



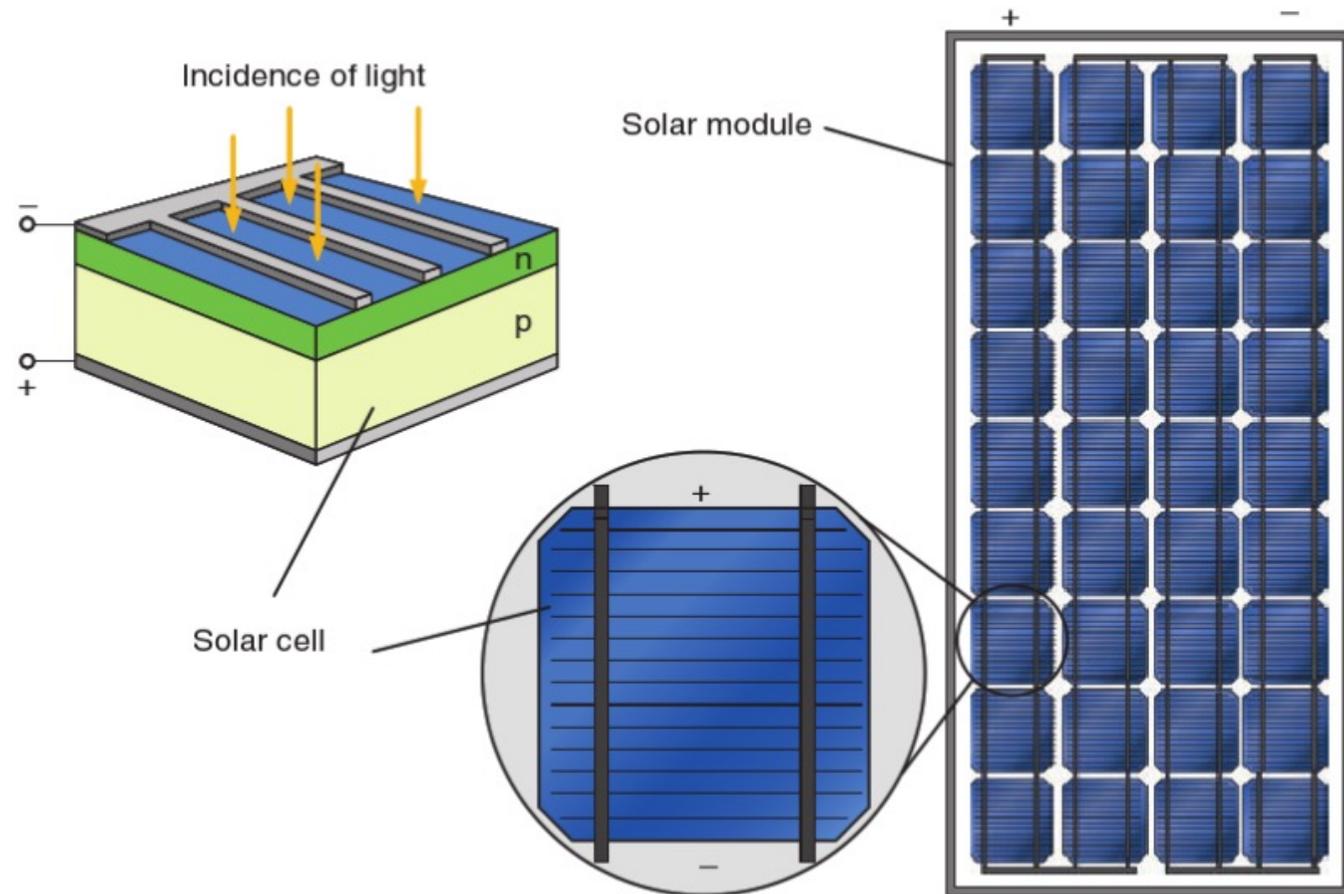
**Levelized cost of energy (LCOE)**

# PV-system



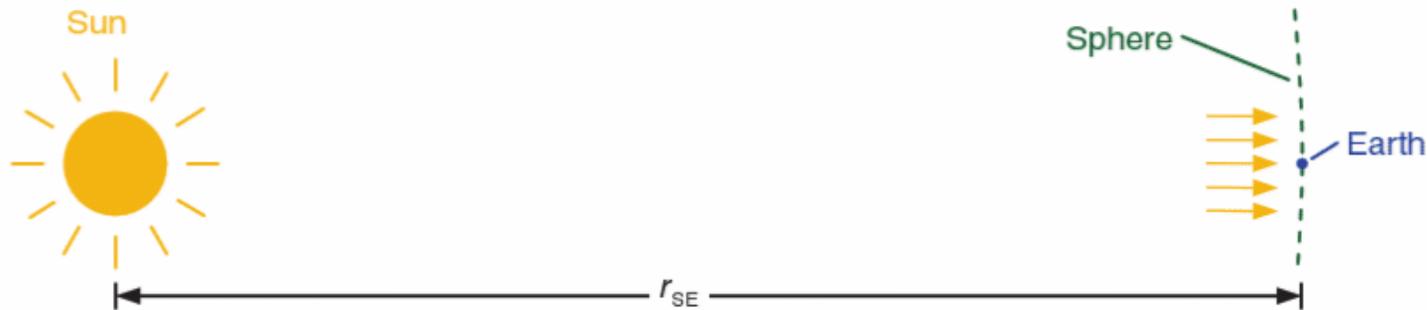
**Figure 1.9** Structure of a grid-coupled photovoltaic plant. An inverter converts the direct current supplied by the solar modules into alternating current and feeds it into the public grid

# PV-cells that build solar modules



**Figure 1.8** The solar cell and solar module as basic components of photovoltaics

# The Power source!

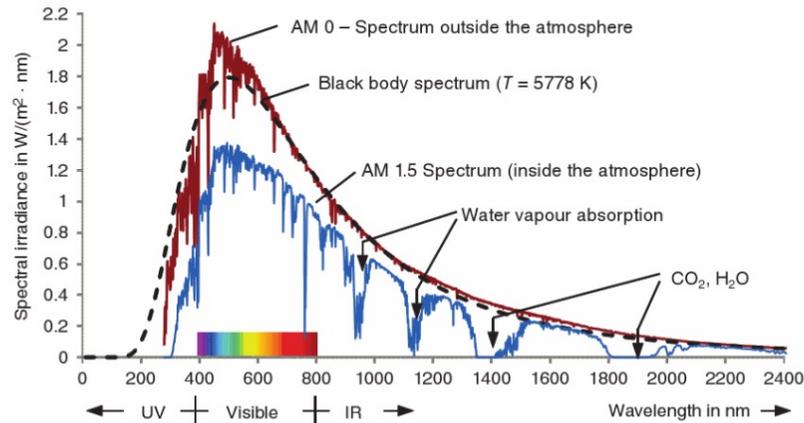


$$E_s = \frac{\text{Radiation power}}{\text{Area of sphere}} = \frac{P_{\text{Sun}}}{4 \cdot \pi \cdot r_{\text{SE}}^2} = \frac{3.845 \cdot 10^{26} \text{ W}}{4 \cdot \pi \cdot (1.496 \cdot 10^{11} \text{ m})^2} = 1367 \text{ W/m}^2$$

Solar constant  
(power density, irradiance):

$$E_s = 1367 \text{ W/m}^2$$

# Spectral irradiance

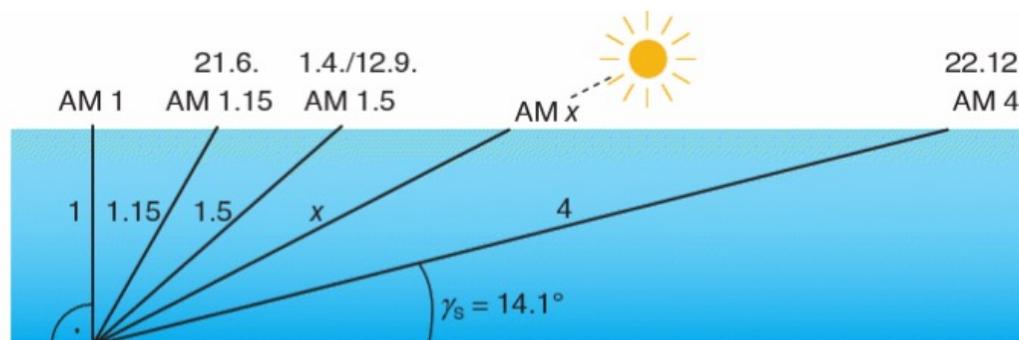


Spectrum and energy change when light passes through the atmosphere

- Reflection
- Absorption
- Scattering

Air mass (AM):

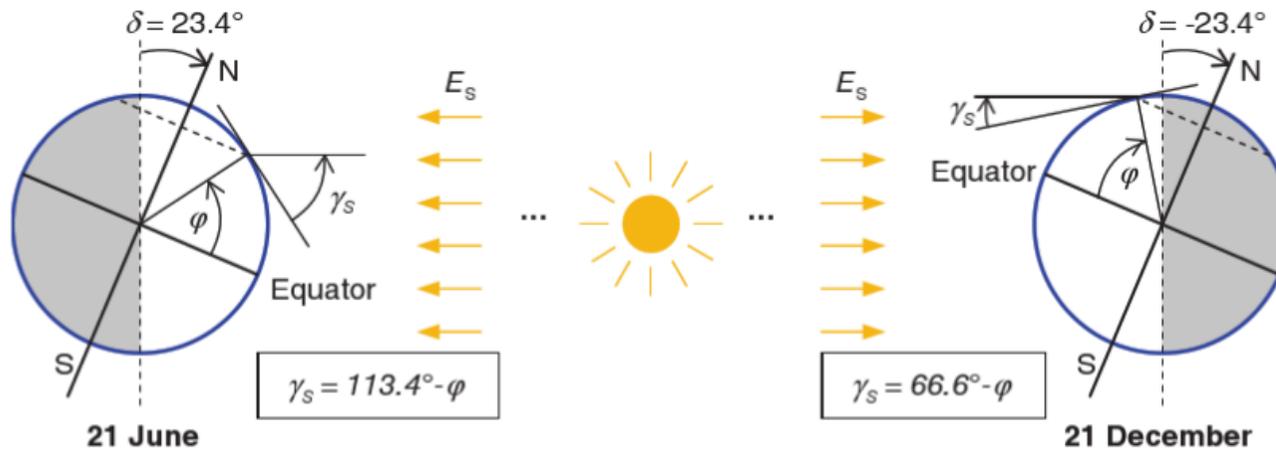
- The relative distance of light travel through atmosphere



$$E_{Direct}(AM0) = 1367 \frac{W}{m^2}$$

$$E_{Direct}(AM1.5) = 835 \frac{W}{m^2}$$

# Solar altitude and azimuth

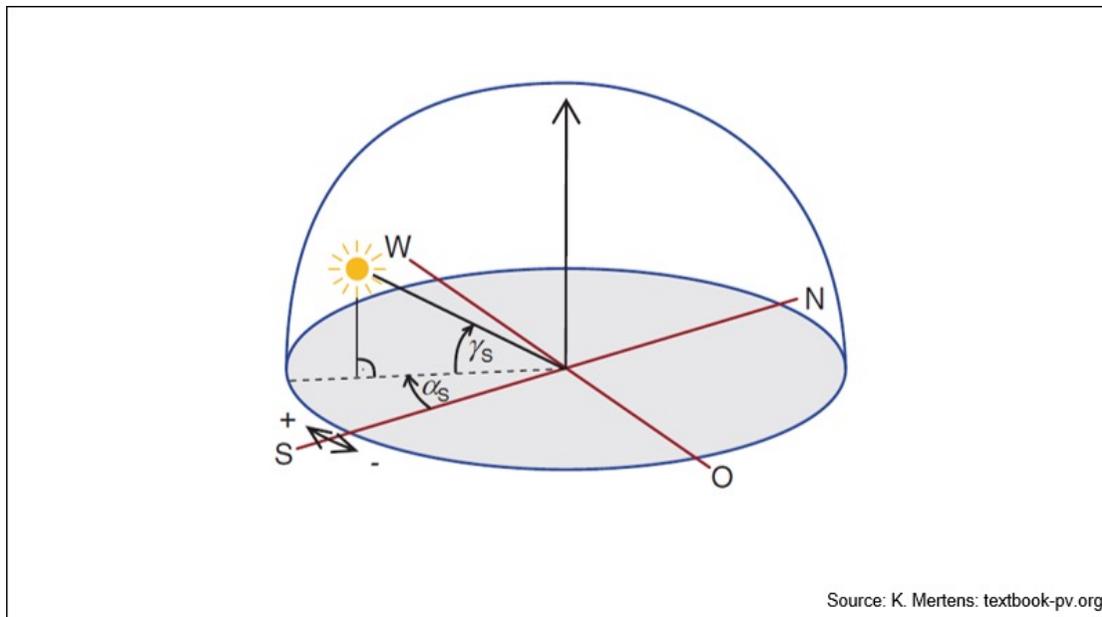


Local solar altitude above horizon,  $\gamma_s$

- Time of year
- Latitude

$$\gamma_{S\_Max} = 113.4^\circ - \varphi.$$

$$\gamma_{S\_Min} = 66.6^\circ - \varphi.$$

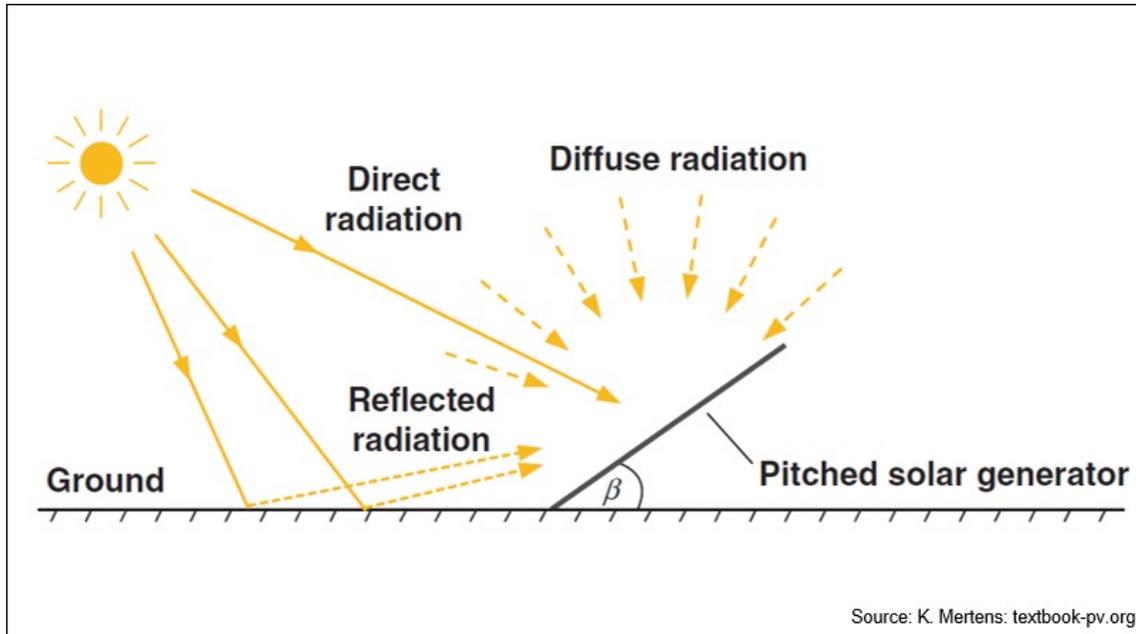


**Azimuth of the sun,  $\alpha_s$**

- Orientation of solar modules related to south

Source: K. Mertens: textbook-pv.org

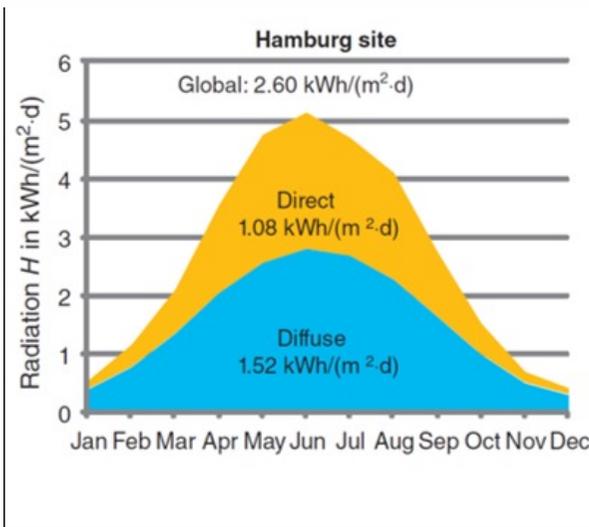
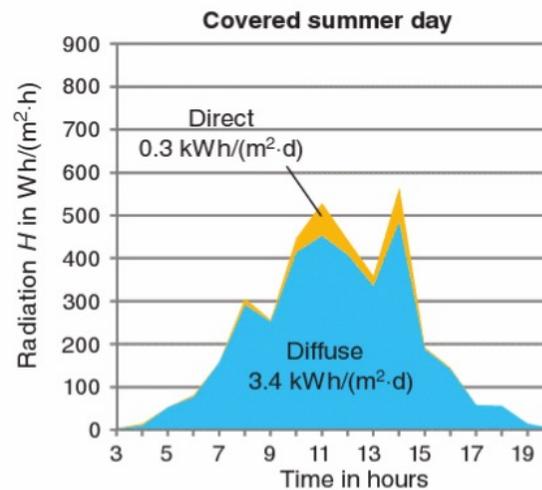
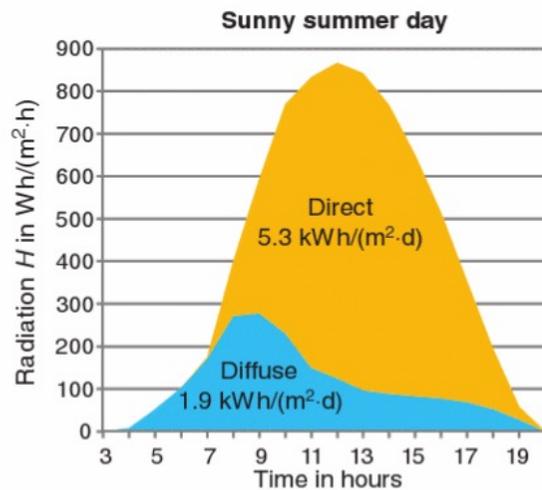
# Standard Test Conditions (STC)



$$E_G = E_{\text{Direct}} + E_{\text{Diffuse}}$$

1.  $E_G = E_{STC} = E_{\text{Direct}}(AM1.5) + E_{\text{Diffuse}} = 1000 \text{ W/m}^2$
2. Module temp,  $\vartheta_{\text{module}} = 25^\circ\text{C}$
3.  $AM = 1.5$

# Available radiation $H$ , Energy per Time unit



Hourly radiation:

$$H \left[ \frac{Wh}{(m^2 \cdot h)} \right]$$

Daily radiation:

$$H \left[ \frac{kWh}{(m^2 \cdot d)} \right]$$

Annual radiation:

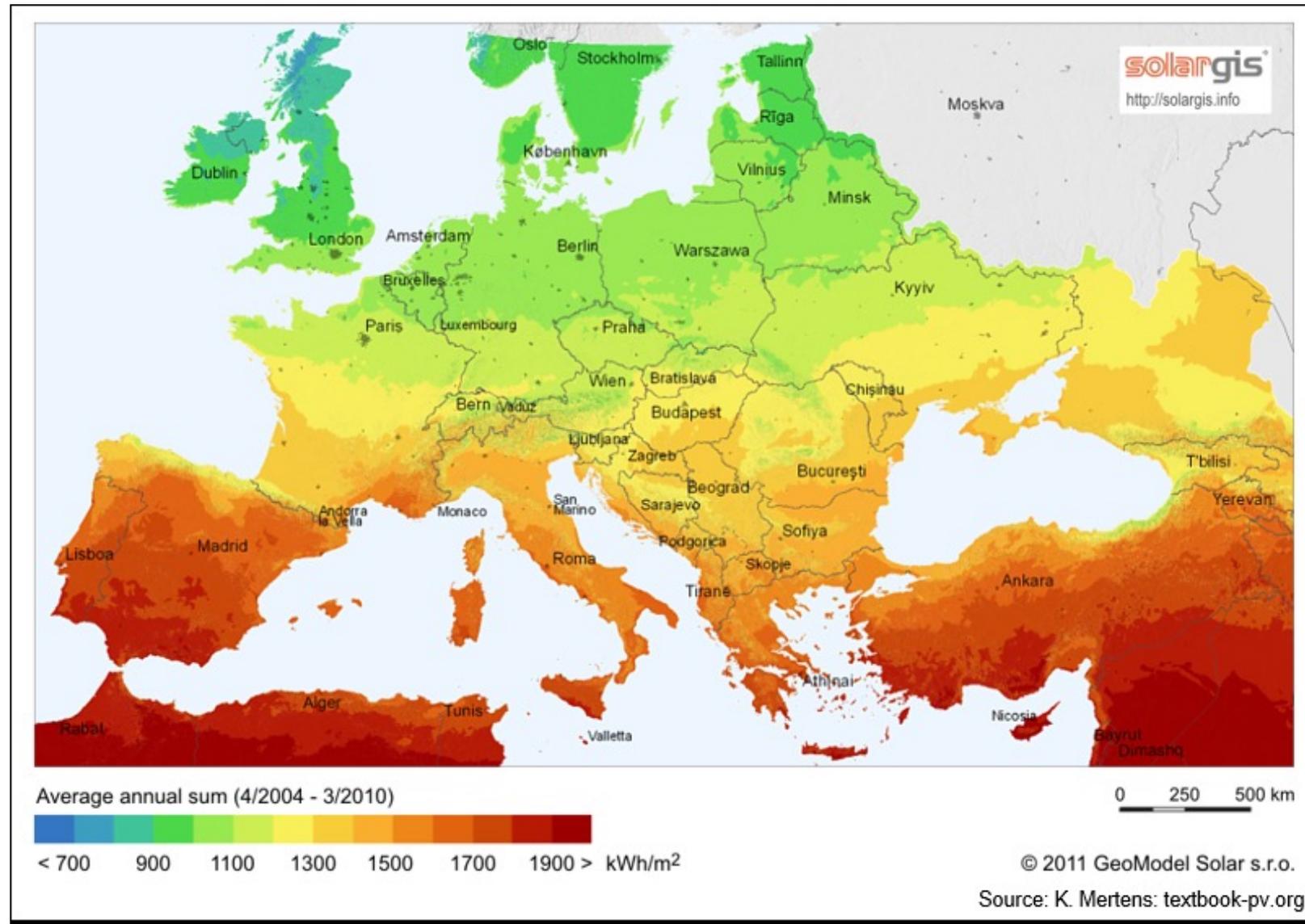
$$H \left[ \frac{kWh}{(m^2 \cdot a)} \right]$$

Global average:

$$H = 3.15 \frac{kWh}{(m^2 \cdot d)} \cdot 365 \frac{d}{a} = 1150 \frac{kWh}{(m^2 \cdot a)}$$

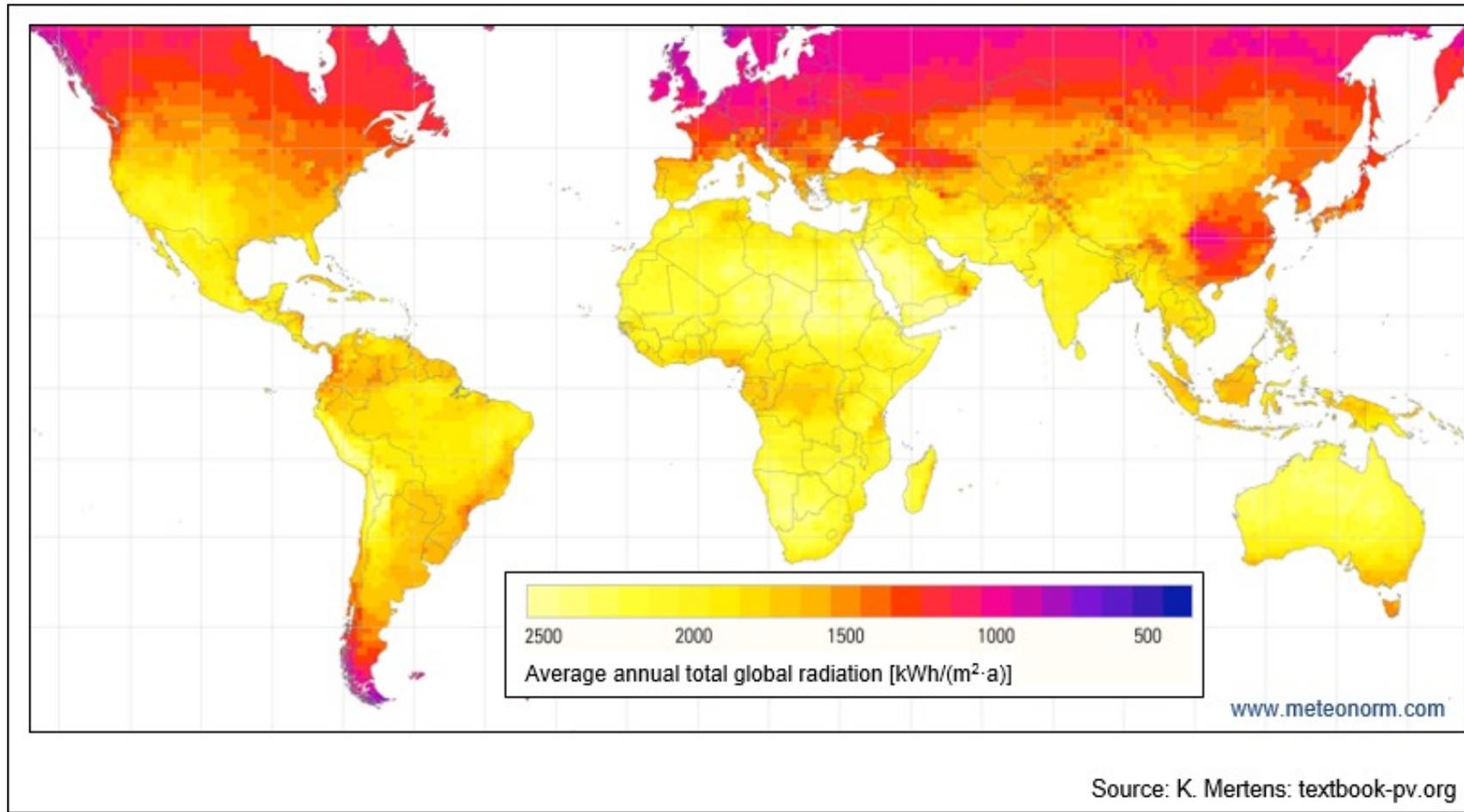
# Global Horizontal Irradiation (GHI)

- Annual irradiation on a horizontal plane



# Global Horizontal Irradiation (GHI)

- Annual irradiation on a horizontal plane



# Average solar irradiation

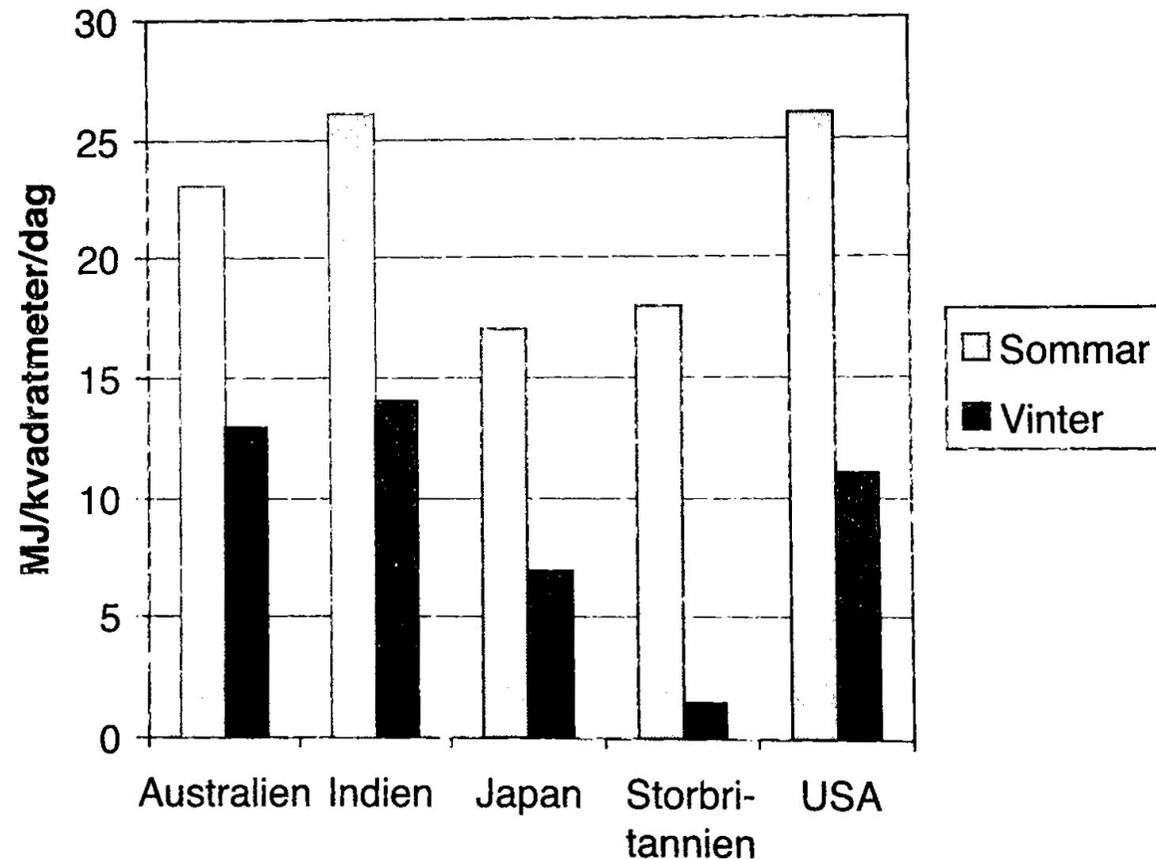
Average solar irradiation for different locations

| Stad           | Solinstrålning | Stad         | Solinstrålning |
|----------------|----------------|--------------|----------------|
| Seattle        | 125            | Neapel       | 200            |
| El Paso        | 240            | Kairo        | 280            |
| Rio de Janeiro | 200            | Johannesburg | 230            |
| Glasgow        | 100            | Bombay       | 240            |
| Tokyo          | 125            | Sydney       | 210            |

*Källa:* Data från Trewartha & Horn, 1980.

In reality the average power varies between 100 and 300W/m<sup>2</sup>.

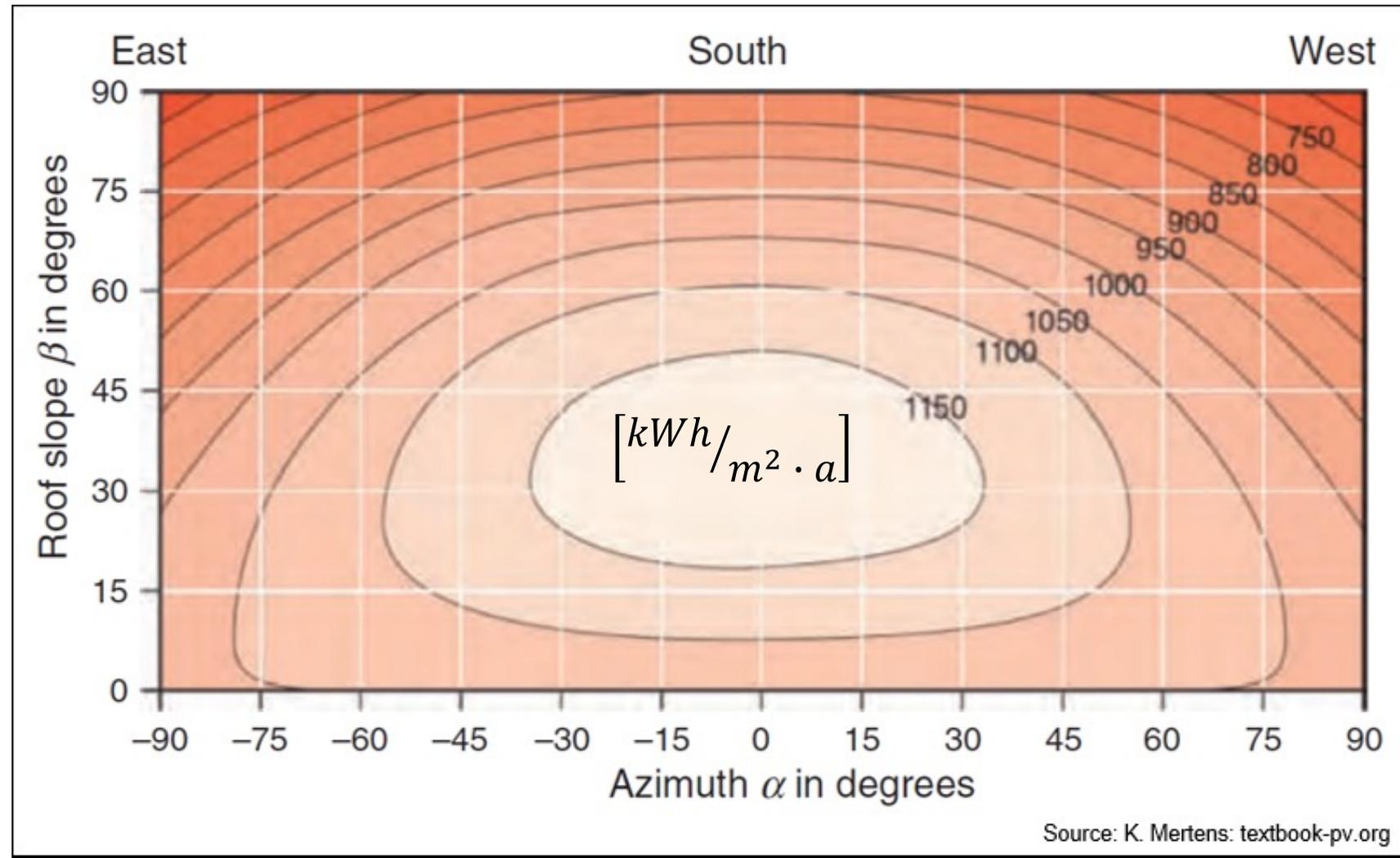
## Average solar irradiation – summer vs winter



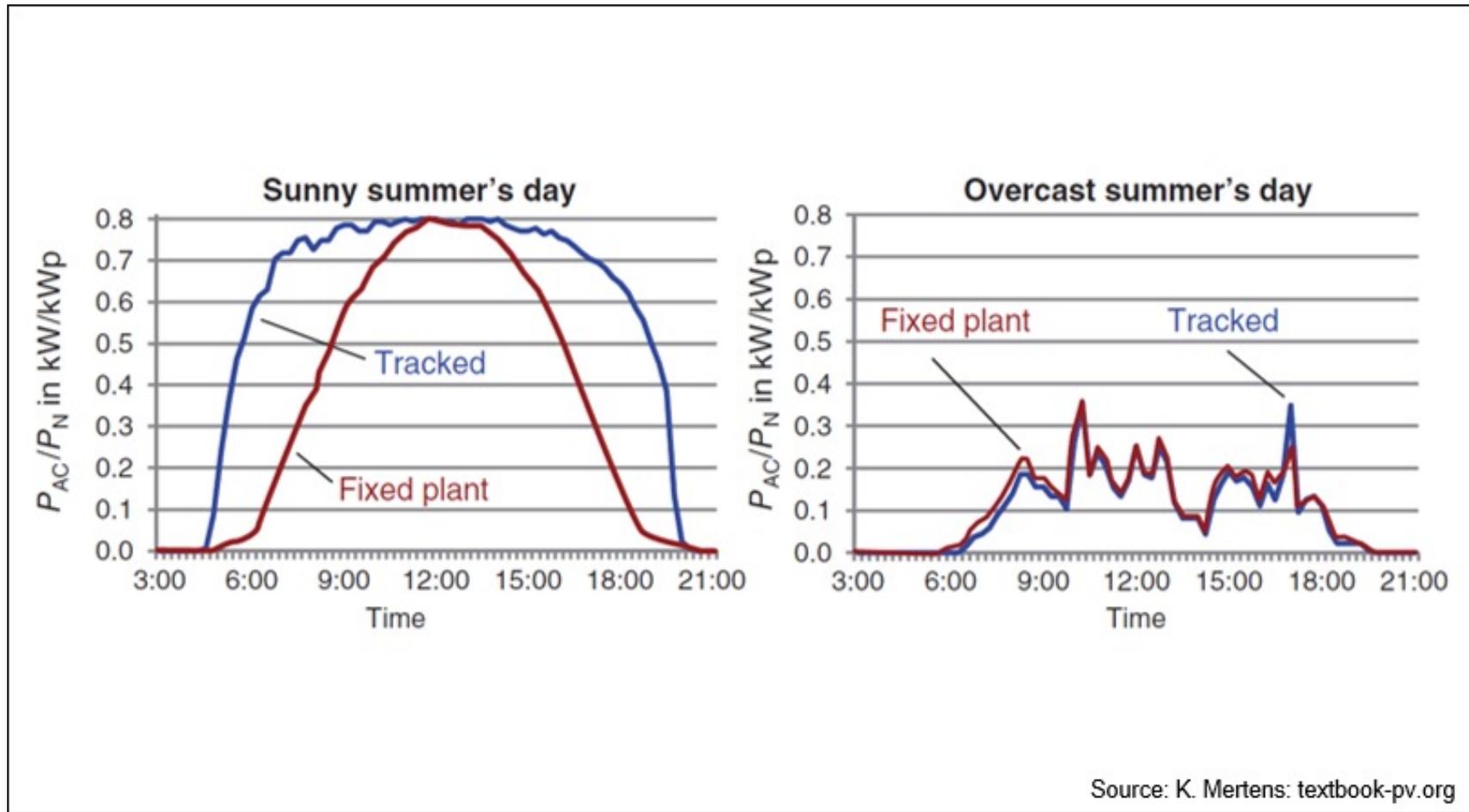
Note that 1 MJ/day corresponds to an average power of 11.6 W, so 210 W/m<sup>2</sup> in Sydney (from previous slide) corresponds to approx 18 MJ/m<sup>2</sup>/day.

**FIGUR 9-1** Genomsnittligt årstidsbaserat inflöde av solenergi per kvadratmeter i valda länder. (Källa: Norton [1992].)

# Dependency of orientation and pitch



# Sun tracking



# Solar irradiation Linköping

Monthly solar irradiation estimates

Example:

Optimal angle

$$\beta = 39^\circ$$

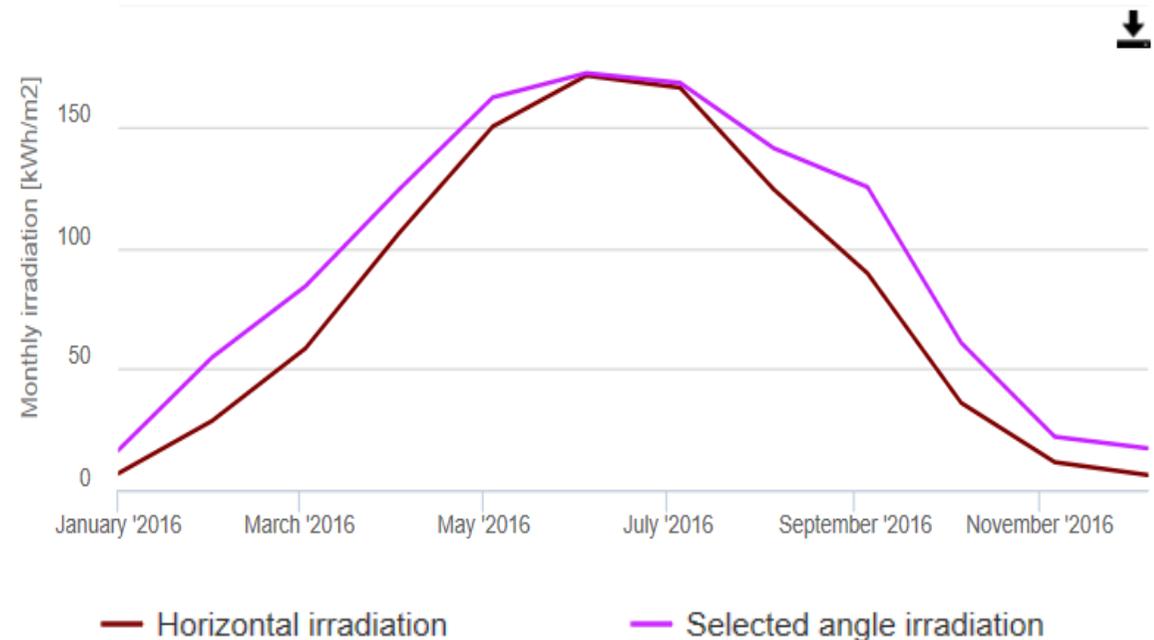
$$H(39) = 3.0 \text{ kWh/m}^2 \cdot \text{d}$$

$$\text{Yearly: } 365 \cdot H(39) = 1095 \text{ kWh/m}^2 \cdot \text{a}$$

$$E_{STC} = 1 \text{ kW/m}^2$$

$$\frac{1095 \left[ \text{kWh/m}^2 \cdot \text{a} \right]}{1 \left[ \text{kW/m}^2 \right]} = 1095 \text{ h/a}$$

1095 full-load sun hours



Database used: PVGIS-Sarah

**PV-GIS**

European Commission,  
Institute of Energy and  
Transport (IET)

# PV module

320 W at STC

1.6 m<sup>2</sup>

5kW = 15.6 modules

Total 25 m<sup>2</sup>

## Elektriska egenskaper(STC 1000W/m<sup>2</sup>, 25°C, AM1.5)

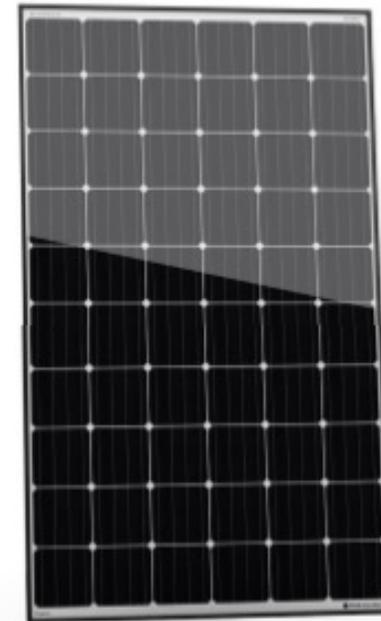
|                               |              |
|-------------------------------|--------------|
| Modell                        | PPAM-Onyxium |
| Max. Effekt [Pmax]            | 320 Wp       |
| Öppenkretsspänning [Voc]      | 40,67 V      |
| Spänning vid maxeffekt [Vmpp] | 32,25 V      |
| Kortslutningsström [Isc]      | 10,49 A      |
| Ström vid maxeffekt [Impp]    | 9,92 A       |
| Modulens effekttolerans       | 0/+3%        |
| Verkningsgrad panel modul     | 19,76%       |

## Fysiska egenskaper

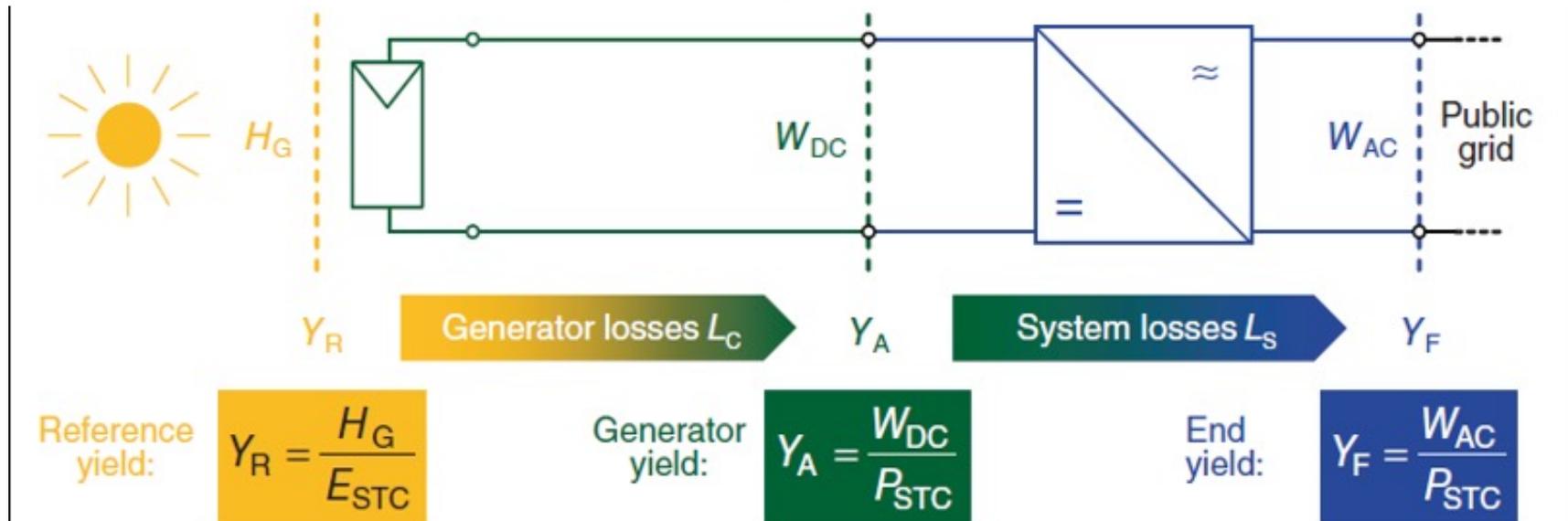
|                           |   |
|---------------------------|---|
| Celltyp                   | Monokristalin   |
| Celldimensioner           | 156x156mm   |
| Celler/Dioder per modul   | 60  |
| Ram                       | Anodiserad Aluminium  |
| Max spänning system       | 1000 V  |
| Modulvikt                 | 19,5 kg   |
| Moduldimensioner          | 1640 x 990 x 40mm   |
| Testade vädertemperaturer | -40°C to +85°C  |
| Max belastning            | 550 kg/m <sup>2</sup> framsida(snö)<br>245 kg/m <sup>2</sup> bak & framsida<br>(vind) |

## Termiska egenskaper

|                                |           |
|--------------------------------|-----------|
| NOCT                           | 46 °C     |
| Spänning temperaturkoefficient | -0.24%/K  |
| Temperatur koefficient ström   | +0.032%/K |
| Temperatur koefficient effekt  | -0,40%/K  |



# Yield for a solar plant



Source: K. Mertens: textbook-pv.org

Available irradiation  $\left[\frac{kWh}{m^2}\right]$ :  $H_G$

Energy output  $\left[\frac{kWh}{m^2}\right]$ :  $W_{DC} = H_G \cdot \eta$

Rated module power [kW]:  $P_{STC} = E_{STC} \cdot \eta$

PV-module efficiency:  $\eta = \frac{P_{STC}}{E_{STC}} = \frac{W_{DC}}{H_G}$

**Yield, no of hours at rated power**

$$Y_A[h] = \frac{W_{DC}}{P_{STC}} = \frac{H_G \cdot \eta}{E_{STC} \cdot \eta} = Y_R$$

# Solar power introduction

- Solar irradiation
- PV-characteristics
- Cell technologies



# The PV-cell

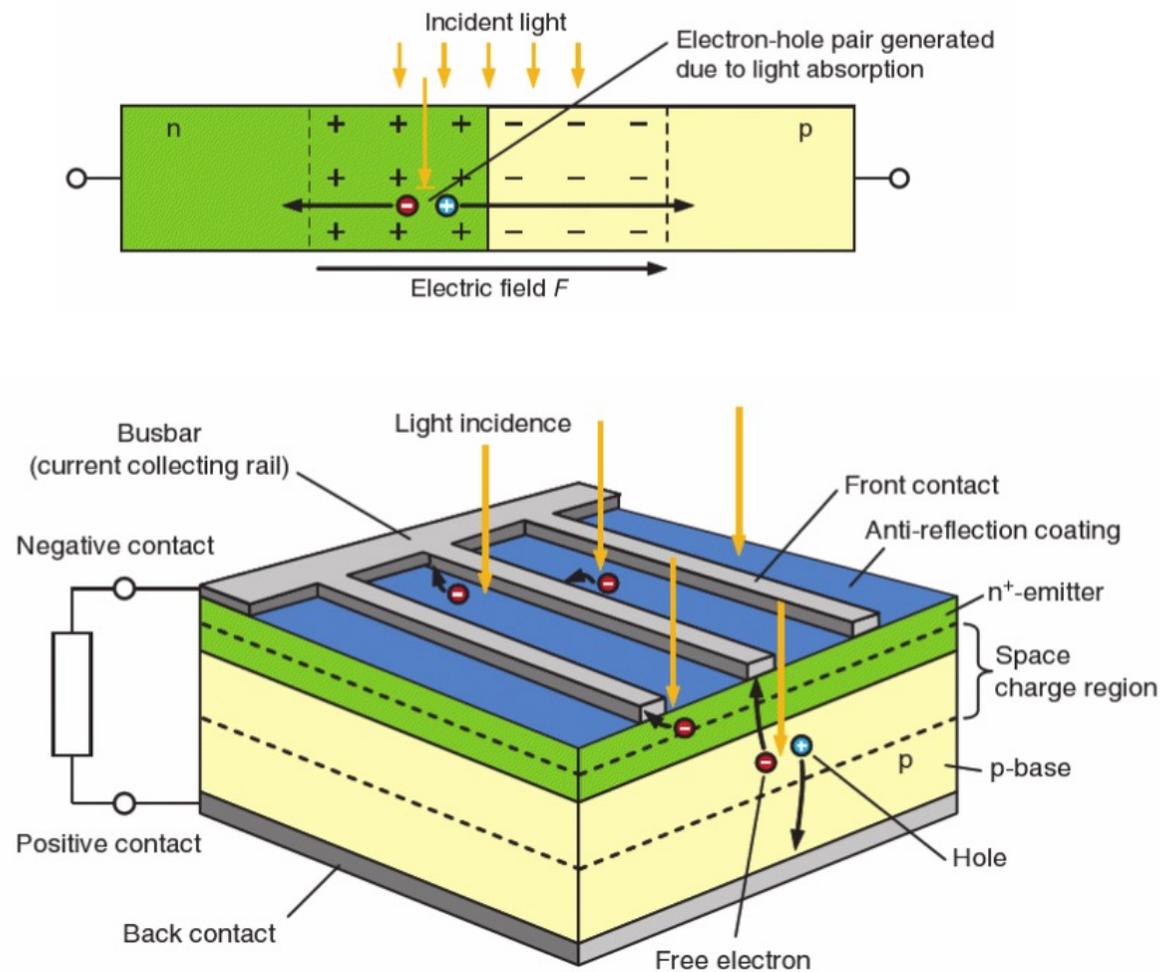


Figure 4.4 Typical silicon solar cell

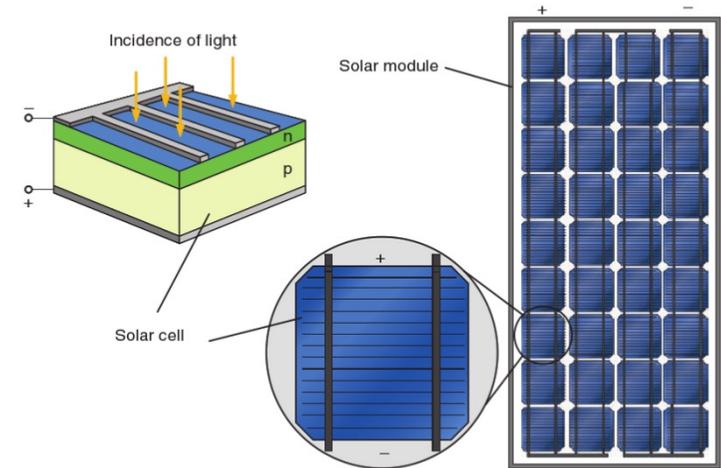


Figure 1.8 The solar cell and solar module as basic components of photovoltaics

# The photodiode

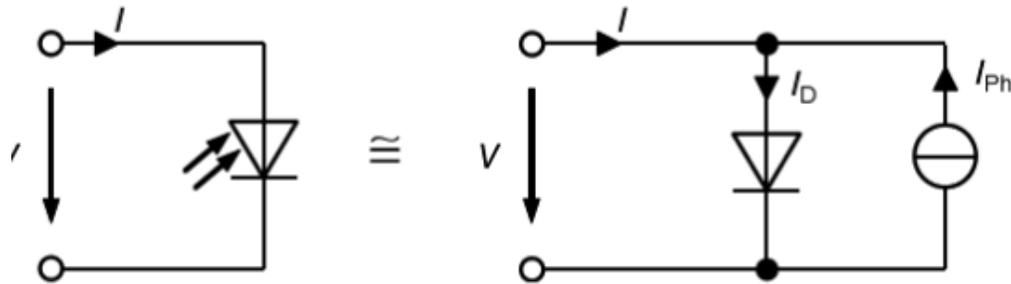
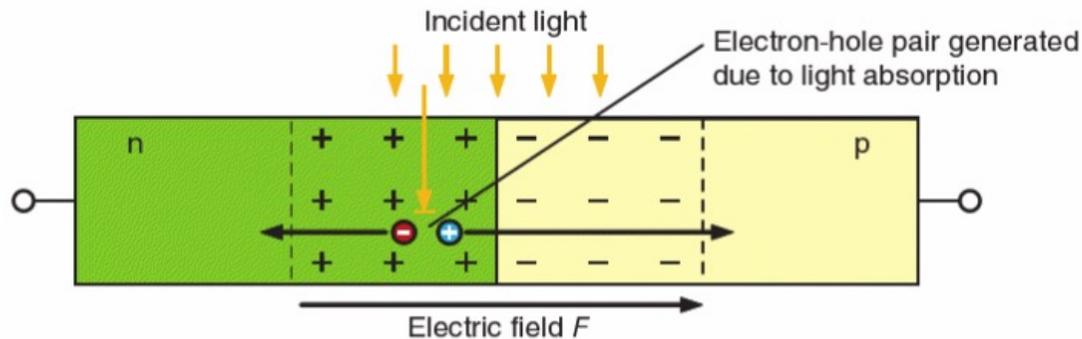
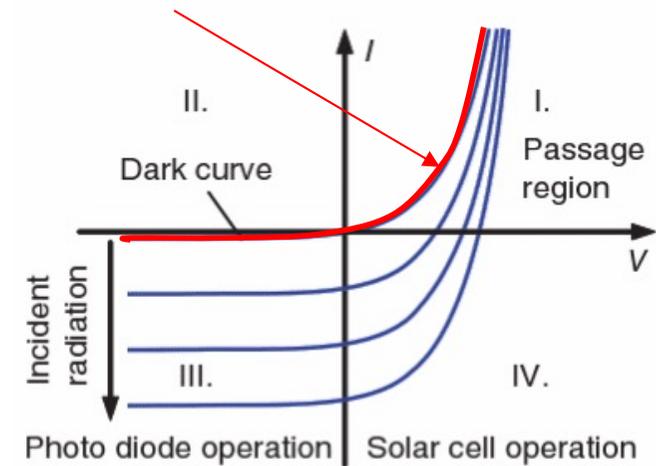


Figure 4.3 Equivalent circuit of the photodiode

Shockley diode equation:  $I_D = I_s \left( e^{\frac{V}{V_T}} - 1 \right)$

- $I_s$  dark current
- $V_T = \frac{kT}{q} = 25.9 \text{ mV}$  (thermal voltage)

Normal diode IV-curve



Photocurrent through photon absorption.  
 $I_{Ph} = const \cdot E$   
 Current source proportional to the irradiance

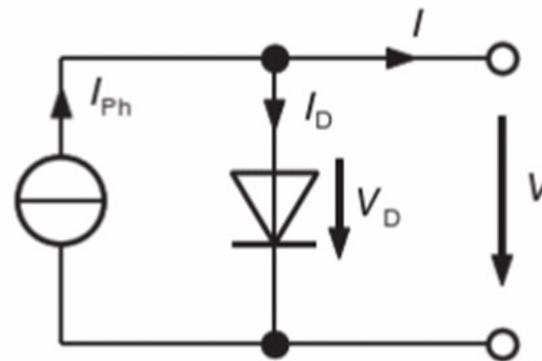
# The PV-cell

Solar-cell defined with generator references

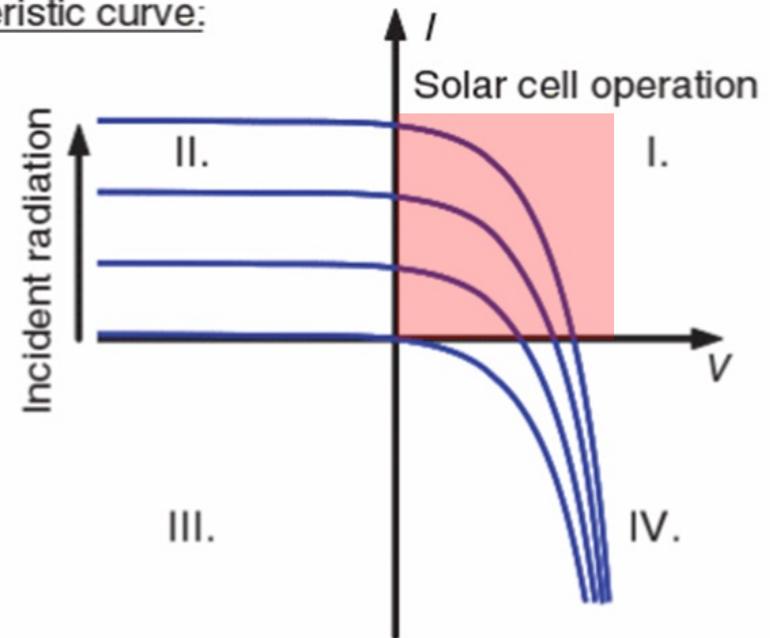
Current direction out of the cell

Only 1<sup>st</sup> quadrant used

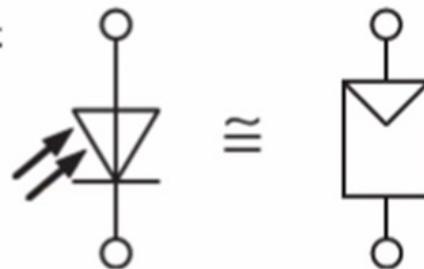
Generator reference-arrow system:



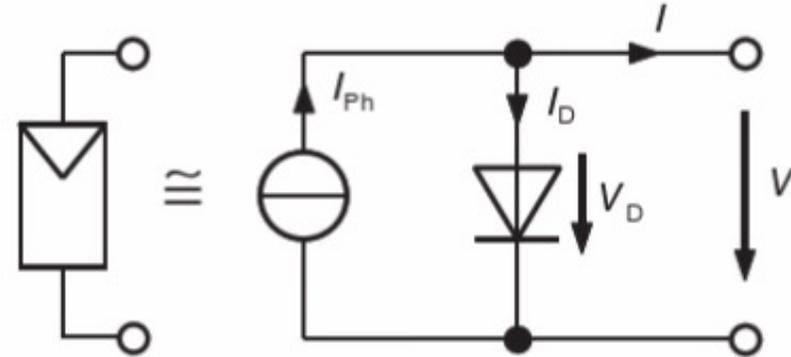
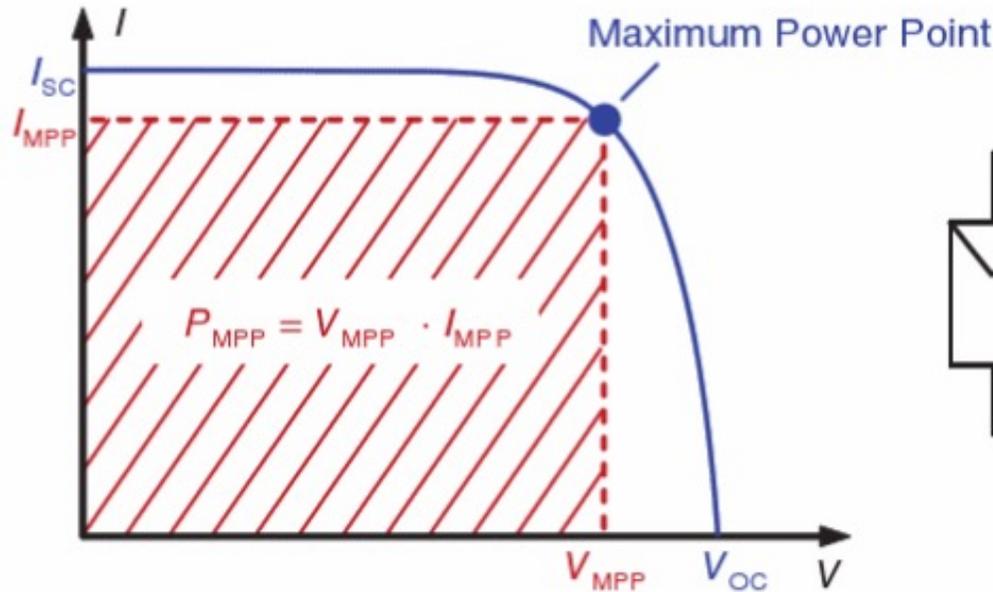
Characteristic curve:



Solar cell symbol:



# IV-characteristics



Shockley diode equation

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot \left( e^{\frac{m \cdot V}{V_T}} - 1 \right)$$

$$V_T = \frac{kT}{q} = 25.9 \text{ mV (thermal voltage)}$$

m ideality factor ( $1 < m < 2$ )

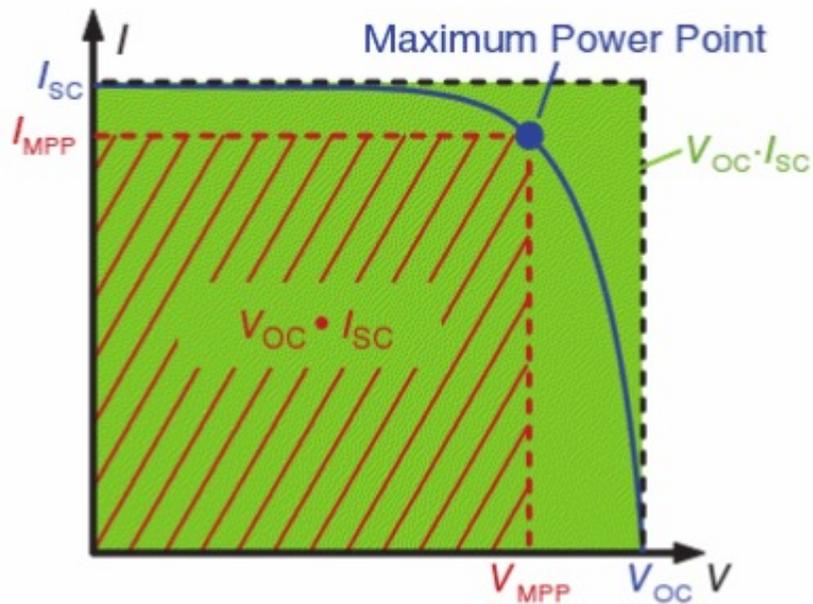
Short circuit current

$$I_{SC} = I(V=0) = I_{Ph} - I_S \cdot (e^0 - 1) = I_{Ph}$$

Open circuit voltage

$$V_{OC} = V(I=0) = m \cdot V_T \cdot \ln \left( \frac{I_{SC}}{I_S} + 1 \right)$$

# Maximum Power Point

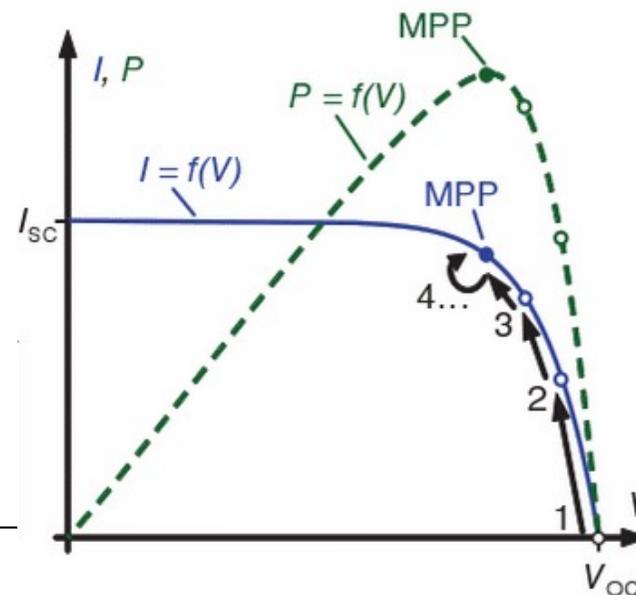


- Fill Factor

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{oc} \cdot I_{sc}} = \frac{P_{MPP}}{V_{oc} \cdot I_{sc}}$$

- Efficiency

$$\eta = \frac{P_{MPP}}{P_{Opt}} = \frac{P_{MPP}}{E \cdot A} = \frac{FF \cdot V_{oc} \cdot I_{sc}}{E \cdot A}$$



# Solar power introduction

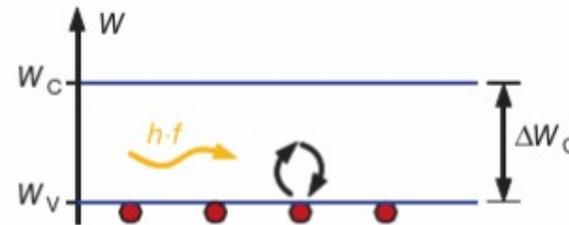
- Solar irradiation
- PV-characteristics
- Cell technologies



# Spectral efficiency

Photon  $\rightarrow$  Electron/Hole-pair  
 Photon energy:  $E = h \cdot f = \frac{h \cdot c}{\lambda}$   
 Bandgap wavelength:  $\lambda_g$

$\lambda > \lambda_g$ : Transmission:



$\lambda < \lambda_g$ : Thermalization:

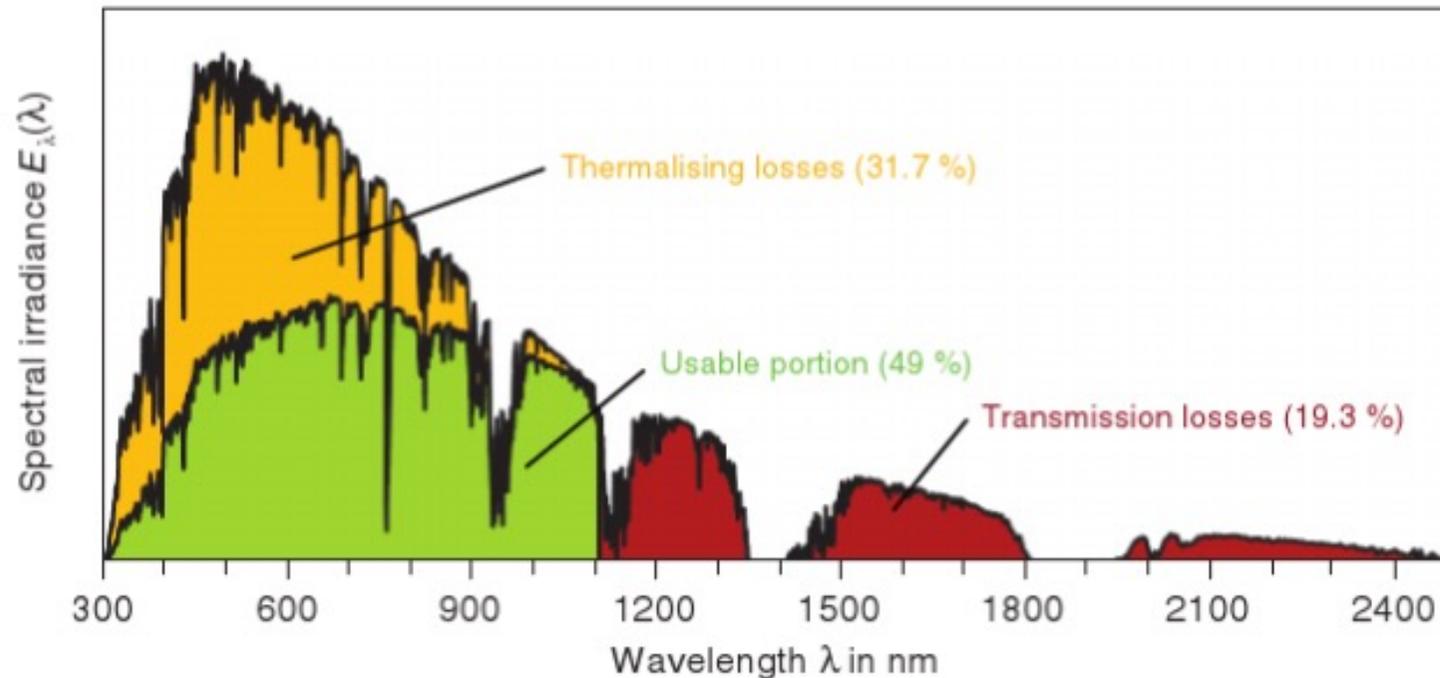
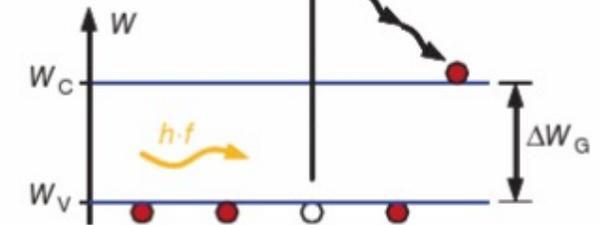


Figure 4.23 Spectral losses in a c-Si solar cell

# Single pn-junction PV-cell

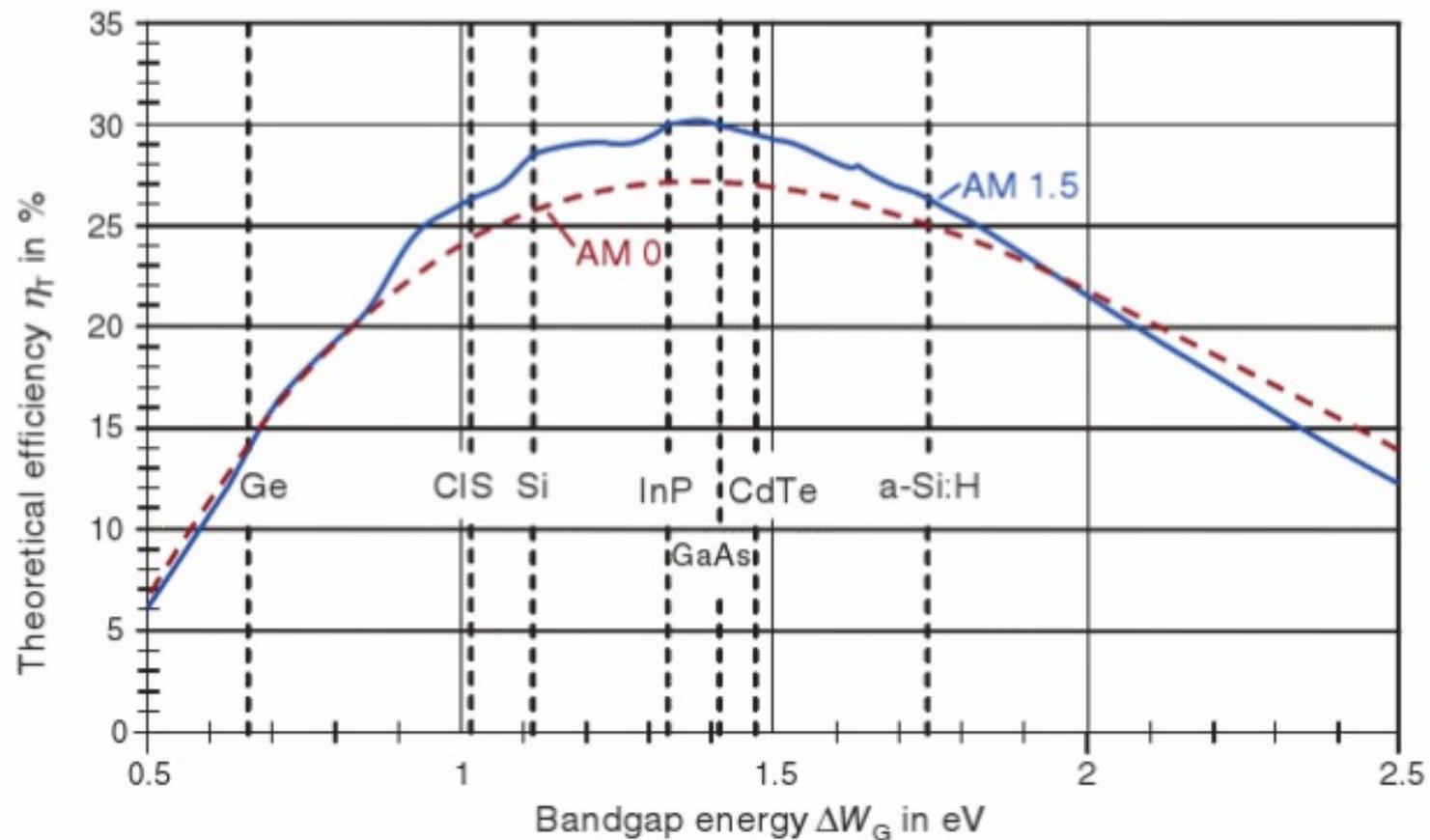
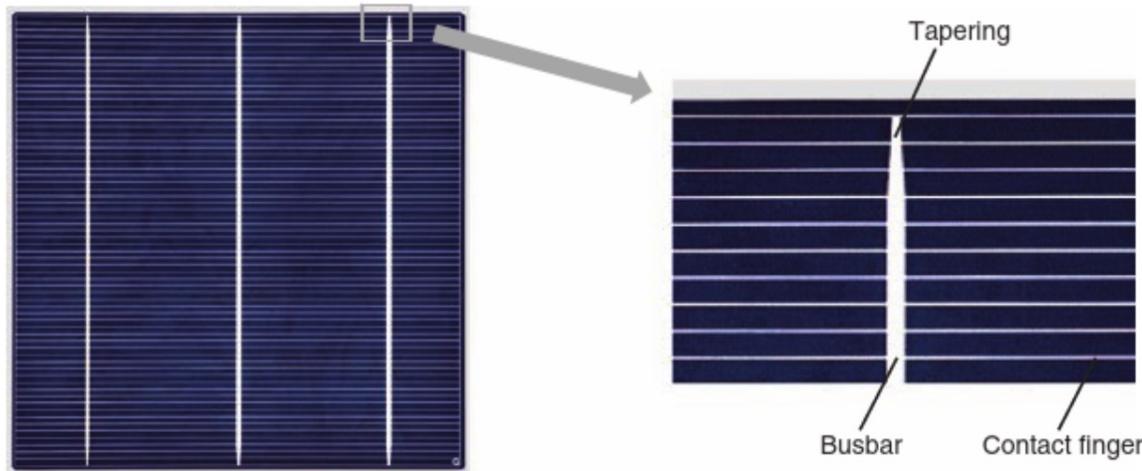


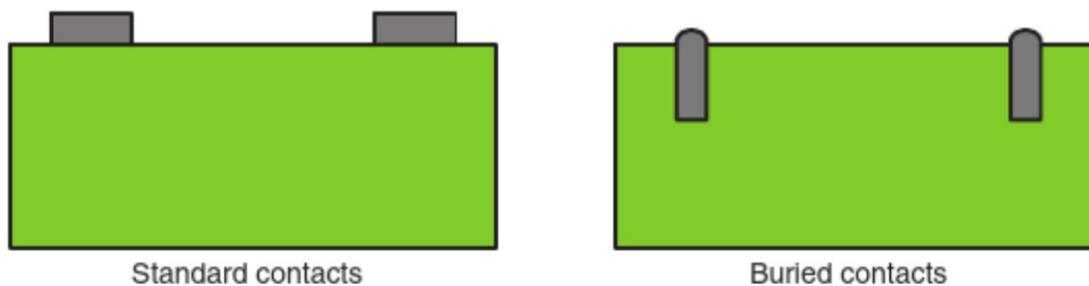
Figure 4.24 Theoretical efficiency in dependency of the bandgap

# Shading from contacts



**Figure 4.27** Front contacts of a solar cell with contact fingers and current collector rails (busbars) (source: Q-Cells)

Contact fingers on the top of the panels reflect photons from entering the panel and create electron-hole pairs. One alternative to decrease the shading is to bury the contacts in the cell.

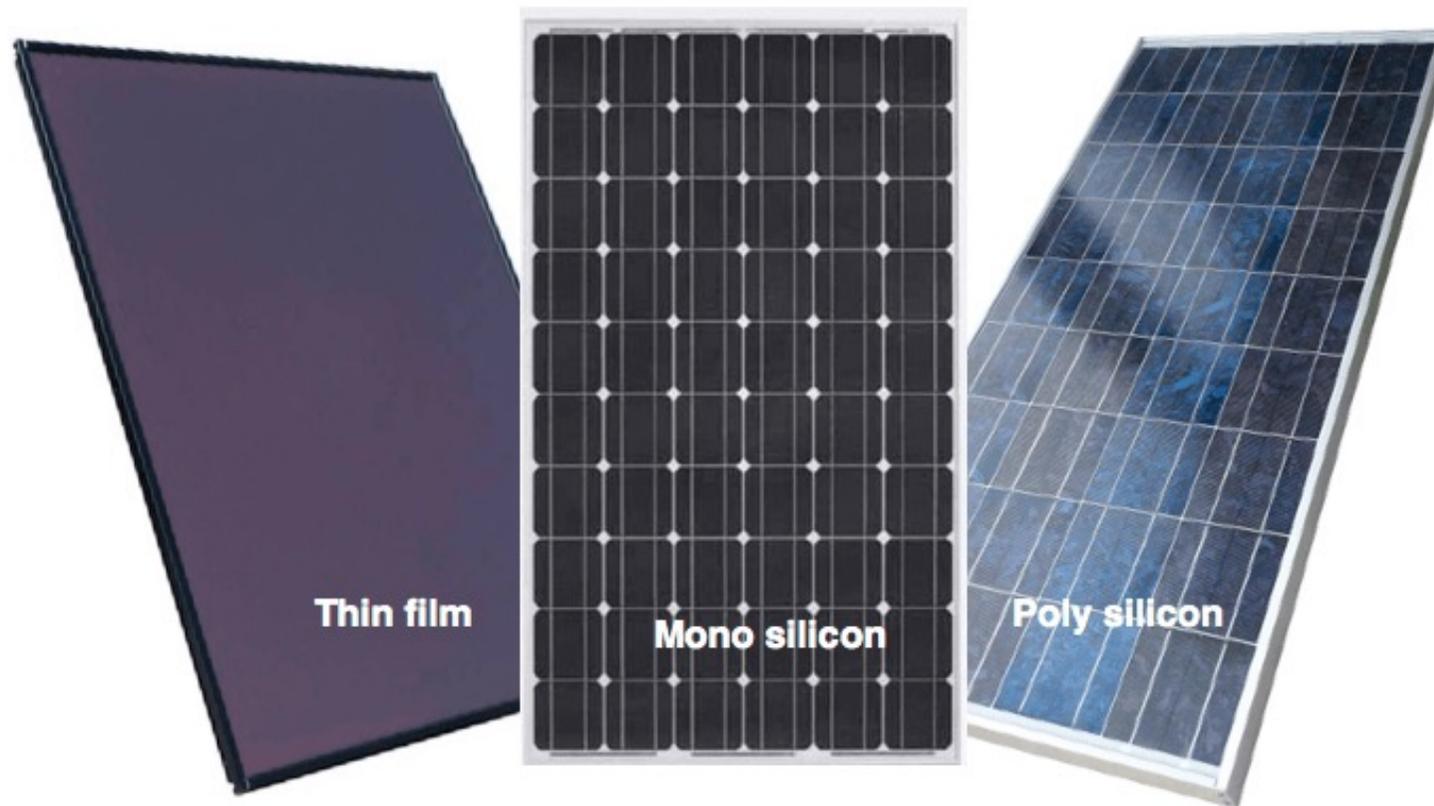


**Figure 4.28** Comparison of standard contacts with the buried contact technology: the shading losses can be significantly reduced

# Cell technologies

c-Si, Crystalline silicon cells. Mono or Poly crystalline

a-Si, Amorphous silicon (Thin film) cells



# Cell technologies

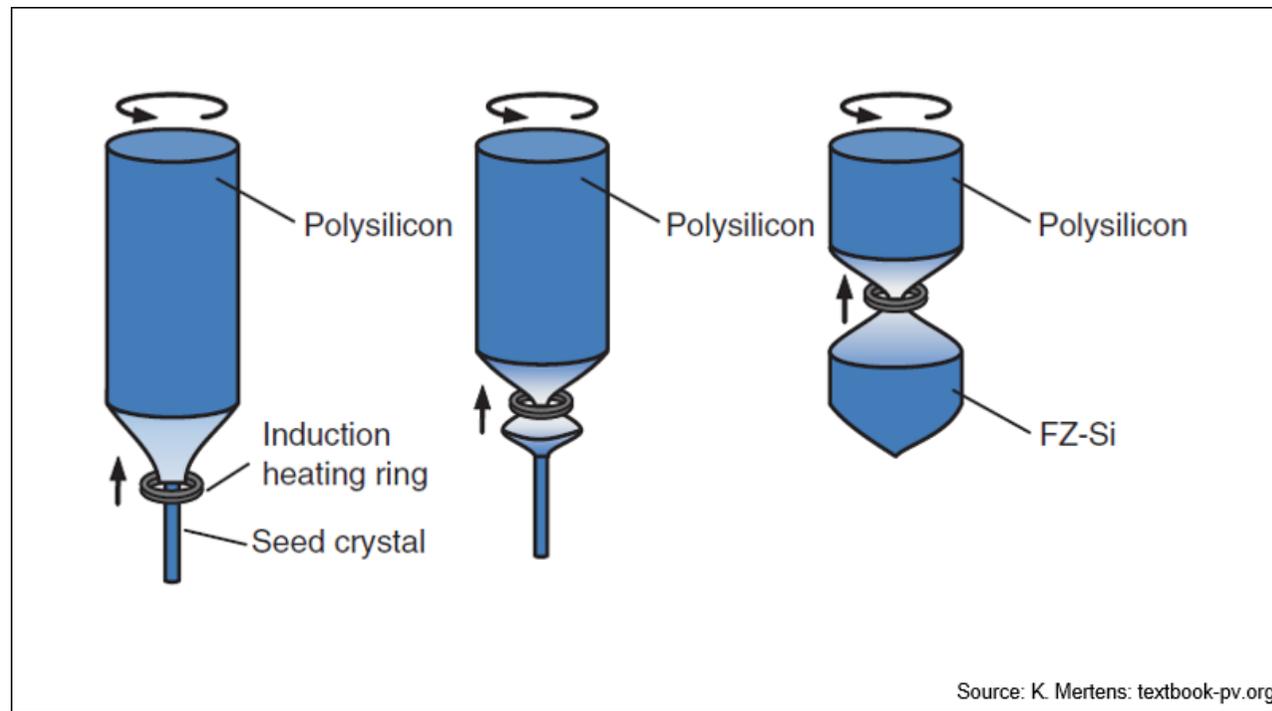
c-Si, Crystalline silicon cells  
 a-Si, Amorphous silicon (Thin film) cells

**Table 5.2** Comparison of the various cell technologies

| Cell technology           | $\eta_{\text{Cell\_Lab}}$ (%) | $\eta_{\text{Module}}$ (%) | Important advantages and disadvantages  |
|---------------------------|-------------------------------|----------------------------|---|
| Mono c-Si                 | 25                            | 20                         | + Very high efficiencies<br>+ Unlimited availability<br>– Presently high energy amortization time   |
| Multi c-Si                | 20.4                          | 17                         | + High efficiencies<br>+ Unlimited availability<br>+ Acceptable energy amortization time  |
| a-Si (single)             | 10.1                          | 7                          | + Low temperature coefficient   |
| a-Si (tandem)             |                               | 8                          | – Efficiency too low  |
| a-Si (triple)             | 13                            | 8.2                        |   |
| a-Si/ $\mu$ c-Si          | 11.7                          | 10                         | + Potential for improvements<br>– Low efficiencies  |
| CdTe                      | 16.7                          | 11                         | + Medium efficiencies<br>– Availability problem<br>+ Potential for improvements<br>– Image problem<br>+ Low energy amortization time      |
| CIS                       | 19.4                          | 15                         | + Acceptable efficiencies<br>+ Potential for improvements<br>+ Low energy amortization time<br>– Availability problem                     |
| Mono c-Si/a-Si (HIT cell) | 23                            | 19                         | + Very high efficiencies<br>+ Great potential for improvements  |
| III/V semiconductors      | 32                            | n.a.                       | + Extremely high efficiencies (with concentration over 40%)<br>– Possible availability problem<br>– Only sensible in concentrator systems |

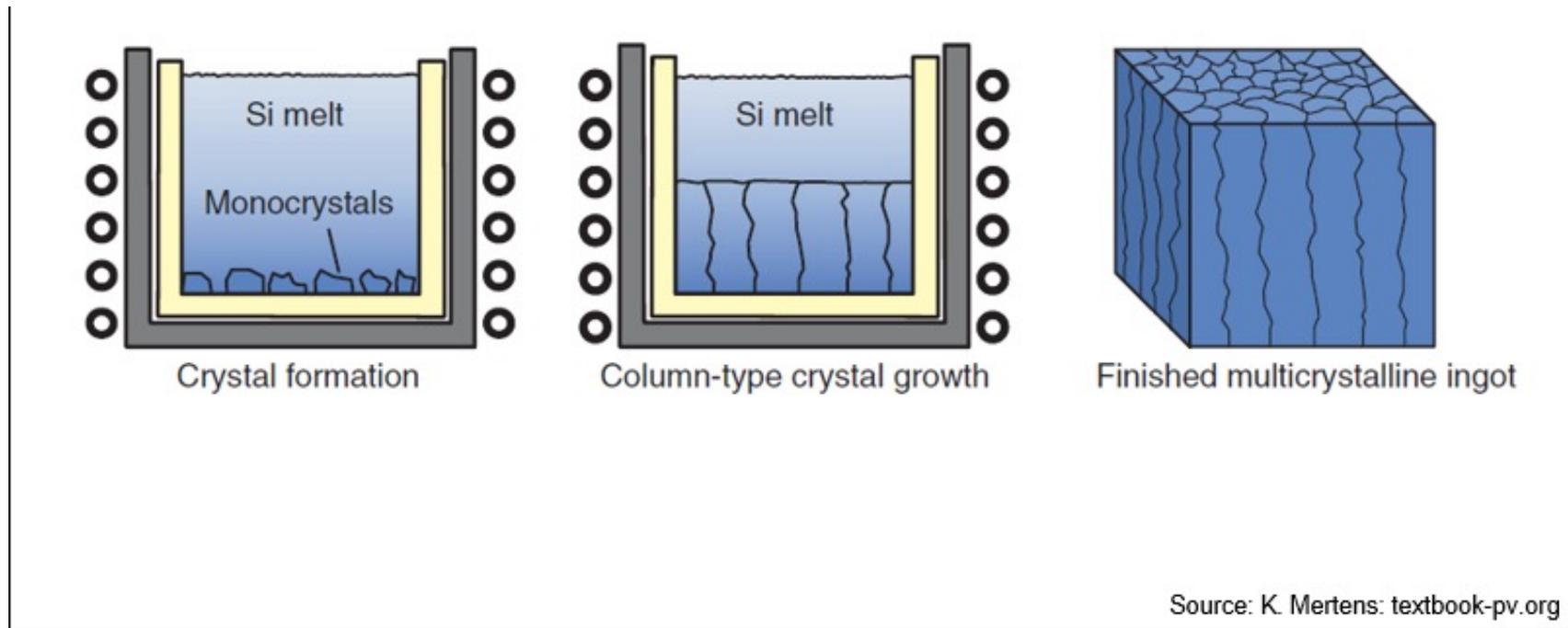
# Mono c-Si, manufacturing

Crystal growth of mono crystalline silicon rod (Ingot)



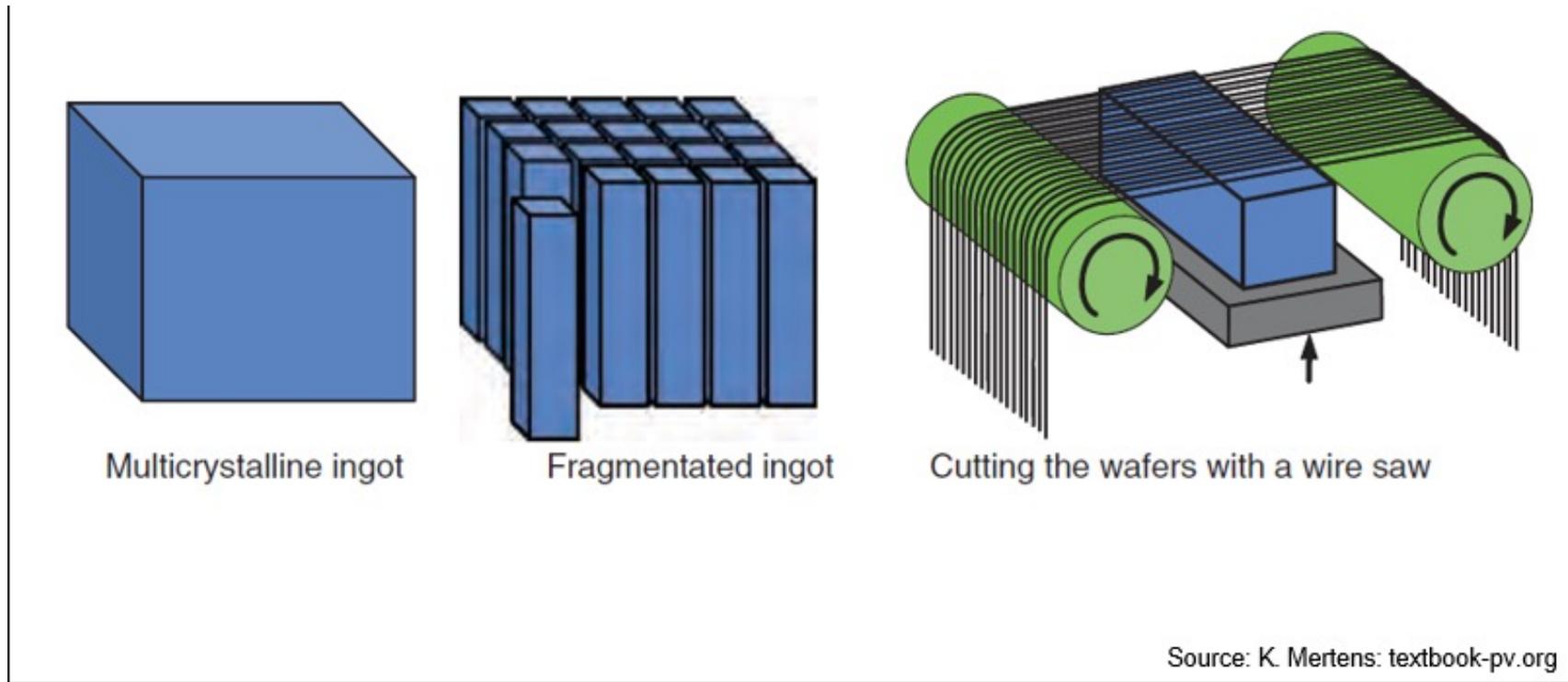
# Poly c-Si, manufacturing

Poly silicon melted and the cooling under controlled conditions



# c-Si, manufacturing process

Wafer cutting of ingots. Saw width  $120\ \mu\text{m}$   
Typical wafer thickness  $180\ \mu\text{m}$



# c-Si, manufacturing process

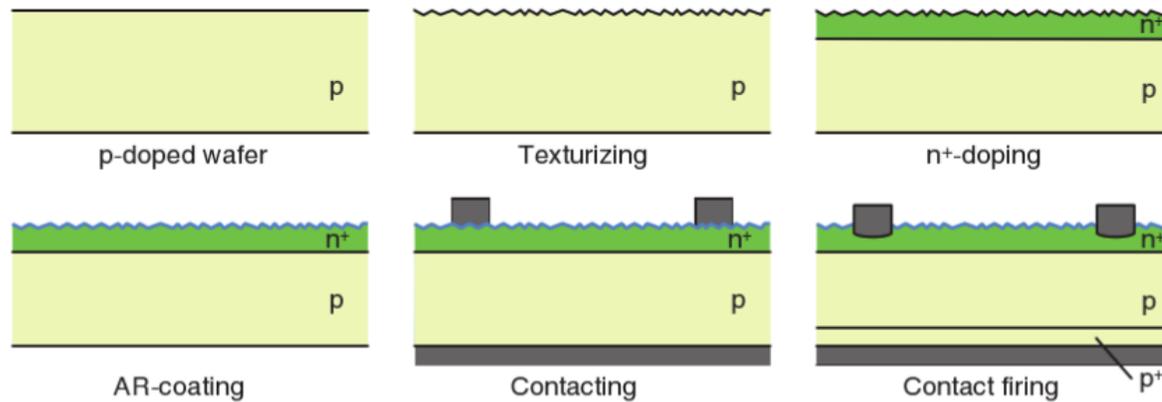
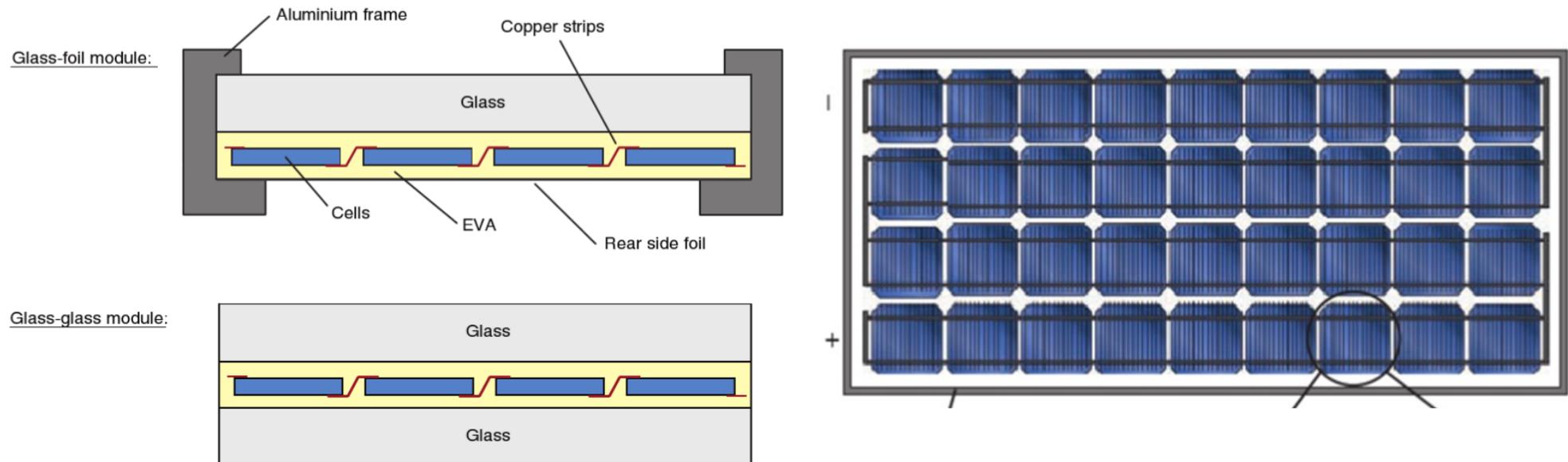


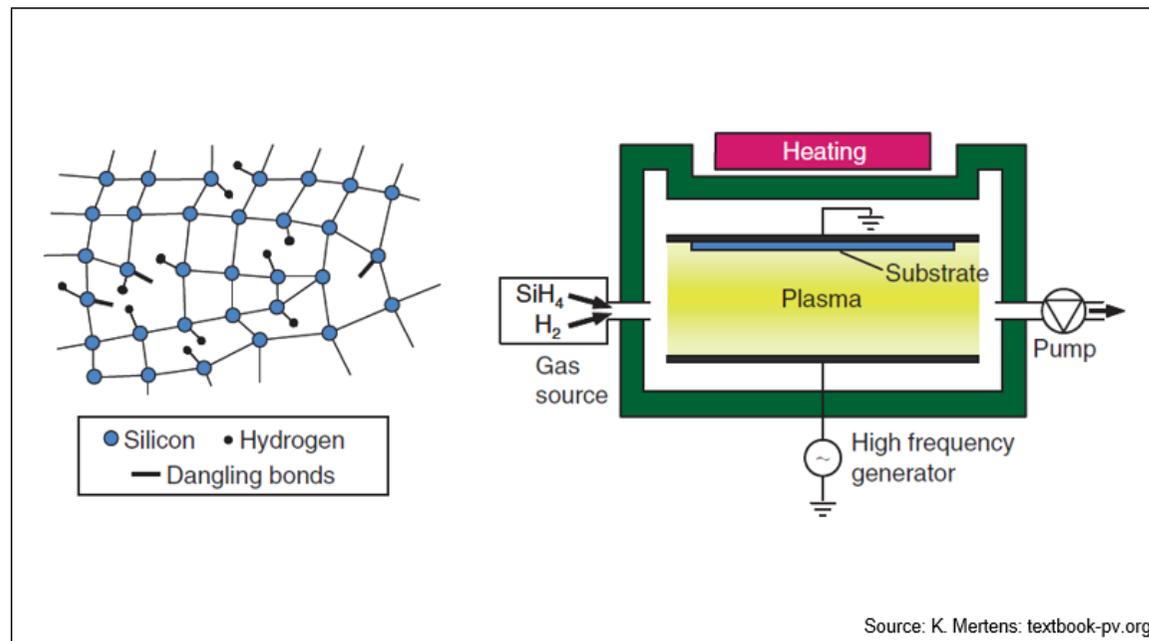
Figure 5.7 Process steps for producing standard cells



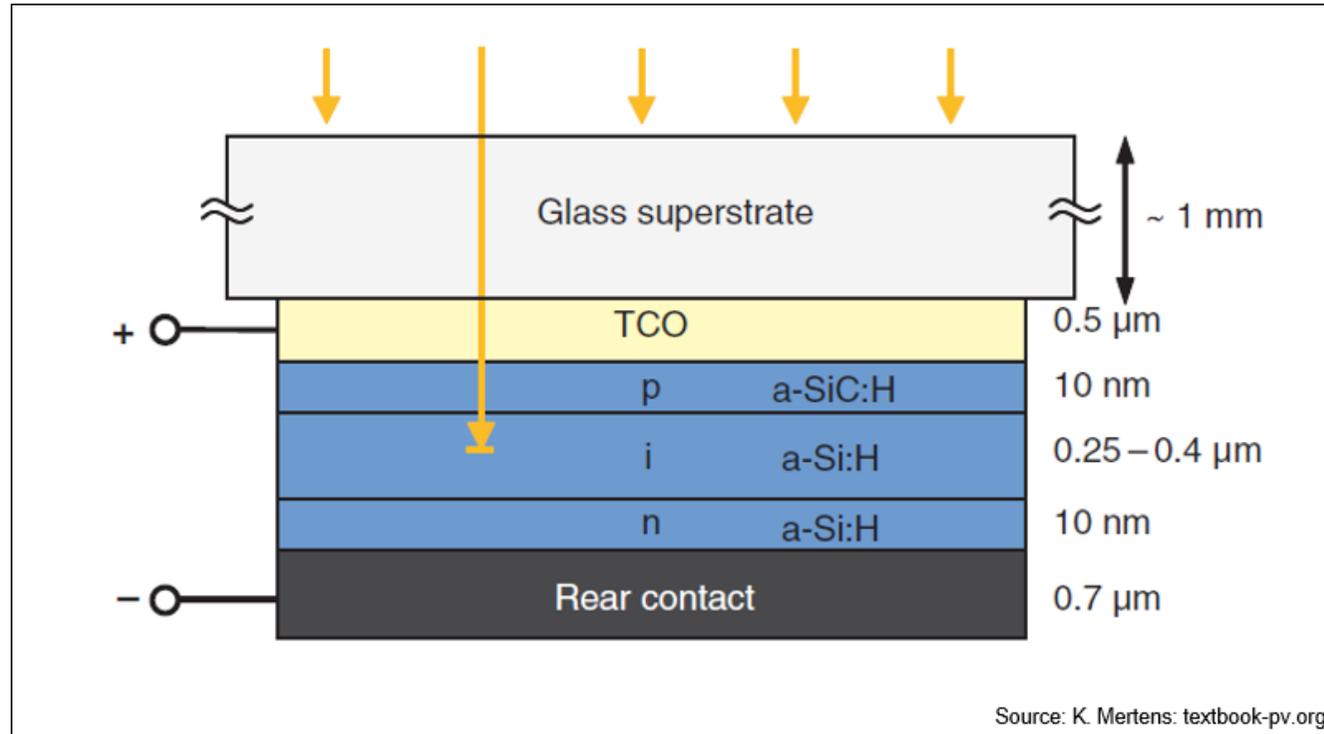
# a-Si, Thin film manufacturing 1

## Chemical Vapor Deposition

Deposition of silicon from gas phase forming an amorphous structure



# a-Si, Thin film manufacturing 2



TCO: Transparent Conducting Oxide

# a-Si, Thin film manufacturing

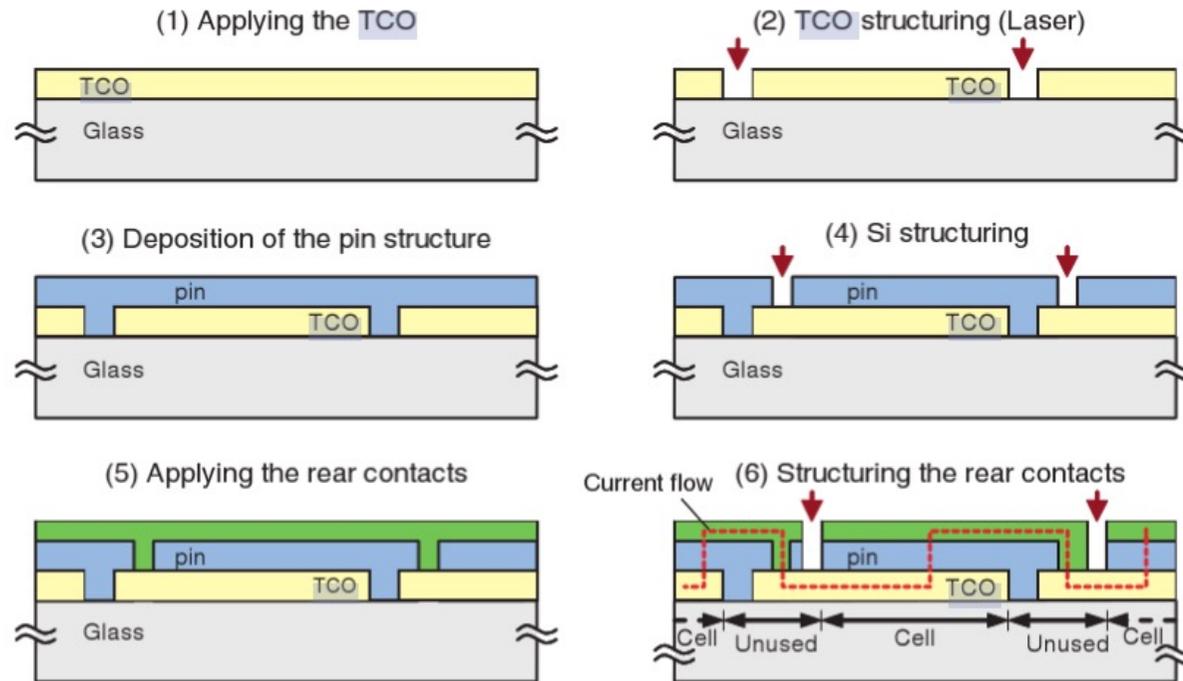
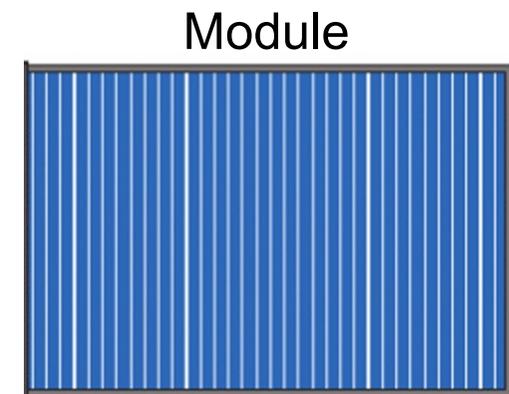
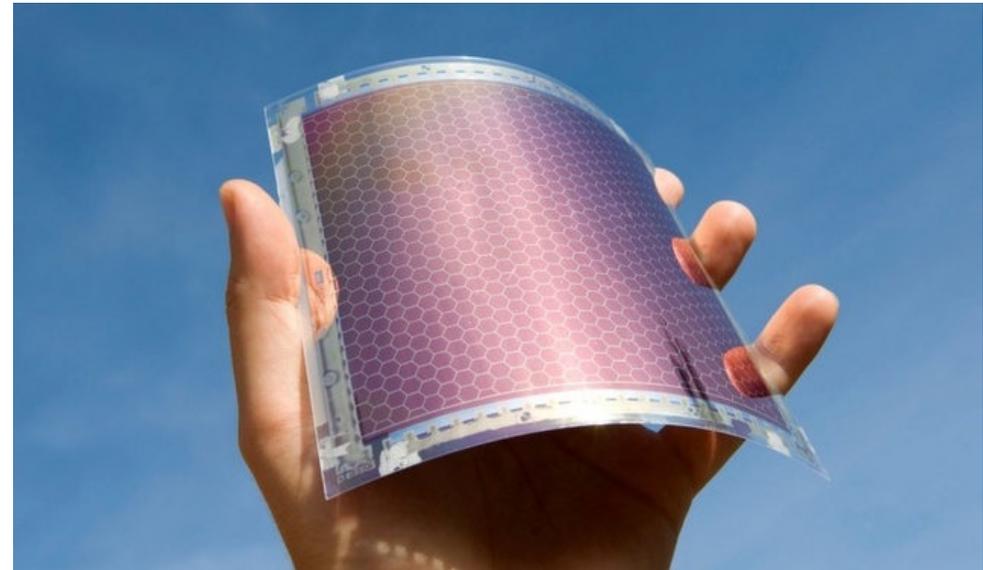
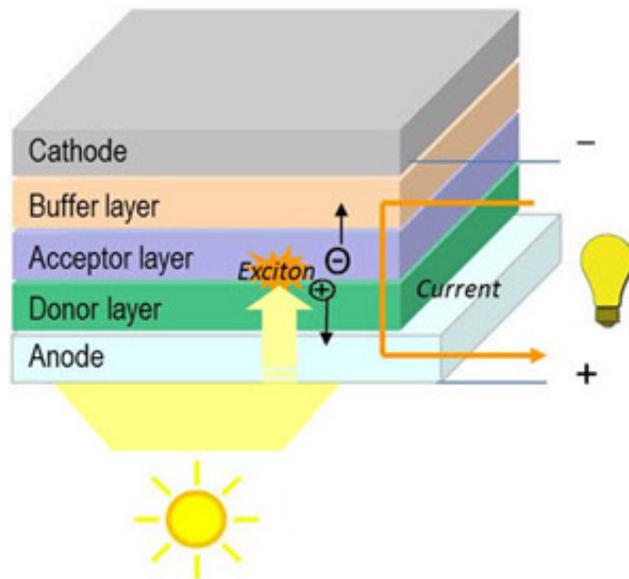


Figure 5.19 Production steps for integrated series connection of the individual pin cells

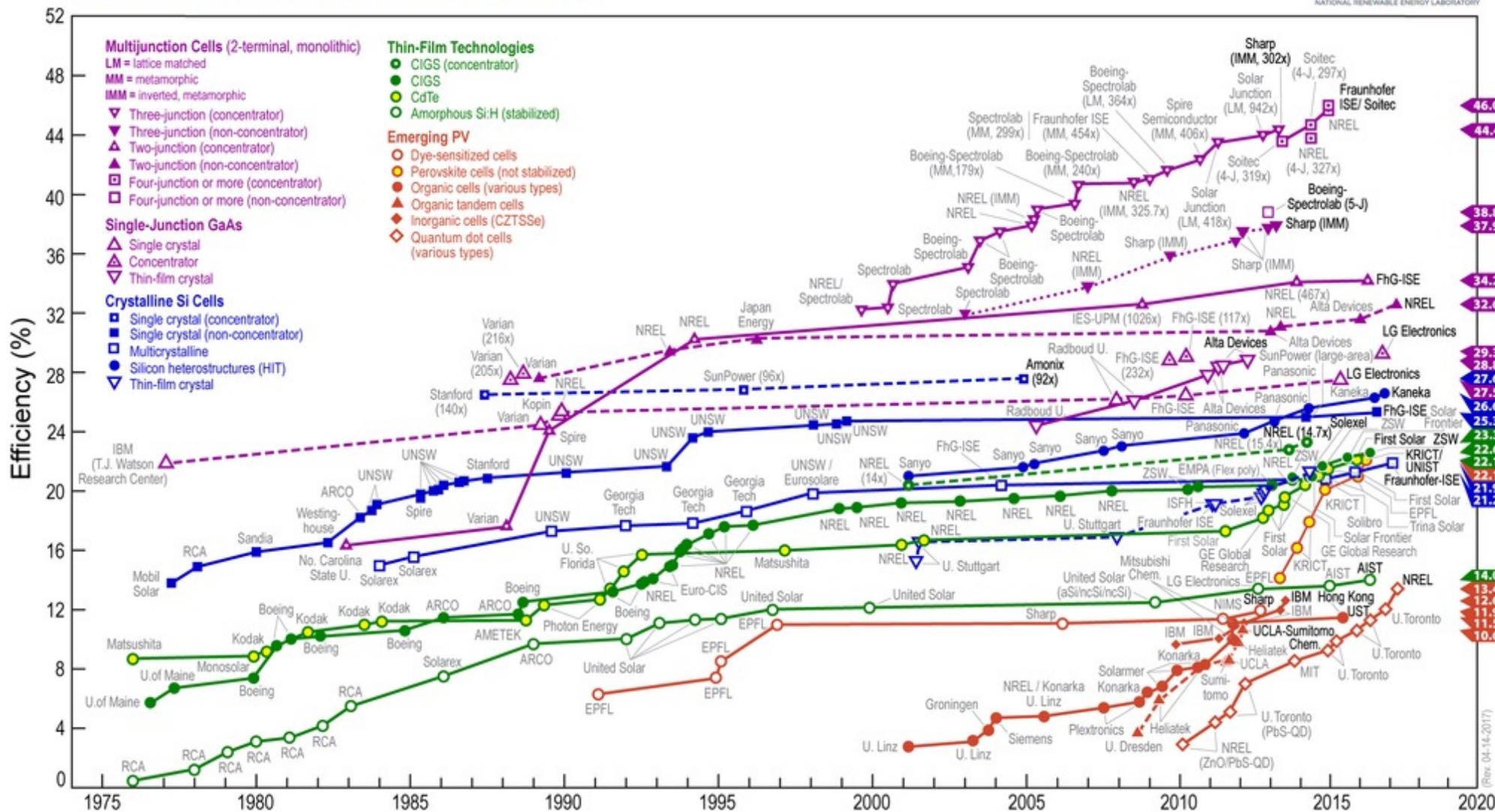


# Organic PV-cells

Made from conductive organic polymers  
Lower production cost (Printed electronics)  
Flexible, transparent, lightweight



# Best Research-Cell Efficiencies



TSTE26  
Lars Eriksson

[www.liu.se](http://www.liu.se)