CONSIDERATIONS ABOUT THE SUSTAINABILITY OF PHOTOVOLTAIC ELECTRICITY GENERATION

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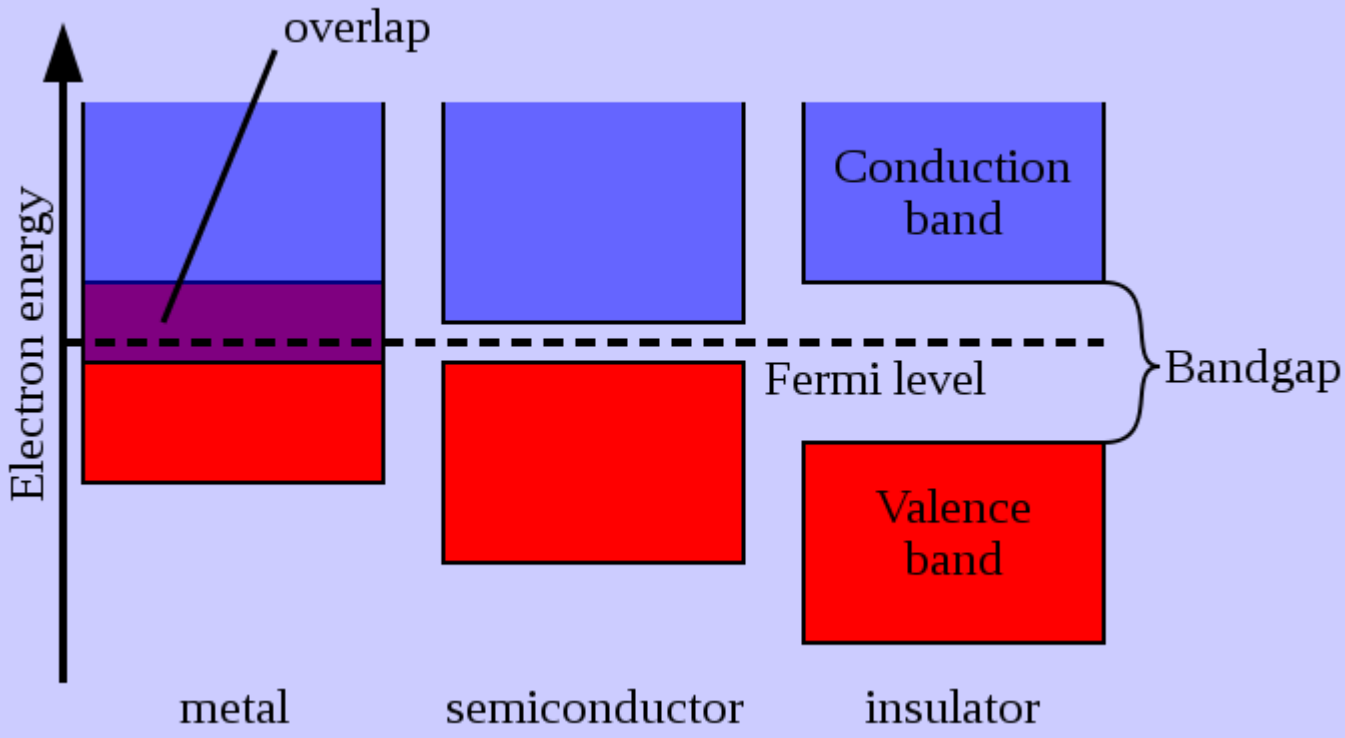
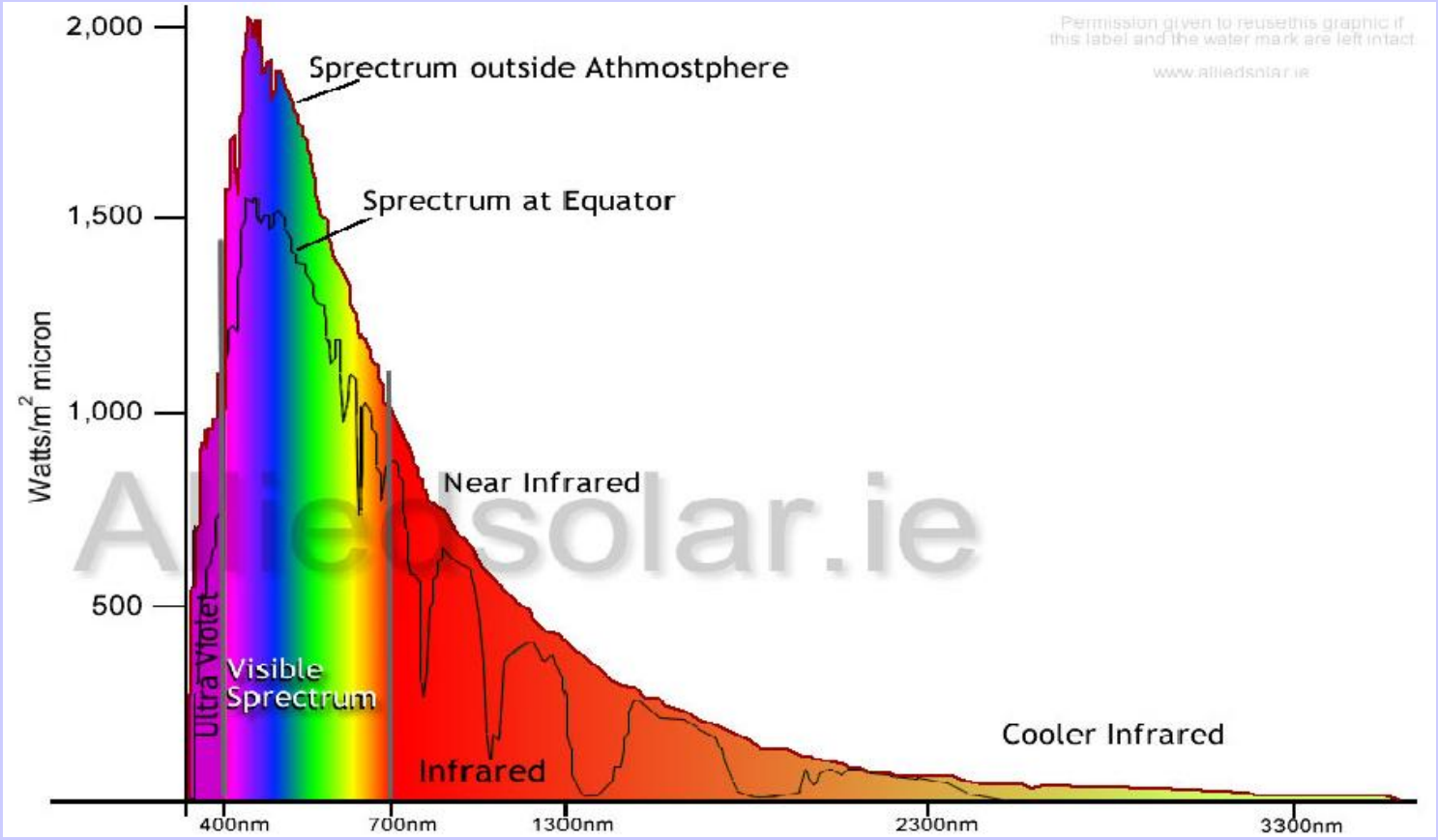
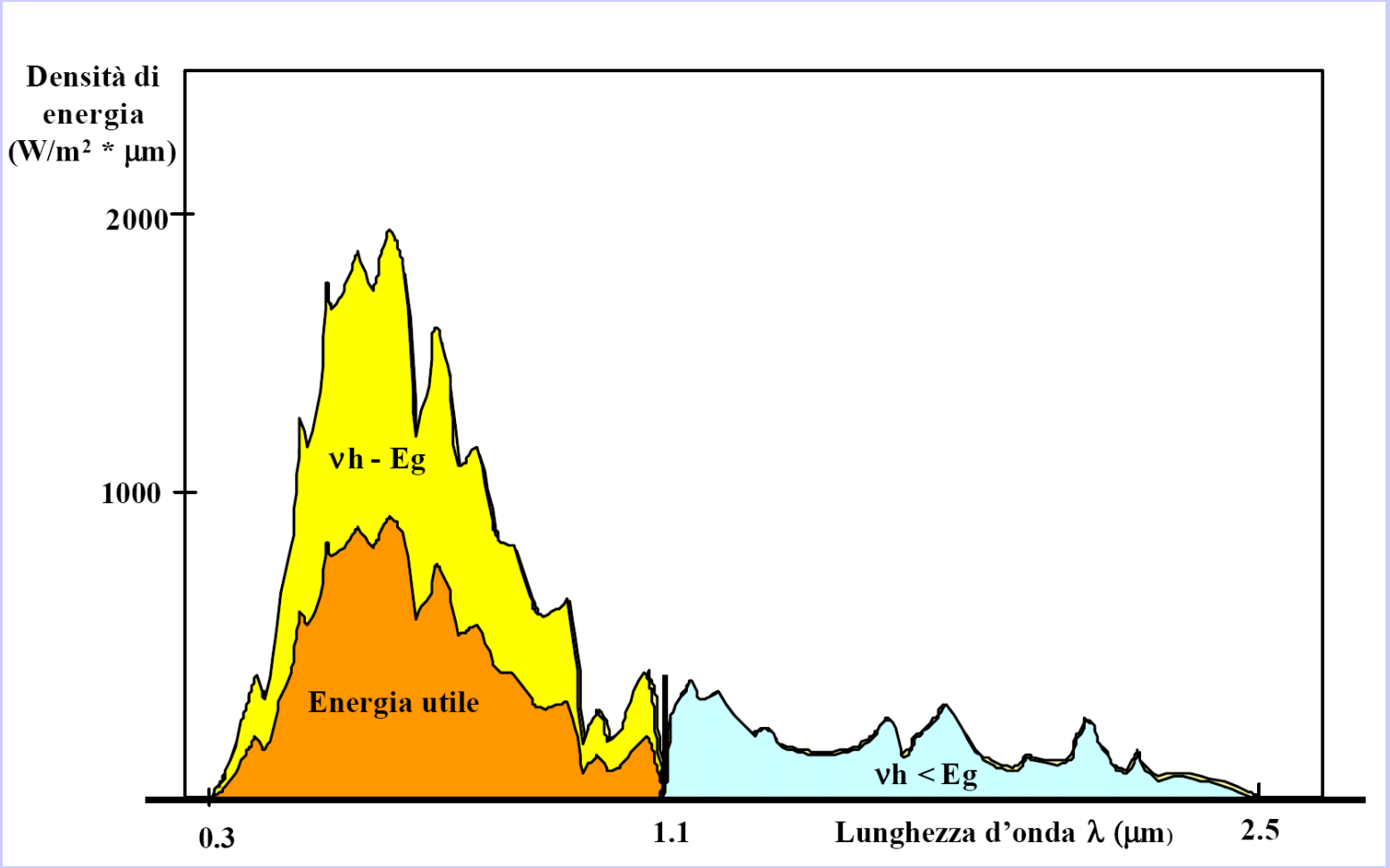
Photovoltaic effect

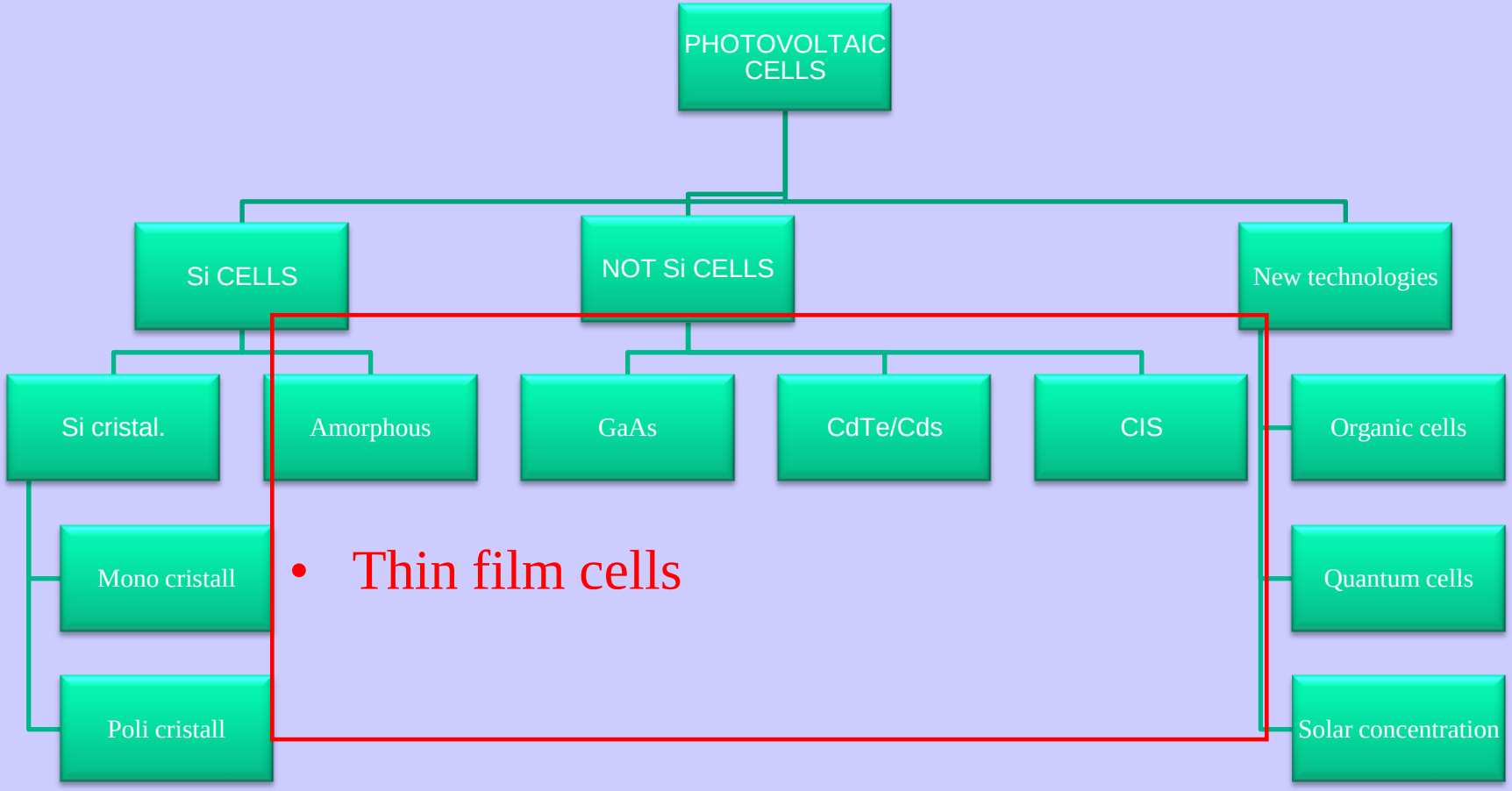
- Discovered by Becquerel (1839)
- Solar irradiance is directly converted into electricity
- It gives the energy gap to electrons to be transferred from the valence band to the conduction band of a semi conductor

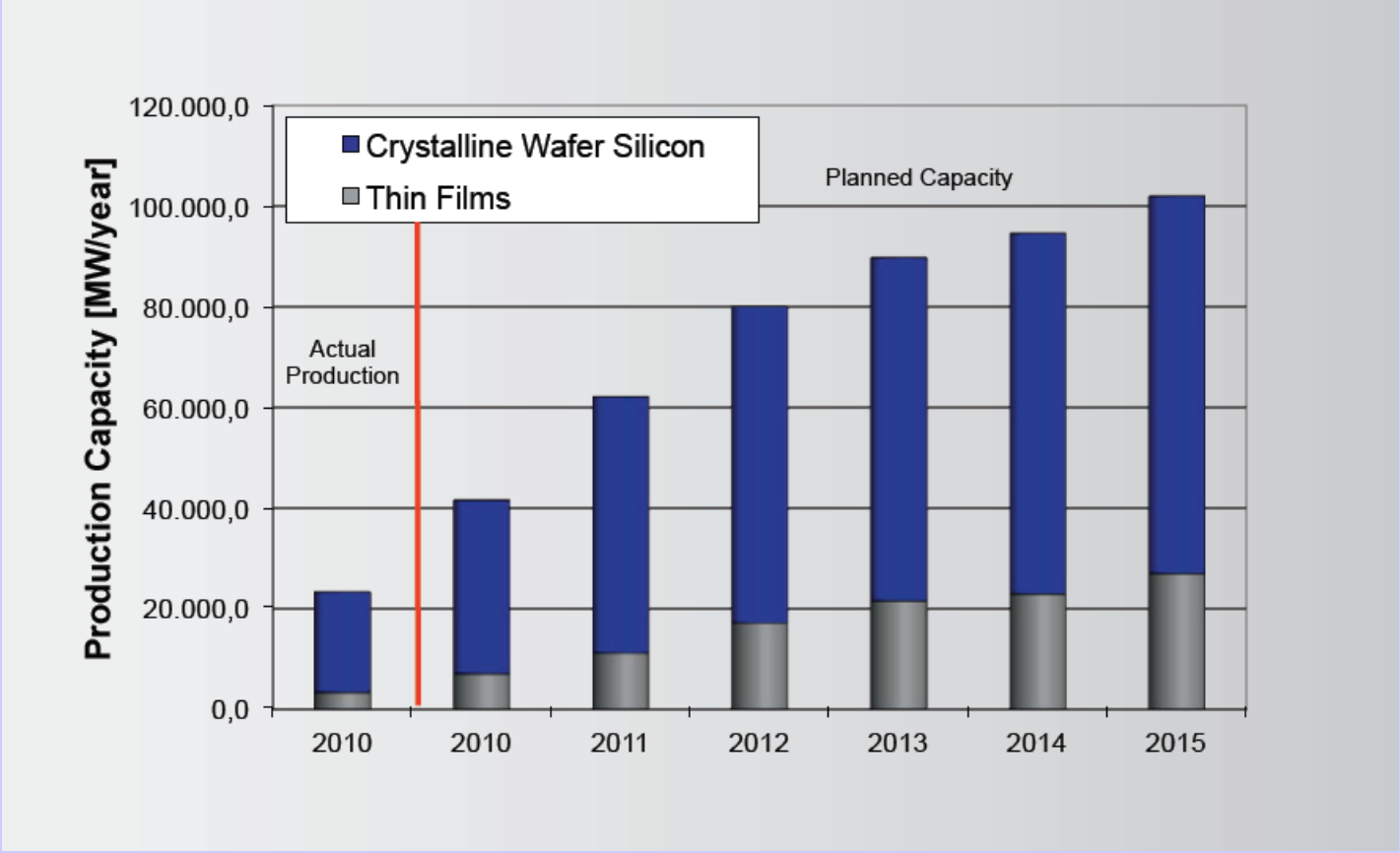

overlap
Electron energy
Conduction band
Fermi level
Bandgap
Valence band
metal
semiconductor
insulator

Spectrum of solar radiation

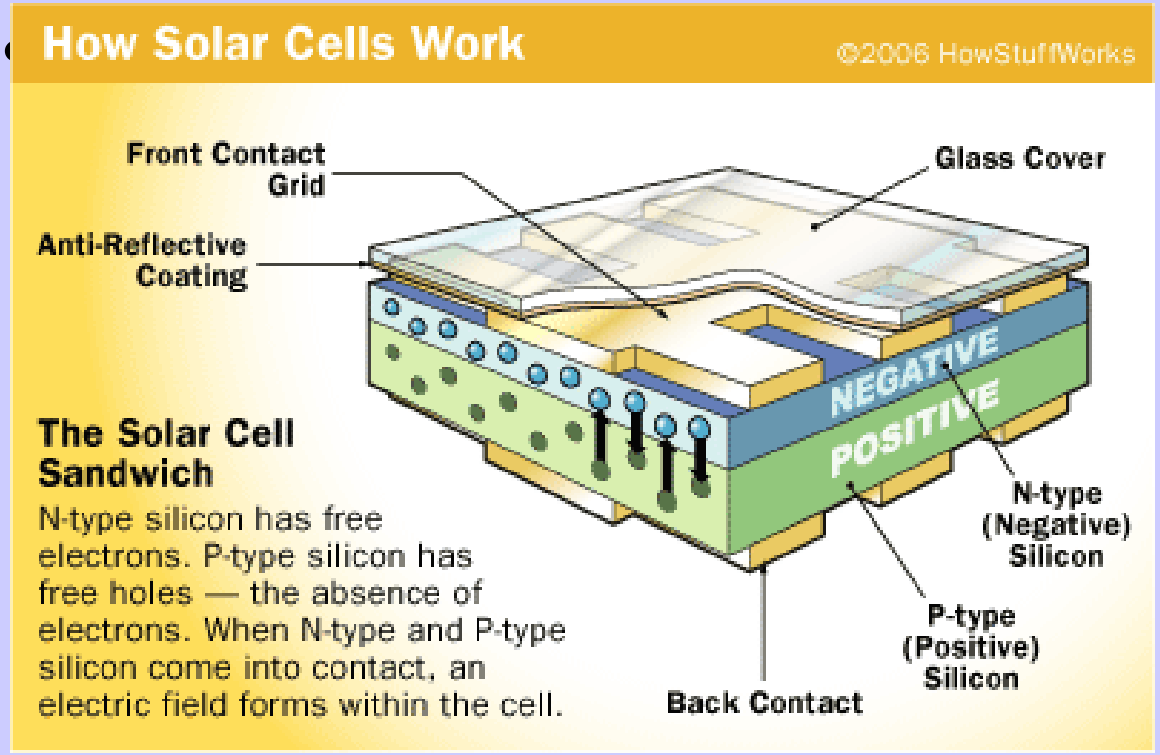


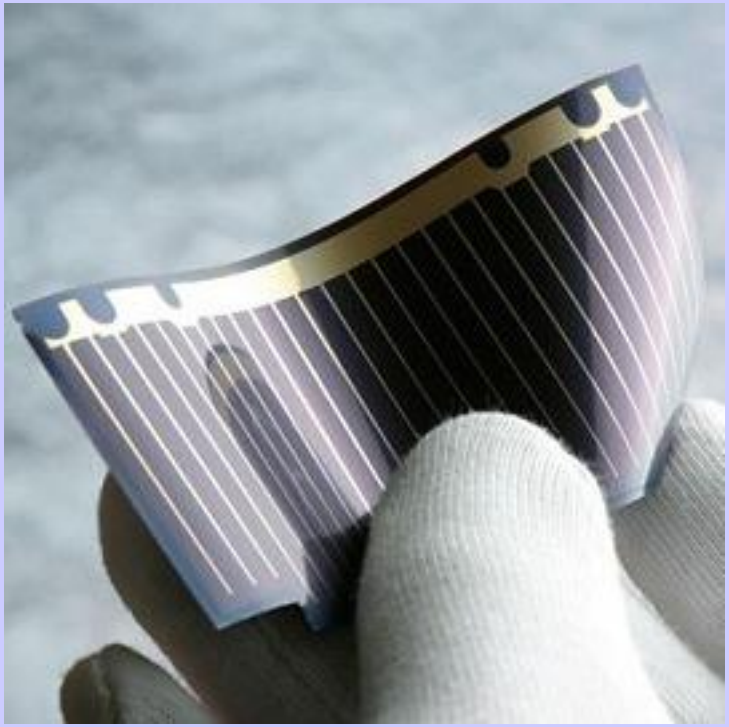

Densità di energia (W/m² * μm)
2000
1000
νh - Eg
Energia utile
νh < Eg
0.3
1.1
Lunghezza d'onda λ (μm)
2.5


PHOTOVOLTAIC CELLS
Si CELLS
NOT Si CELLS
New technologies
Si cristal.
Amorphous
GaAs
CdTe/Cds
CIS
Organic cells
Mono cristall
Quantum cells
Poli cristall
Solar concentration
• Thin film cells


Production Capacity [MW/year]
120.000,0
100.000,0
80.000,0
60.000,0
40.000,0
20.000,0
0,0
Crystalline Wafer Silicon
Thin Films
Actual Production
Planned Capacity
2010
2010
2011
2012
2013
2014
2015

Silicon cells

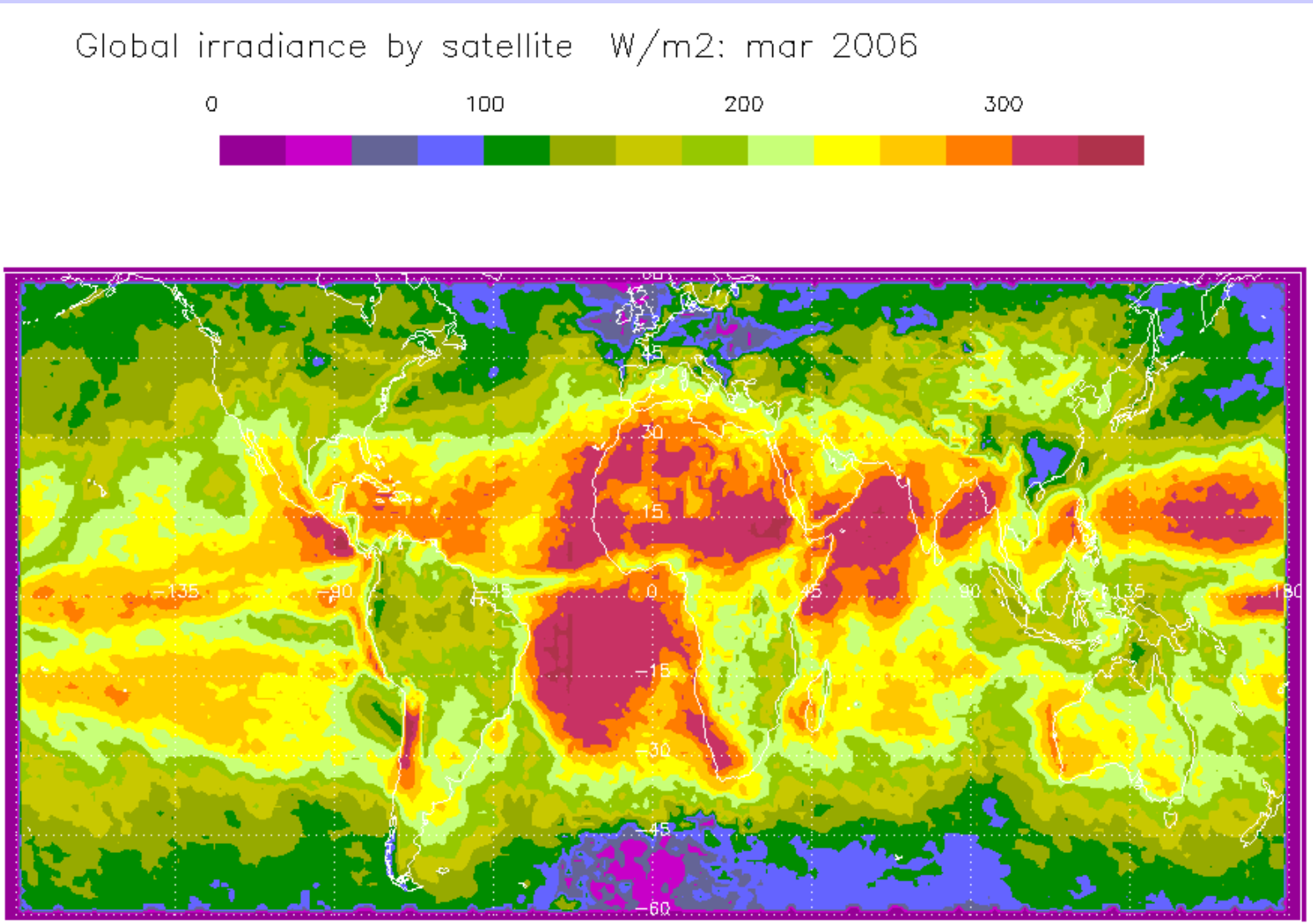




	Efficiency [%]	**[Wp/m^2]**	**Widespread light**
Si mono crystalline	12-20	130	-
Si poli crystalline	10-15	120	-
Amorphous	6-10	110	+
CIGS	13-20		+
CIGSS	25		+
CdTe	15	100	+
Grätzel Cells	7-10		+

SOLAR IRRADIANCE

- I_0=1367 W/m^2
- I= 1000 W/m^2
- I= 170 W/m^2 average value in Italy
- I= 109 W/m^2 average value in Finland
- I= 192 W/m^2 average value in Portugal


Global irradiance by satellite W/m2: mar 2006
0
100
200
300
-135
-90
-45
0
45
90
135
180
30
15
-15
-30
-45
-60
www.meteonorm.com
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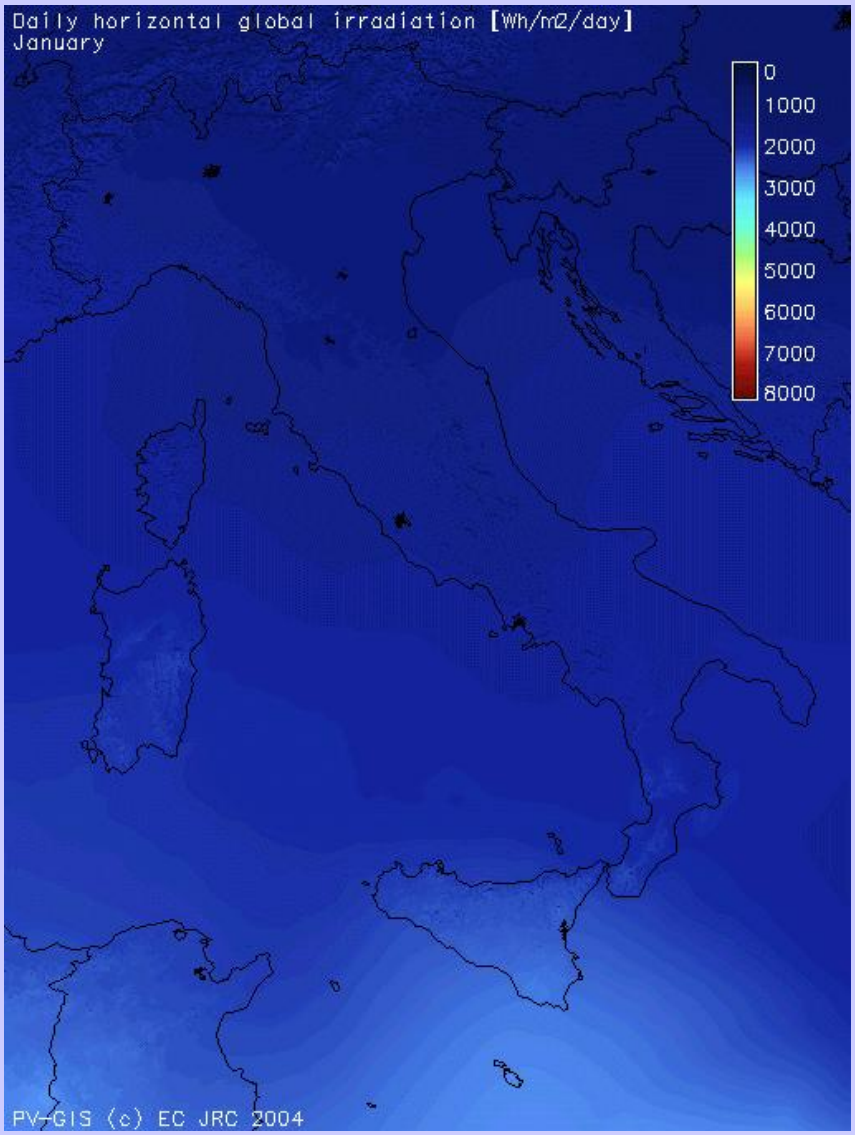

Daily horizontal global irradiation [Wh/m2/day]
January
0
1000
2000
3000
4000
5000
6000
7000
8000
PV-GIS (c) EC JRC 2004

- Total annual energy requirement is about 11 Gtep
- Total solar energy on earth (land) is about 13000 Gtep

- Considering an average efficiency of a solar cell about 15%

In Italy it is possible to produce

E_{el}=223 kWh/m^2

So, to produce the overall Italian electric demand (350 10^{12} kWh)

We need 1600 km^2 of solar cells

- Low energy density (marginal lands)
- Time and space variability
- Problem of energy storage
- Integrative sources- not alternative

PHOTOVOLTAIC PLANT

- suitable for small distributed production
- promoted by many countries policy

DURING OPERATION

- completely clean
- without CO_2 production

BUT DURING WHOLE PANEL LIFE?

Life Cycle Assessment

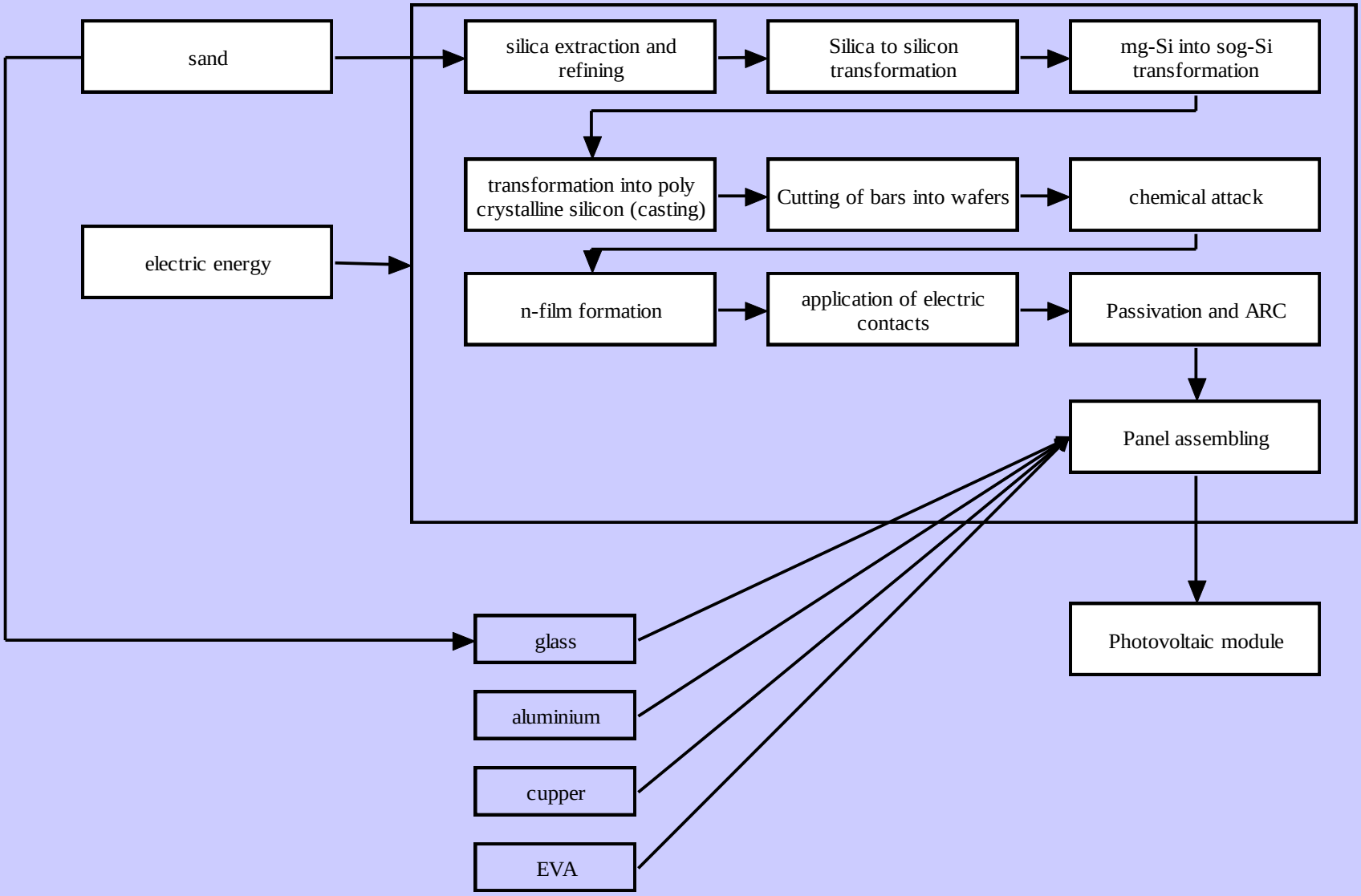
- takes into account mass and energy flows from silica extraction to final panel assembling
- the operation of the panels has been considered
- disposal has been considered, too

LCA assumptions: Poli-crystalline Si cell

Silica into silicon transformation	carbothermal
mg-SI into sog-Si transformation	UCC process
casting and wafer production	conventional casting process
wafer area	12.5×12..5 cm^2
wafer thickness	200 μm
posterior metallisation	100 %
anterior metallisation	7 %
EVA sheet thickness	0.5 mm
module area	0.65 m^2
cells per module	36 cells
operation life	25 years
module efficiency	16 %

9 UNIT OPERATIONS

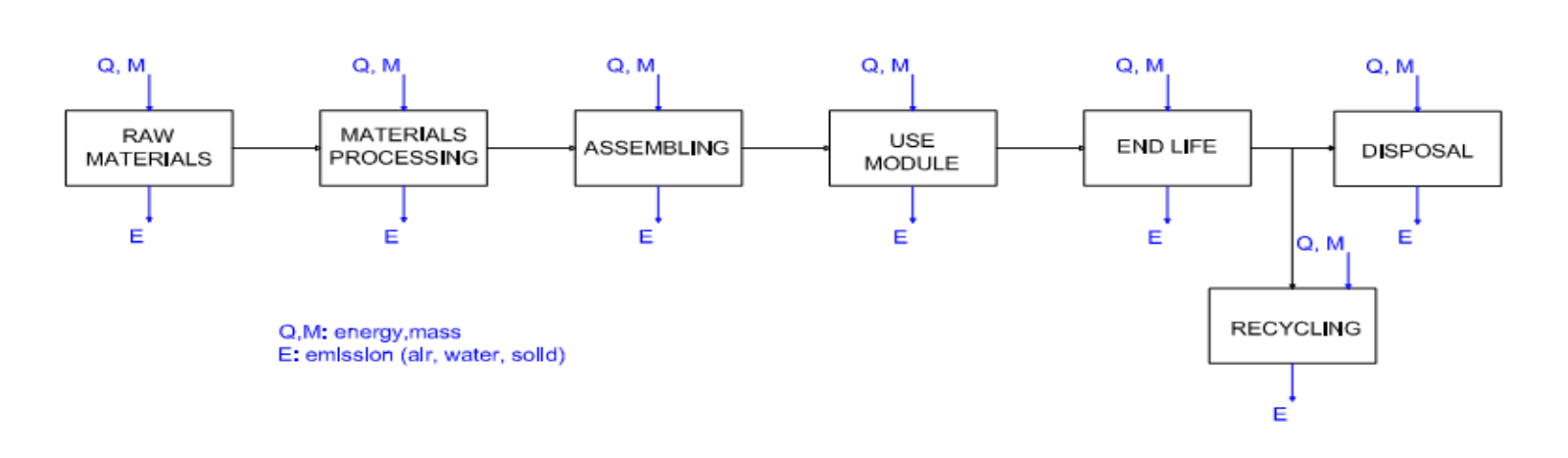
1. Silica extraction and refining
2. Silica to silicon transformation
3. Metallurgic to solar silicon transformation
4. Transformation to polycristalline silicon and wafer production
5. Chemical attack
6. n-film formation
7. Application of electric contacts
8. Passivation and AntiReflection Coating
9. Panel assembling


sand
electric energy
silica extraction and refining
Silica to silicon transformation
mg-Si into sog-Si transformation
transformation into poly crystalline silicon (casting)
Cutting of bars into wafers
chemical attack
n-film formation
application of electric contacts
Passivation and ARC
Panel assembling
glass
aluminium
cupper
EVA
Photovoltaic module

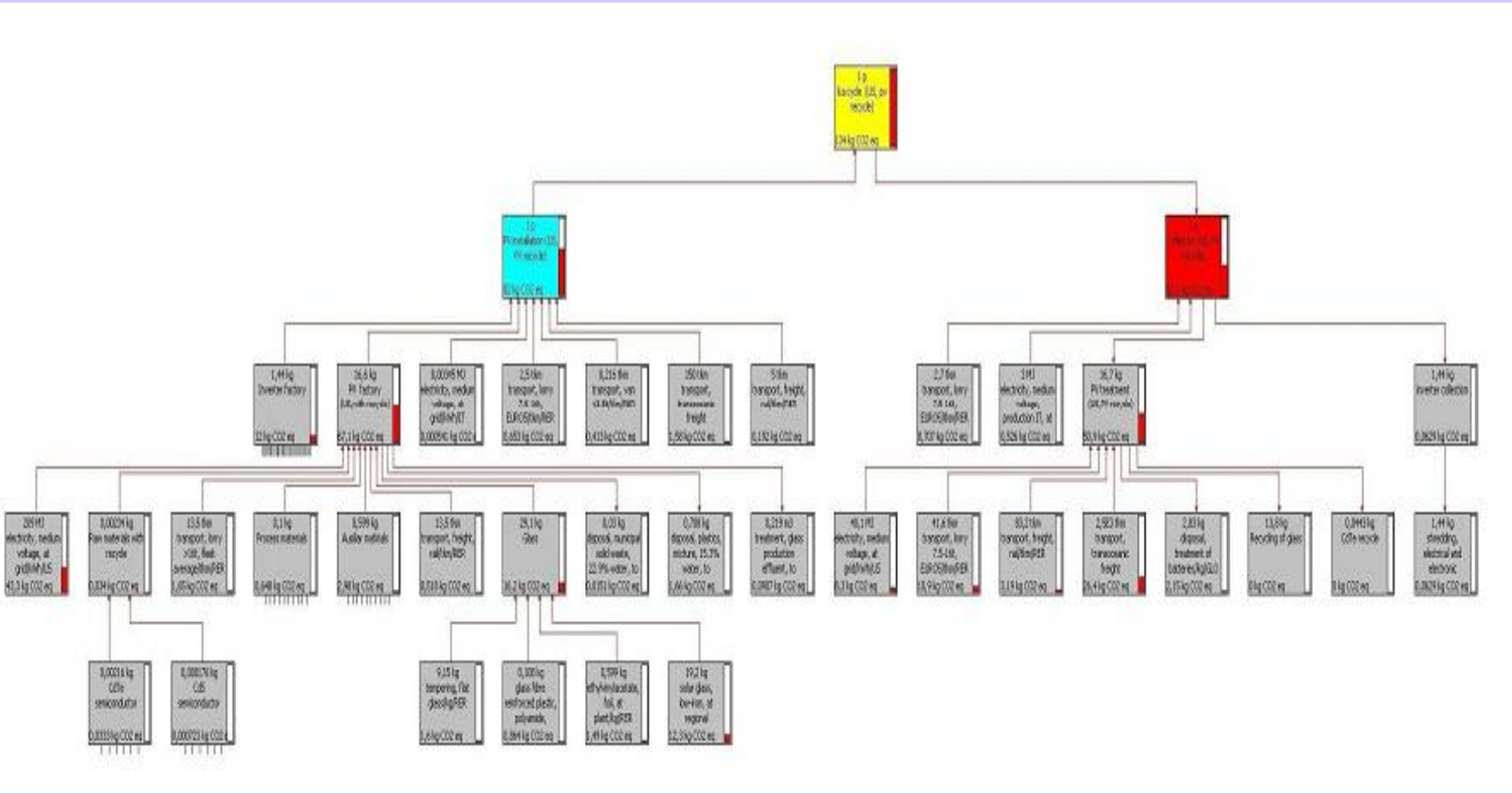
LCA assumptions: TeCd cell

PV module		
Cell materials	0,047	kg/m^2
Glass	29	kg/m^2
EVA	0,6	kg/m^2
Others [Sn, ITO, Al, ZnO]	0,7	kg/m^2
Electricity	59	kWh/m^2
BOS		
Al	0,11	kg/m^2
Steel	0,76	kg/m^2
Cu	0,47	kg/m^2
Plastic	0,03	kg/m^2
Electricity	6	MJ/m^2

CdTe cell production system



CdTe cell - LCA Scheme



Input data- PV factory

	Quantity	Unit	Type
PV factory (US)	1	kg	output
Electricity, medium voltage, at grid/US S	3,49	kWh	energy
Photovoltaic panel factory/GLO/I S	0,00000024	p	resources
Raw materials	0,002811	kg	resources
Transport, lorry >16t, fleet average/RER S	0,81	tkm	energy
Process materials	0,006006	kg	resources
Auxiliary materials	0,036	kg	resources
Transport, freight, rail/RER S	0,81	tkm	energy
Glass	1,7455	kg	resources
Heat, waste	12,57	MJ	air emission
Cadmium	1,26E-10	kg	air emission
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH S	0,0018	kg	waste
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH S	0,0425	kg	waste
Treatment, glass production effluent, to wastewater treatment, class 2/CH S	0,01315	m3	waste

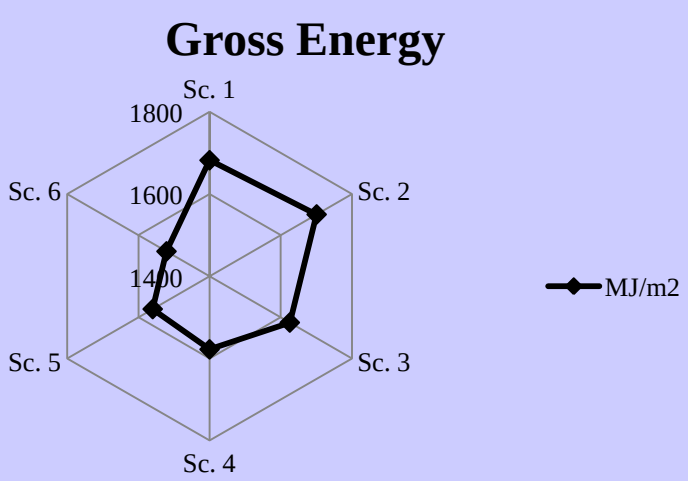
MASS STREAM ANALYSIS

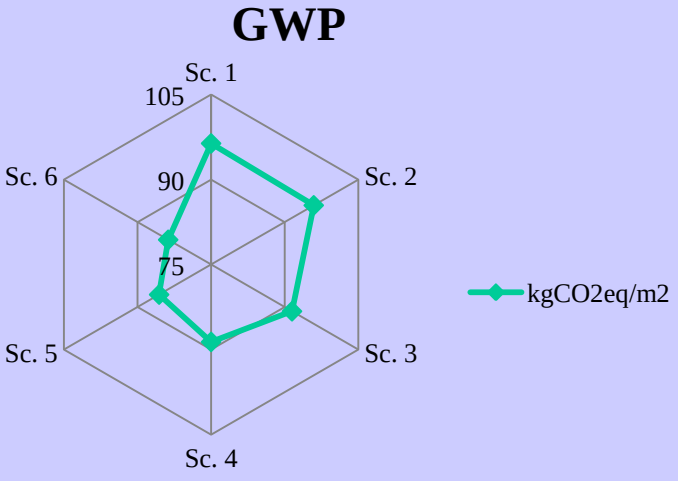
materials	operation	value
quartz	1	2,8 kgSiO_2/kg mg-Si
wood coal	2	0,37 kg/kg mg-Si
low ash coal	2	0,56 kg/kg mg-Si
coke	2	0,37kg/kg mg-Si
rejected wood	2	1,32 kg/kg-mg-Si
mg-Si	3	1,02 kg/kg-sog-Si
$SiHCl_3$	3	0,078 kg/kg-sog-Si
argon	4	5,75 g/wafer
mineral oil	5	15,5 g/wafer
SiC)	5	20 g/wafer
KOH	5	13g/wafer
HNO_3	5	0,6 g/wafer
$POCl_3$	6	0,09 g/wafer
HF	6	1,1 g/wafer
CF_4	6	0,08 g/wafer
Al-Ag paste	7	0,78 g/wafer
Ag paste	7	0,10 g/wafer
SiH_4	8	0,03 g/wafer (18 ml)
NH_3	8	0,13 g/wafer (178 ml)
N_2	8	1,55 g/wafer
copper strips	9	0,5 g/wafer (18 g/module)
EVA	9	640 g/module
tempered glass	9	4700 g/module
Tedlar/Al/Tedlar	9	91 g/module
Al into Tedlar	9	0,09 g/module
polyester	9	440 g/module
silicone adhesive	9	38 g/module
Al	9	1200 g/module

ENERGY STREAM ANALYSIS

operation	value	unit
1	0,2	kWht/kg mg-Si
2	51,3	kWh/kg mg-Si
3	106	kWht/kg sog-Si
4	0,19	kWh_e/wafer
5	-	kWh_e/wafer
6	0,11	kWh_e/wafer
7	0,11	kWh_e/wafer
8	-	kWh_e/wafer
9	3,8	kWh_e/module

Results





	No recycling US	Re cycling in US	Recycling in I US	No recycling DE	Recycling DE	Recycling in I DE
GE(MJ/m²)	1682,4	1700,9	1625,5	1578,0	1559,9	1521,1
CO_{2eq} (kg/m²)	96,4	95,9	91,5	88,7	85,6	83,7
NO_x (g/m²)	324,4	341,5	313,8	252,6	239,7	241,9
SO_x (g/m²)	600,1	603,6	558,3	377,8	322,7	336,0
PM10 (g/m²)	62,6	66,5	61,0	51,1	52,5	49,7
Cd (mg/m²)	11,6	3,4	3,3	11,1	2,8	2,8

PRIMARY ENERGY (US PRODUCTION)

	SCENARIO 1 MJ/m^2		SCENARIO 2 MJ/m^2		SCENARIO 3 MJ/m^2	
Raw materials	12,00	0,713%	0,60	0,035%	0,60	0,00037
Glass+EVA	386,00	22,944%	386,00	22,694%	386,00	23,747%
auxiliary materials	47,50	2,823%	47,50	2,793%	47,50	2,922%
Others processes	11,70	0,695%	11,70	0,688%	11,70	0,720%
Transport	38,44	2,285%	38,44	2,260%	38,44	2,365%
Electricity	720,00	42,797%	720,00	42,330%	720,00	44,295%
waste	1,28	0,076%	1,28	0,075%	1,28	0,079%
PV Factory	1216,92	72,335%	1205,52	70,875%	1205,52	74,165%
Inverter	220,00	13,077%	220,00	12,934%	220,00	13,535%
Transport	46,74	2,778%	46,74	2,748%	46,74	2,876%
Electricity	0,01	0,001%	0,01	0,001%	0,01	0,001%
PV installation	266,75	15,856%	266,75	15,683%	266,75	16,411%
PV treatment	178,00	10,580%	30,40	1,787%	30,40	1,870%
Inv. Treatment	1,25	0,074%	1,25	0,073%	1,25	0,077%
Transport	11,70	0,695%	51,27	3,014%	11,81	0,726%
Electricity	7,73	0,459%	145,73	8,568%	109,73	6,751%
Collection	198,68	11,810%	228,65	13,443%	153,19	9,424%
TOTAL	1682,35	100,000%	1700,92	100,000%	1625,46	100,000%

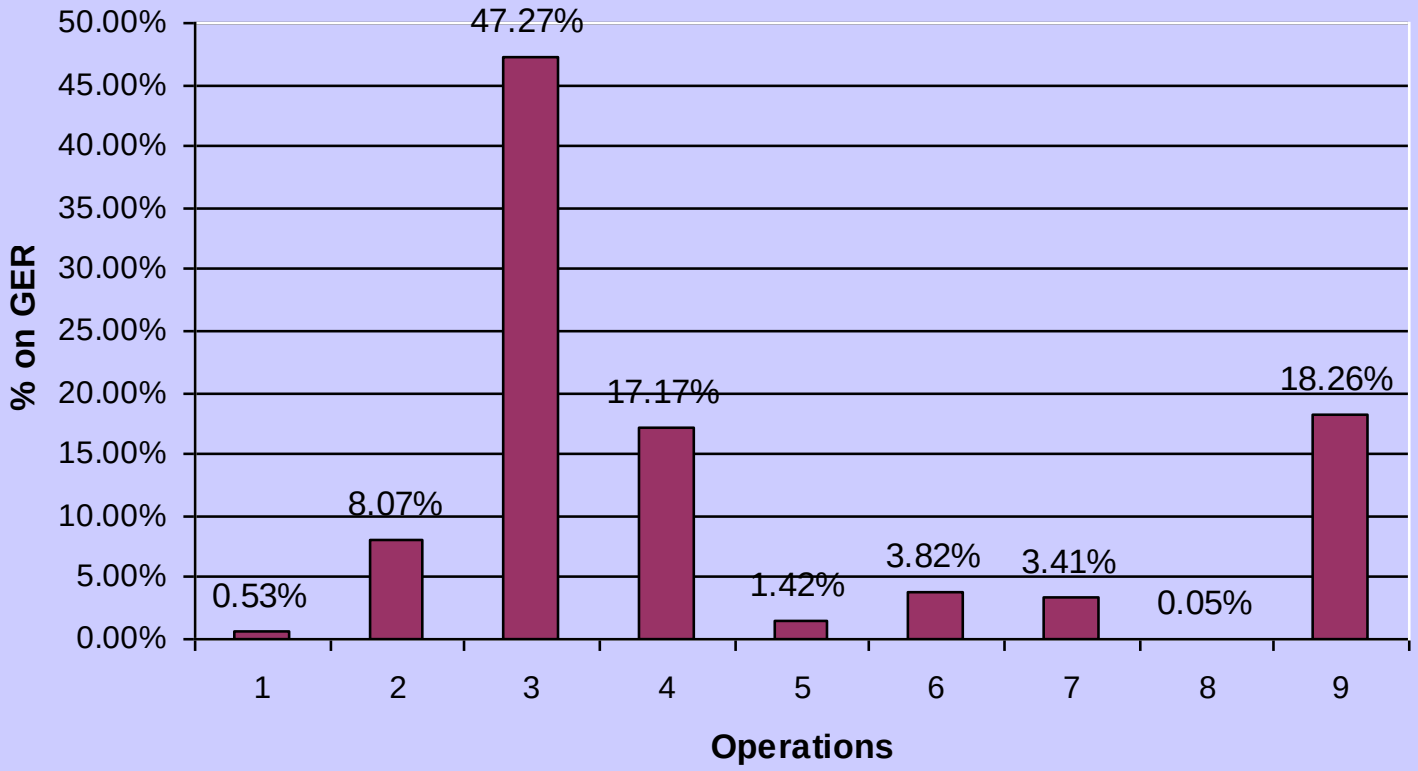
CO2 Emissions-US production

	SCENARIO 1 ($kgCO_{2eq}/m^2$)		SCENARIO 2 ($kgCO_{2eq}/m^2$)		SCENARIO 3 ($kgCO_{2eq}/m^2$)	
Raw materials	0,680	0,71%	0,034	0,04%	0,034	0,04%
Glass+EVA	16,200	16,81%	16,200	16,89%	16,200	17,71%
ausiliars materials	2,980	3,09%	2,980	3,11%	2,980	3,26%
Others processes	0,648	0,67%	0,648	0,68%	0,648	0,71%
Transport	2,168	2,25%	2,168	2,26%	2,168	2,37%
Electricity	43,300	44,92%	43,300	45,14%	43,300	47,33%
waste	1,766	1,83%	1,766	1,84%	1,766	1,93%
PV Factory	67,742	70,28%	67,096	69,95%	67,096	73,34%
Inverter	12,000	12,45%	12,000	12,51%	12,000	13,12%
Transport	2,646	2,75%	2,646	2,76%	2,646	2,89%
Electricity	0,001	0,00%	0,001	0,00%	0,001	0,00%
PV installation	14,647	15,20%	14,647	15,27%	14,647	16,01%
PV treatment	12,700	13,18%	2,150	2,24%	2,150	2,35%
Inv. Treatment	0,063	0,07%	0,063	0,07%	0,063	0,07%
Transport	0,707	0,73%	3,133	3,27%	0,713	0,78%
Electricity	0,526	0,55%	8,826	9,20%	6,816	7,45%
Collection	13,996	14,52%	14,172	14,78%	9,742	10,65%
TOTAL	96,384	100,00%	95,914	100,00%	91,485	100,00%

PM10 Emissions US production

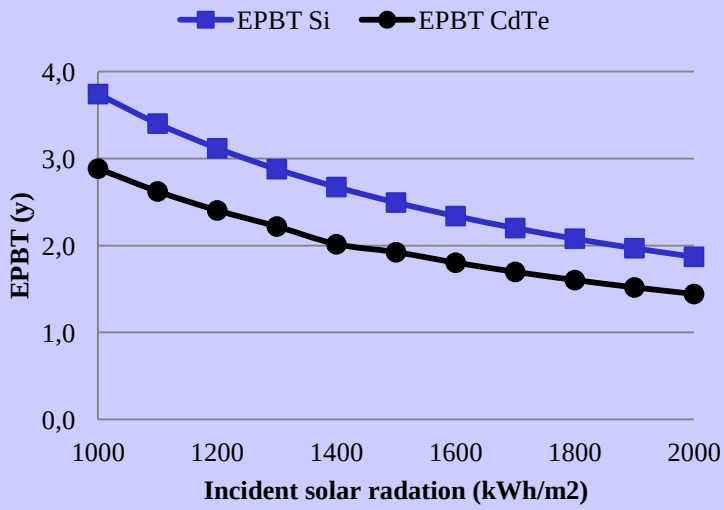
	SCENARIO 1 (gPM10/m^2)		SCENARIO 2 (gPM10/m^2)		SCENARIO 3 (gPM10/m^2)	
Raw materials	0,556	0,89%	0,028	0,04%	0,028	0,01%
Glass+EVA	7,610	12,16%	7,610	11,44%	7,610	1,36%
auxiliary materials	3,250	5,19%	3,250	4,89%	3,250	0,58%
Others processes	0,139	0,22%	0,139	0,21%	0,139	0,02%
Transport	1,267	2,03%	1,267	1,90%	1,267	0,23%
Electricity	34,600	55,30%	34,600	52,01%	34,600	6,20%
waste	0,008	0,01%	0,008	0,01%	0,008	0,00%
PV Factory	47,430	75,81%	46,902	70,50%	46,902	8,40%
Inverter	8,810	14,08%	8,810	13,24%	8,810	1,58%
Transport	1,570	2,51%	1,570	2,36%	1,570	0,28%
Electricity	0,000	0,00%	0,000	0,00%	0,000	0,00%
PV installation	10,380	16,59%	10,380	15,60%	10,380	1,86%
PV treatment	4,330	6,92%	0,736	1,11%	0,736	0,13%
Inv. Treatment	0,045	0,07%	0,045	0,07%	0,045	0,01%
Transport	0,169	0,27%	1,616	2,43%	0,173	0,03%
Electricity	0,211	0,34%	6,851	10,30%	2,801	0,50%
Collection	4,755	7,60%	9,248	13,90%	3,755	0,67%
TOTAL	62,565	100,00%	66,530	100,00%	61,037	10,93%

GER=1494 MJ/panel

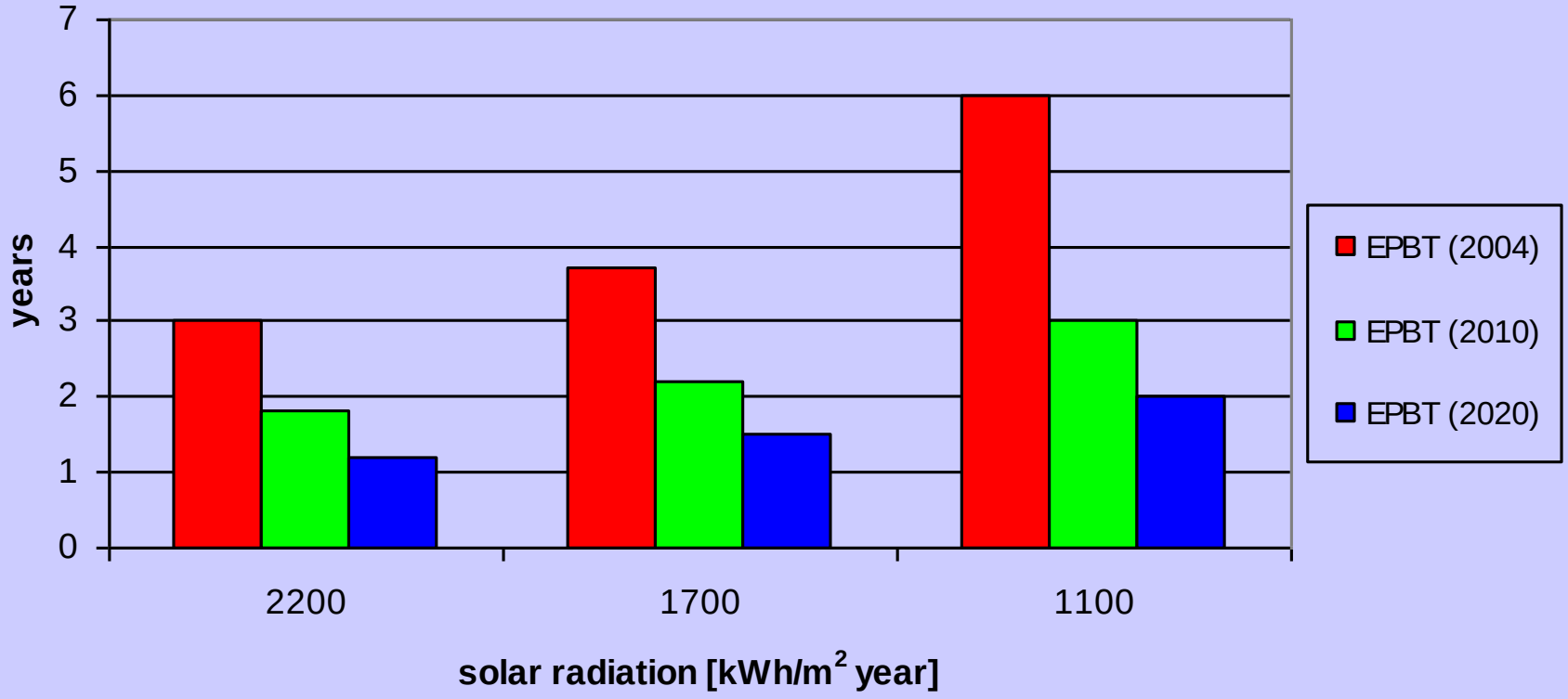


EPBT

kWh/m^2	Si-po PV		CdTe PV	
H_0	NEPBT (y)	gCO_{2eq}/kWh	NEPBT (y)	gCO_{2eq}/kWh
1200	3,1	51,35	2,4	41,28
1300	2,8	47,40	2,2	38,10
1400	2,6	44,02	2,0	34,61
1500	2,5	41,08	1,9	33,02
1600	2,3	38,51	1,8	30,96
1700	2,2	36,25	1,7	29,14



EPBT
Energy Pay Back Time

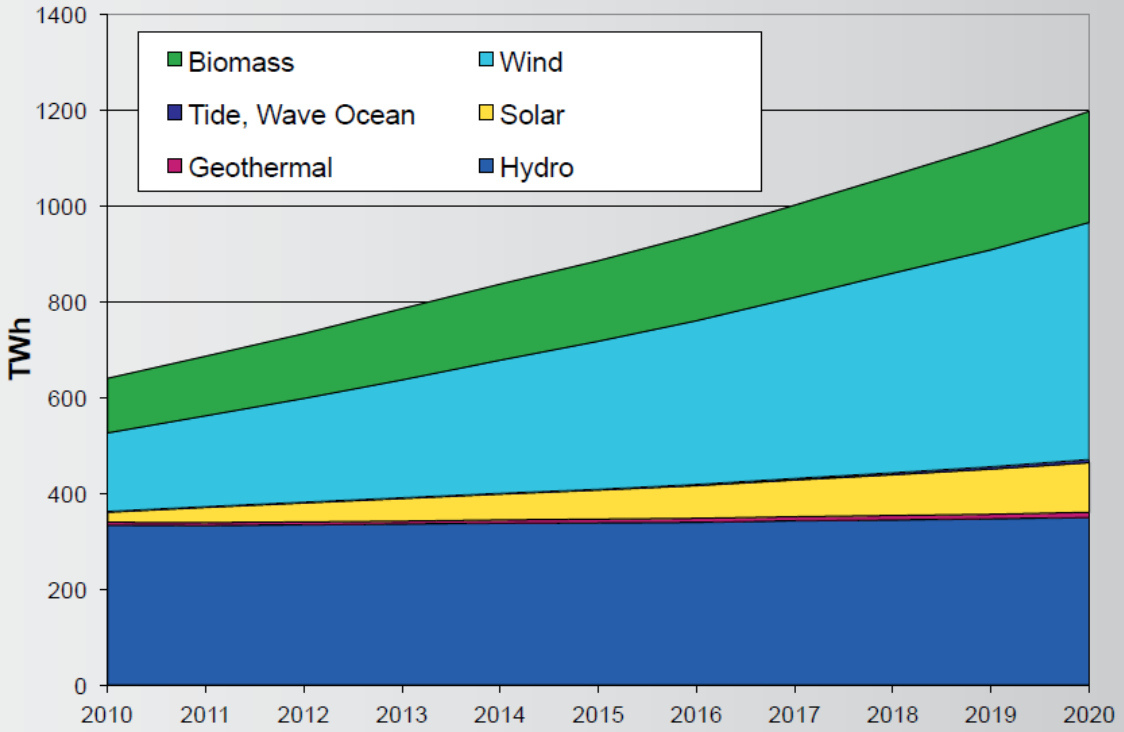


Country	Annual electric production [TWh]	[kgCO2/kWh]	Annual emissions CO2 [tCO2]	Annual CO2 reduction [tCO2/kWp]
AUSTRALIA	242,5	0,841	203.959.320	1,11
AUSTRIA	61,1	0,211	12.883.660	0,19
BELGIUM	90,4	0,248	22.418.952	0,2
CANADA	593,6	0,243	144.253.305	0,29
CZECH REPUBLIC	82,6	0,517	42.693.343	0,42
DENMARK	36	0,536	19.310.472	0,46
FINLAND	70,3	0,315	22.130.010	0,26
FRANCE	575,4	0,08	46.032.000	0,07
GERMANY	619	0,574	355.306.000	0,48
GREECE	61,1	0,801	48.941.100	1,02
HUNGARY	35,7	0,409	14.620.114	0,4
IRELAND	25,1	0,642	16.105.854	0,52
ITALY	302,4	0,569	172.042.271	0,75
JAPAN	1.133,60	0,508	575.860.672	0,52
REPUBLIC OF KOREA	354,1	0,498	176.341.800	0,5
LUXEMBOURG	90,4	0,295	26.667.705	0,25
THE NETHERLANDS	102	0,512	52.224.000	0,45
NEW ZEALAND	42,4	0,187	7.928.426	0,22
NORWAY	138,1	0	0	0
PORTUGAL	46	0,491	22.575.689	0,68
SPAIN	291,9	0,444	129.606.264	0,53
SWEDEN	154,1	0,042	6.474.048	0,04
SWITZERLAND	59,8	0,007	418.404	0,01
TURKEY	162	0,489	79.209.687	0,68
UNITED KINGDOM	399,3	0,532	212.442.496	0,42
UNITED STATES	4.239,20	0,609	2.581.697.769	0,76

Comparison with other technologies

System	MJ/kWh	gCO_{2eq}/kWh	μgCd/kWh	mgNOx/kWh	mgSOx/kWh	mgPM10/kWh
Coal	11,50	1000,00	4,57	2920,00	4900,00	1460,00
Gas	11,70	633,00	0,68	880,00	880,00	397,00
oil	12,20	860,00	39,50	2770	6710,00	84,2
Nuclear	12,70	7,66	1,09	31,00	32,60	10,40
PV CdTe	0,64	35,38	1,15	70,01	114,68	8,58
PV Si	0,68	49,78	0,90	90,00	160,00	11,00
Hidro	0,04	3,91	0,08	0,09	5,27	19,60
Biogas	2,68	94,7	6,17	166,00	204,00	32,10

Fig. 11: Planned European electricity production according to the National Renewable Energy Action Plans



LAST CONSIDERATIONS

- COSTS
- RESEARCH
- SOCIAL IMPACT

Fig. 3: Cumulative Photovoltaic Installations from 2000 to 2009 (data source: EPIA [Epi 2010], Eurobserver [Sys 2010] and own analysis)

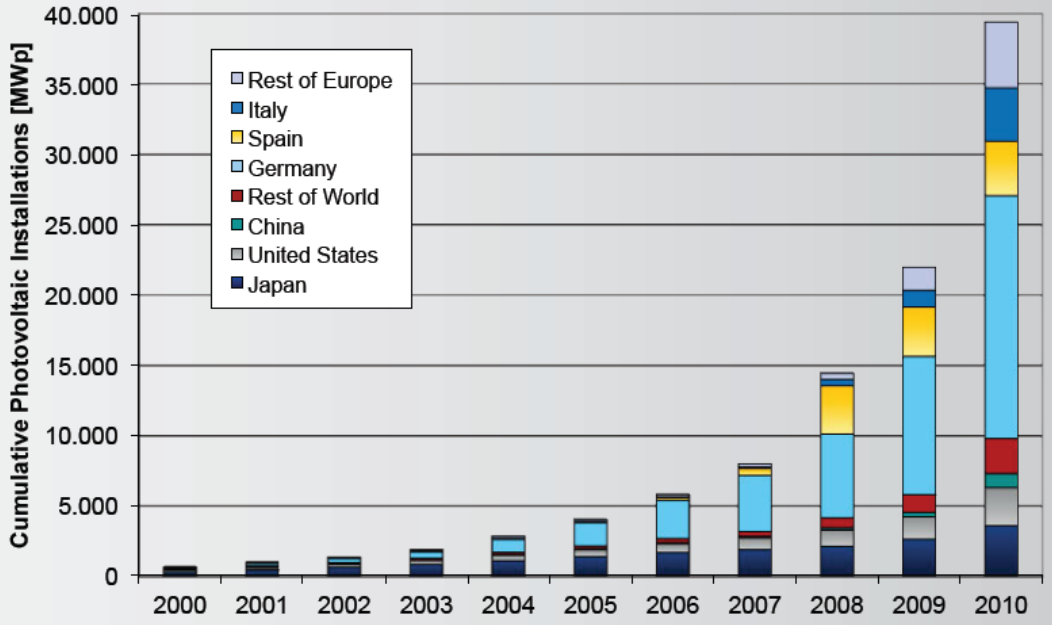


Fig. 1: World PV Cell/Module Production from 2000 to 2010
(data source: Navigant [Min 2010, 2011], Photon International [Pho 2011], PV News [Pvn 2011] and own analysis)

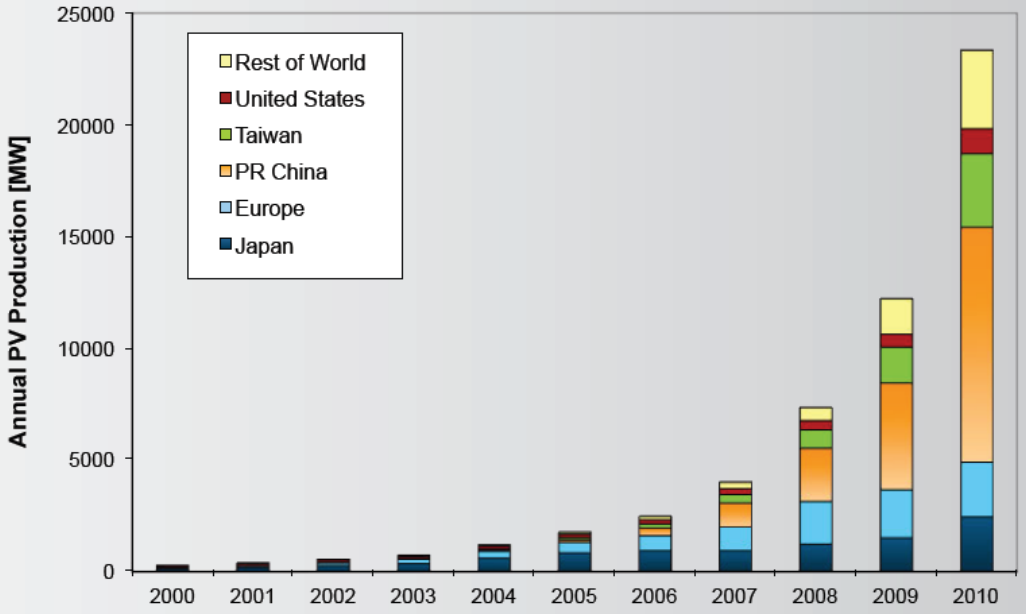


Fig. 5: New installed or decommissioned electricity generation capacity in Europe in 2010