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Life cycle assessment of photovoltaic electricity generation

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Abstract

The paper presents the results of a life cycle assessment (LCA) of the electric generation by means of photovoltaic panels. It considers mass and energy flows over the whole production process starting from silica extraction to the final panel assembling, considering the most advanced and consolidate technologies for polycrystalline silicon panel production. Some considerations about the production cycle are reported; the most critical phases are the transformation of metallic silicon into solar silicon and the panel assembling. The former process is characterised by a great electricity consumption, even if the most efficient conversion technology is considered, the latter by the use of aluminium frame and glass roofing, which are very energy-intensive materials. Moreover, the energy pay back time (EPBT) and the potential for CO_2 mitigation have been evaluated, considering different geographic collocations of the photovoltaic plant with different values of solar radiation, latitude, altitude and national energetic mix for electricity production.

Keywords: Life cycle assessment; Photovoltaic panels; Energy pay back time

1. Introduction

In these last years, energy-related problems are becoming more and more important and involve the rational use of resources, the environmental impact due to the emission of pollutants and the consumption of non-renewable resources. With regard to energy systems, many projects aimed at the mitigation of these problems are being planned, also to fulfil the more and more restrictive environmental laws: they concern the increase of traditional plant and device efficiency [1,2], the diffusion of cogenerative systems, the study of innovative plant configurations, the use of not traditional fuels and of renewable resources. In this last context, solar energy is commonly considered as a very good solution, particularly for small distributed (household) thermal and/or electric energy production. Many countries have introduced policy to promote the installation of new renewable source plants in order to reach the Kyoto protocol targets, and often a specific mention to photovoltaic plants is reported [3,4]. The public opinion, too, is particularly favourable to the use of solar energy, which seems to be completely clean and without any environmental impact. For these reasons, the capacity of photovoltaic power plants, converting solar energy directly to electricity, is increasing: in 10 years (1994–2004) it has grown by 16 times, +44.5% only in the last 2 years (2003–2004) [5].

While during the operation this technology can be considered almost absolutely clean, evaluating the production process of the panels is important in order to consider the emissions and the energy consumption during the whole panel life. For these reasons, only a deeper analysis can give a more correct basis to evaluate the real environmental sustainability of this kind of plants.

This paper presents the results of a life cycle assessment (LCA) [6,7] of the electric generation by means of photovoltaic panels. It takes into account mass and energy flows over the whole production process starting from silica extraction to the final panel assembling. The most advanced and consolidate technologies have been considered for the production of polycrystalline silicon panels, which are the most common nowadays in the market.

Abbreviations: EPBT, energy pay back time (year); ERF, energy return factor; GER, gross energy requirement (MJ/panel); GWP, global warming potential (kg CO_{2eq}/panel); PCM, potential for CO_2 mitigation (t CO_{2eq}/kWp); Mg-Si, metallurgic silicon; Sog-Si, solar-grade silicon.

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The operation of the panels has been analysed, too, in order to evaluate the annual electric production and so the energy pay back time (EPBT) and the potential for CO_2 mitigation (PCM) for different geographic collocations of the photovoltaic plant with different values of solar radiation. The different national energetic mix for electricity generation of each location has been considered, too.

In this way, the real energetic and environmental performance of a photovoltaic panel can be evaluated.

Table 1
Most important assumptions of the LCA

Silica into silicon transformation	Carbothermal
mg-SI into sog-Si transformation	UCC process
Casting and wafer production	Conventional casting process
Wafer area	$12.5 \times 12.5\,cm^2$
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
Operation life	28 years
Module efficiency	16%

2. LCA goal and scope definition

The core of a photovoltaic plant is the solar cell converting the luminous energy into electricity by means of the photovoltaic effect, which consists in the generation of an electromotive force when the radiation reaches a semiconductor plate presenting a potential gap. Today, the semiconductor used for cells is almost always silicon: either monocrystalline, or polycrystalline or amorphous. Crystalline cells are the most common. For this reason a $0.65\,m^2$ panel of polycrystalline silicon produced using current and consolidate technologies has been chosen to define the "functional unit" [6–8] of the LCA. Its conversion efficiency has been assumed equal to 0.16 and its operation life equal to 28 years, as average values reported by many authors [9–11]. The most important assumptions are reported in Table 1. The production processes of the materials used during the cells' production process have been included in the analysis.

3. Inventory

The production process is schematised in Fig. 1. Nine different "unit operations" have been identified in the whole process.

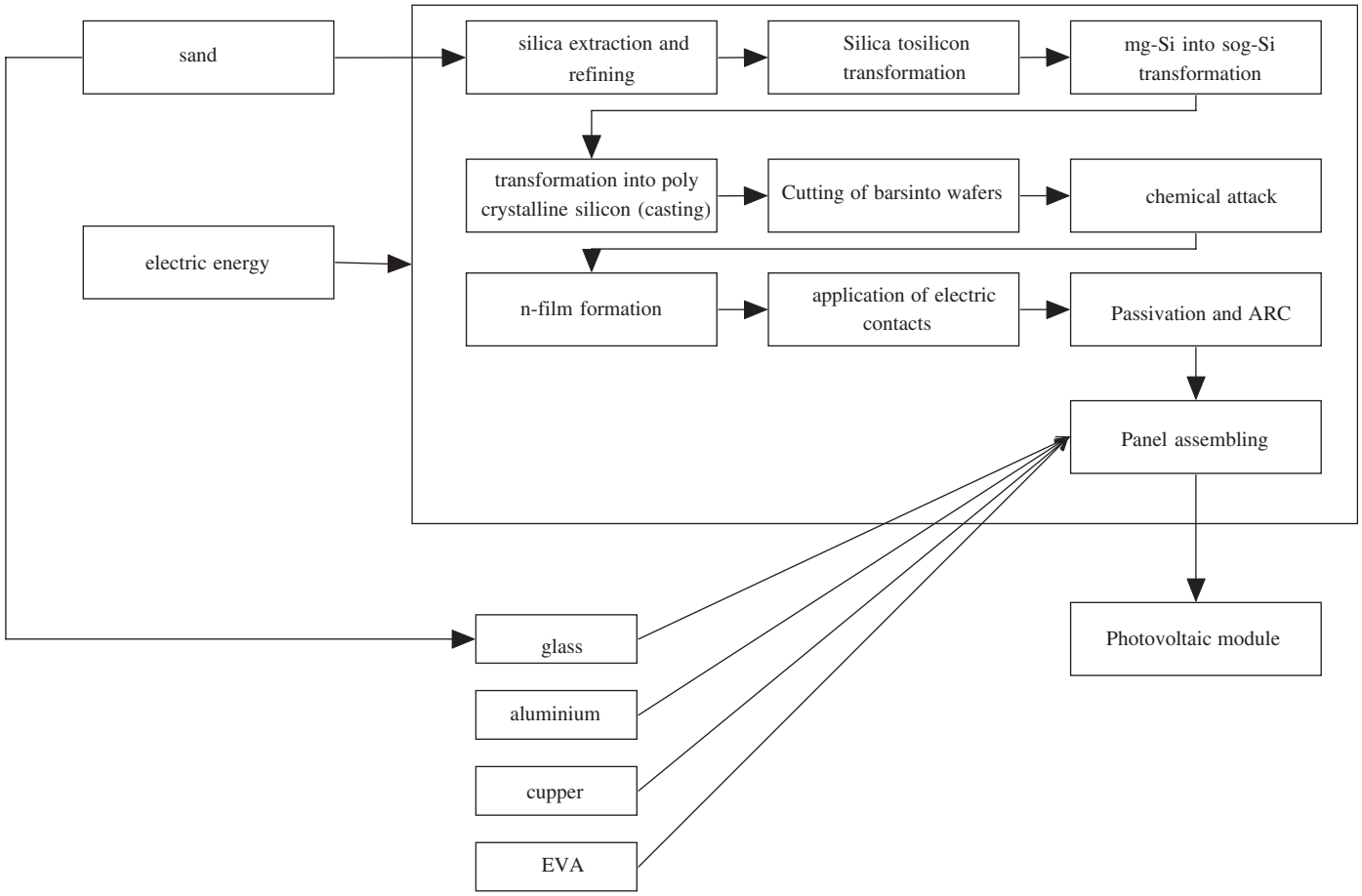

Fig. 1. Schematisation of the production process of a photovoltaic module.

The data collected during mass and energy flows analysis have been organised as forecast by ISO 14040 [7]. For the calculation they have been implemented into the Boustead Model V5.0 [12], able to perform life-cycle calculations and having a very rich database with more than 6000 industrial operations.

Some simplifications have been introduced to simulated operations that are not present in the model. They have been substituted by other processes included in the Boustead database, similar for energy consumption and emissions production. For example, in the chemical attack the production process of NaOH (present in the database) has been considered instead of KOH production process. A comparison analysis has been performed starting from literature data to confirm that negligible differences have been introduced in the LCA results.

The results of mass and energy flows analysis for each phase are summarised in Tables 2–4, while Table 5 reports the synthesis of emissions analysis.

3.1. Silica extraction and refining

The extraction of silica, very abundant on the earth, is made out from sand and is a very mature process [14].

Table 2
Mass and energy stream analysis

Type	Description	Quantity	Unit
Operation 1: Extraction and refining			
Output	Product	1 kg SiO_2	–
Input	Silica sand 98%	2.85	kg/kg SiO_2
Input	Primary energy	0.72	MJ/kg SiO_2
Output	Powder	166	mg/kg SiO_2
Output	PM 10	19	mg/kg SiO_2
Output	Generic emissions	300,000	mg/kg SiO_2
Operation 2: Silica into silicon transformation			
Output	Product	1 kg mg-Si	–
Input	SiO_2	1.18	kg/kg mg-Si
Input	Charcoal	7.99	MJ/kg mg-Si
Input	Low ash coal	19.38	MJ/kg mg-Si
Input	Coke	11.36	MJ/kg mg-Si
Input	Wood scrap	20.86	MJ/kg mg-Si
Input	Electricity	47	MJ/kg mg-Si
Output	CO_2	4,500,000	mg/kg mg-Si
Output	H_2O	1,100,000	mg/kg mg-Si
Output	SiO_2	0.02	kg/kg mg-Si
Output	SO_2	10,000	mg/kg mg-Si
Operation 3: Transformation mg-Si into sog-Si			
Output	Product	1 kg sog-Si	–
Input	Mg-Si	1.02	kg/kg sog-Si
Input	$SiHCl_3$	0.07	kg/kg sog-Si
Input	Primary energy	106	kWht/kg sog-Si
Output	Silicon residues	0.01	kg/kg sog-Si
Output	SiO_2	0.03	kg/kg sog-Si
Output	$CaCl_2$	0.1	kg/kg sog-Si
Operation 5: Chemical attack and texturing			
Output	Product	1 wafer	–
Input	KOH	12.4	g/wafer
Input	KNO_3	0.6	g/wafer
Input	Wafer	1	
Input	Electricity	–	kWh_e/wafer
Output	KOH	11.4	g/wafer
Operation 4: Casting and wafer production			
Output	Product	1 wafer	–
Input	sog-Si	16	g/wafer
Input	Argon	5.75	g/wafer
Input	Mineral oil	15.5	g/wafer
Input	Silicon carbide	20	g/wafer
Input	Cleaning solution	5.3	g/wafer
Input	Formic acid	3.4	g/wafer
Input	Electricity	0.19	kWh_e/wafer
Output	Argon	5.75	g/wafer
Output	Mineral oil	15.5	g/wafer
Output	Si in the oil	7.2	g/wafer
Output	Silicon carbide	12.8	g/wafer
Output	Cleaning solution	3.4	g/wafer
Operation 6: n-film formation			
Output	Product	1 wafer	–
Input	$POCl_3$	0.09	g/wafer
Input	HF	1.1	g/wafer
Input	CF_4	0.08	g/wafer
Input	Wafer	1	
Input	Electricity	0.11	kWh_e/wafer
Output	NaH_2PO_4	0.06	g/wafer
Output	NaOCl	0.09	g/wafer
Output	NaF	0.24	g/wafer
Output	CaF_2	2.1	g/wafer
Output	CO_2	0.01	g/wafer
Operation 7: Application of the electric contacts			
Output	Product	1 wafer	–
Input	Al–Ag paste	0.78	g/wafer
Input	Ag paste	0.1	g/wafer
Input	Wafer	1	
Input	Electricity	0.11	kWh_e/wafer
Output	Solvents	0.21	g/wafer
Output	CO_2	0.04	g/wafer
Operation 8: Passivation and arc			
Output	Product	1 wafer	–
Input	SiH_4	0.03	g/wafer
Input	NH_3	0.13	g/wafer
Input	N_2	1.55	g/wafer
Input	Wafer	1	
Input	Electricity	–	kWh_e/wafer
Output	N_2	1.55	g/wafer
Operation 9: Panel assembling			
Output	Product	1 module	–
Input	Copper strip	18	g/module
Input	Cells	36	cells/module
Input	Glass	4700	g/module
Input	Tedlar/Al/Tedlar	91	g/module
Input	Polyester	440	g/module
Input	Silicone adhesive	38	g/module
Input	Aluminium frame	1200	g/module
Input	EVA sheets	640	g/module
Input	Electricity	3.8	kWh_e/module
Output	Wasted cells	1.08	g/module
Output	EVA sheets	29	g/module
Output	Silicone adhesive	1	g/module

Table 3
Synthesis of 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	0.37 kg/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	13 g/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

Table 4
Synthesis of 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

3.2. Silica to silicon transformation

The extraction of silicon from silica is very expensive and requires a lot amount of energy [9,13,14]. Pulverised quartz and a mixture of coal [15] are fused in a crucible by means of an electric arc and then a reduction process takes place:

$$SiO_2 + 2C \rightarrow Si + 2CO.$$

The result is metallurgic silicon (mg-Si), whose purity of about 98% is not enough for solar cells.

Table 5
Synthesis of emissions analysis

Emissions	Operation	Value	Unit
Into air			
Dust	1	185	mg/kg mg-Si
CO_2	2	4.5	kg/kg mg-Si
CO_2	6	0.01	g/wafer
SO_2	2	0.01	kg/kg mg-Si
SI dust	3	0.01	kg/kg sog-Si
Argon gas	4	5.75	g/wafer
N_2	8	1.55	g/wafer
Solvents	7	0.21	g/wafer
H_2O	7	0.04	g/wafer
Into water			
$CaCl_2$	3	0.1	kg/kg sog-Si
KOH	5	11.4	g/wafer
NaH_2PO_4	6	0.06	g/wafer
NaOCl	6	0.09	g/wafer
NaF	6	0.24	g/wafer
Solid waste			
SiO_2	2	0.02	kg/kg mg-Si
SiO_2	3	0.03	kg/kg sog-Si
CaF_2	6	2.1	g/wafer
Rejected cells (cells/m^2)	9	3.2	–
EVA	9	29	g/module
Silicone adhesive	9	1	g/module
Rejected modules	9	0.11	
Other			
Si in oil mineral	4	7.2	G/wafer
SiC	4	12.8	G/wafer
Mineral oil	4	15.5	G/wafer

3.3. mg-Si into solar silicon transformation

Different methods exist to obtain solar-grade silicon (sog-Si). In this work the process developed by the Union Carbide Corporation (UCC) has been considered [13,14,16]. It consists of silicon hydrogenation in a fluid bed reactor at 500 °C and 3.5 MPa with a copper-based catalyst and a series of fractionated distillations eliminating impurities. In the last distillation a pyrolysis process takes place, from which sog-Si is obtained. Its purity is about $1–10^{-3}$ to 10^{-6}.

3.4. Transformation into polycrystalline silicon and wafer production

For the transformation of silicon into polycrystalline silicon, the casting (or HEM) method has been considered [15,16]. It takes to the formation of columnar silicon, where the crystals are vertically aligned. In this way, the wafers cut from the column form cells whose behaviour is very similar to that of mono-crystalline silicon. The wafers are square 10×10 or $15 \times 15\,cm^2$, thickness about $200-350\,\mu m$.

3.5. Chemical attack

This is the first phase of the solar cell itself production. In this paper, a process using a $KOH–NH_3$ solution has been chosen to remove the damages on the wafer surface due to the sawing and to texture the surface itself for a better solar radiation absorption.

3.6. n-Film formation

The film is created by means of the diffusion of phosphorus on the surface of the wafer [14]. Usually, the process takes place at high temperature (850–900 °C) and consists of the gurgling of nitrogen into liquid $POCl_3$; then saturated nitrogen passes over the wafer in the presence of oxygen and a film diffusing phosphorus is created:

$$4POC1_3 + 3O_2 \rightarrow 2P_2O_3 + 6Cl_2.$$

The exceeding P_2O_5 is removed by means of a chemical attack with HF. At last, to avoid short circuits, wafers are plasma sliced.

3.7. Application of the electric contacts

The anterior and posterior contacts are mainly made by Al and Ag and are deposed by means of a vacuum evaporation of suitable pastes.

3.8. Passivation and antireflection coating (ARC)

The cells are passivated and coated by an antireflection film. The plasma enhanced chemical vapour deposition (PECVD) process has been considered, which performs both the phases at the same time. It consists in a plasma enhanced chemical deposition of Si_3N_4, which takes place in a reactor by means of sylane (SiH_4) and ammonia (NH_3) at 400−450 °C.

3.9. Panel assembling

The cells are tested and then assembled by means of copper strips covered by tin. A classical configuration of 4×9 cells has been assumed, which gives 18 V at maximum power allowing a good storage in the Pb batteries usually connected to the module. Then the cells are encapsulated between two ethylene vinyl acetate (EVA) sheets. The anterior part of the module is at last covered by a transparent tempered glass sheet, the posterior by a Tedlar/Al/Tedlar sheet. An aluminium frame is then applied and, on the posterior face, also a connection box [14,17–20].

4. Impact assessment

Briefly, the most important results of the analysis are the calculation of a gross energy requirement (GER) [6,7,12] of 1494 MJ/panel (0.65 m^2 surface) and a greenhouse effect or global warming potential (GWP), concerning the contribution of the process to climate change, of 80 kg of equivalent CO_2/panel. Note that GER [7], which is the energy supplied to the system by the environment to maintain the process, is comprehensive of

- direct energy, consumed during the process itself;
- indirect energy, consumed to produce and transport the materials used into the process;
- feedstock energy, which is the energetic content of the materials used as they are and not as fuels.

Figs. 2 and 3 summarise the per cent contribution of each operation. The most critical phases are the transformation of metallic into solar silicon (1190.1 MJ/panel) and the panel assembling (272.7 MJ/panel). The former process is characterised by great electricity consumption, even if the most efficient conversion technology has been considered, the latter by the use of aluminium frame and glass roofing, which are very energy-intensive

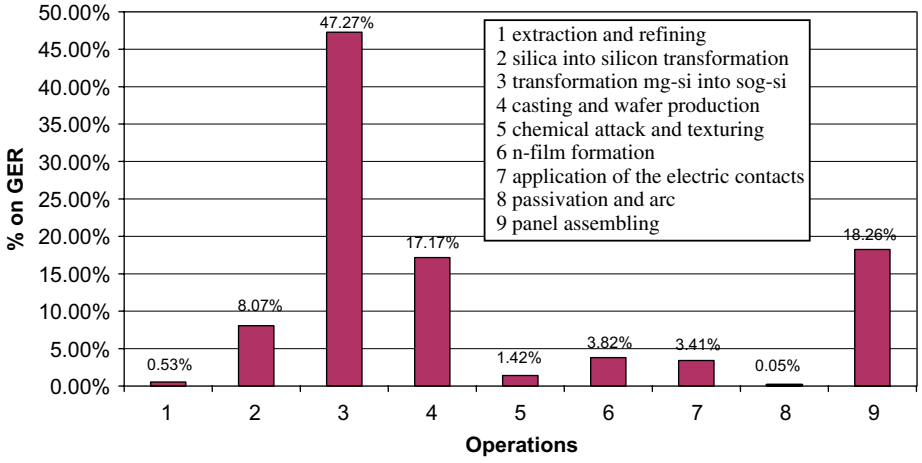

Fig. 2. Contribution of each unit operation to the GER as percentage. Total GER = 1494 MJ/panel.

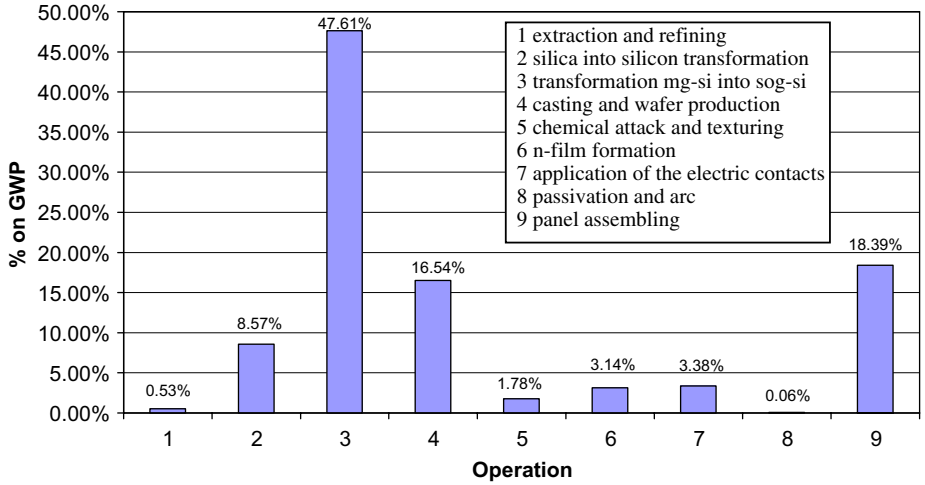

Fig. 3. Contribution of each unit operation to the GWP as percentage of total GWP = 80 kg_{CO_2}/panel.

Table 6
EPBT and ERF for different photovoltaic plant locations

Country	Town	Solar radiation (kWh/m^2)	Latitude	Altitude (m)	Annual production (kWh/kWp)	EPBT (years)	ERF
Australia	Sydney	1614	−33.55	1	1319	3.728	7.5
Austria	Vienna	1108	48.20	186	906	5.428	5.2
Belgium	Brussels	946	50.50	77	788	6.241	4.5
Canada	Ottawa	1377	45.25	75	1188	4.140	6.8
Czech Republic	Prague	1000	50.06	261	818	6.012	4.7
Denmark	Copenhagen	985	55.75	1	850	5.786	4.8
Finland	Helsinki	956	60.13	0	825	5.961	4.7
France	Paris	1057	48.52	32	872	5.640	5.0
France	Marseille	1540	43.18	7	1317	3.734	7.5
Germany	Berlin	999	52.32	35	839	5.862	4.8
Germany	Munich	1143	48.21	515	960	5.123	5.5
Greece	Athens	1563	38.00	139	1278	3.848	7.3
Hungary	Budapest	1198	47.30	103	988	4.978	5.6
Ireland	Dublin	948	53.20	9	811	6.064	4.6
Italy	Rome	1552	41.53	15	1315	3.740	7.5
Italy	Milan	1251	45.28	103	1032	4.765	5.9
Japan	Tokyo	1168	35.40	14	955	5.150	5.4
Republic of Korea	Seoul	1215	37.30	30	1002	4.908	5.7
Luxembourg	Luxembourg	1035	49.62	295	862	5.705	4.9
The Netherlands	Amsterdam	1045	52.21	−1	886	5.551	5.0
New Zealand	Wellington	1412	−41.17	21	1175	4.185	6.7
Norway	Oslo	967	59.56	13	870	5.653	5.0
Portugal	Lisbon	1682	35.44	16	1388	3.543	7.9
Spain	Madrid	1660	40.25	589	1394	3.528	7.9
Spain	Sevilla	1754	37.24	5	1460	3.368	8.3
Sweden	Stockholm	980	59.21	16	860	5.718	4.9
Switzerland	Bern	1117	46.57	524	922	5.334	5.2
Turkey	Ankara	1697	39.55	1102	1400	3.513	8.0
United Kingdom	London	955	51.30	20	788	6.241	4.5
United Kingdom	Edinburgh	890	55.57	32	754	6.522	4.3
United States	Washington	1487	38.52	14	1249	3.937	7.1

materials. In this last phase, materials consumption gives a higher impact than electricity consumption. In fact, aluminium frame contributes for 22.3%, glass roofing for 23%, EVA for 18.9% and polyester for the electric box for 14.6%, while the electricity use contribution is only 15.6%.

The metallic to solar silicon transformation also gives the highest contribution to GWP, just for its great electricity consumption. Note that the use of wood bark during silica into silicon transformation gives a negative contribution to CO_2 production.

Table 7
Electricity production [5] and CO_2 emissions in different countries

Country	Nuclear (TWh)	Hydro (TWh)	Coal (TWh)	Oil (TWh)	Gas (TWh)	PV and others (TWh)	Total (TWh)	CO_2 emissions (Mt/year)	CO_2 average emissions ($kgCO_2/kWh$)
Australia	0.0	17.0	186.7	2.4	34.0	2.4	242.5	203.70	0.840
Austria	0.0	37.2	9.2	1.8	11.0	1.9	61.1	15.72	0.257
Belgium	50.6	1.8	12.7	0.9	23.5	0.9	90.4	23.85	0.264
Canada	77.2	344.3	112.8	17.8	35.6	5.9	593.6	145.08	0.244
Czech Republic	25.6	1.7	51.2	0.0	3.3	0.8	82.6	52.60	0.637
Denmark	0.0	0.0	19.8	1.8	7.6	6.8	36.0	24.81	0.689
Finland	19.0	7.7	22.5	0.7	11.9	8.5	70.3	28.36	0.403
France	448.8	63.3	28.8	11.5	17.3	5.7	575.4	47.20	0.082
Germany	173.3	24.8	321.9	6.2	61.9	30.9	619.0	354.59	0.573
Greece	0.0	5.5	36.7	9.2	8.6	1.1	61.1	49.11	0.804
Hungary	11.4	0.4	9.7	1.8	12.5	0.0	35.7	16.87	0.473
Ireland	0.0	1.0	8.0	2.5	13.0	0.6	25.1	16.05	0.640
Italy	0.0	45.4	45.4	78.6	120.9	12.1	302.4	172.47	0.570
Japan	294.7	102.0	317.4	147.4	272.1	0.0	1133.6	575.39	0.508
Republic of Korea	131.0	7.1	138.1	31.9	42.5	3.5	354.1	186.67	0.527
Luxembourg	0.0	22.6	0.0	0.0	65.1	2.7	90.4	28.58	0.316
The Netherlands	4.1	0.0	28.6	3.1	60.2	6.0	102.0	57.92	0.568
New Zealand	0.0	24.6	3.4	0.0	10.2	4.2	42.4	7.87	0.186
Norway	0.0	136.7	0.0	0.0	0.0	1.4	138.1	0.00	0.000
Portugal	0.0	15.6	14.3	6.0	7.4	2.7	46.0	23.19	0.504
Spain	70.1	49.6	84.7	26.3	43.8	17.4	291.9	128.62	0.441
Sweden	77.1	60.1	4.6	4.6	0.0	7.7	154.1	8.93	0.058
Switzerland	24.5	32.9	0.0	0.0	0.6	1.8	59.8	0.26	0.004
Turkey	0.0	40.5	37.3	11.3	72.9	0.0	162.0	79.91	0.493
United Kingdom	87.9	8.0	139.8	8.0	147.8	7.8	399.3	212.08	0.531
United States	805.5	296.7	2162.0	127.2	678.3	169.5	4239.2	2577.43	0.608

Moreover, the EPBT has been evaluated. A photovoltaic plant constituted by 36 cells of 300 μm thickness and 100 cm^2 area each has been considered. The plant is grid connected roof installed (30° tilt angle). Many geographic collocations of the plant with different values of solar radiation have been assumed [21]: Table 6 summarises the results. The EPBT is estimated fairly shorter than the panel operation life even in the worst conditions (6.5 years). Table 6 also reports the values of the energy return factor (ERF), which is defined as the ratio between expected panel life (28 years) and EPBT. It represents how many times the plant pays back the energy needed for its production. In the best case, a photovoltaic plant can produce more than 8 times this energy.

The CO_2 return time [22] has been considered, too, comparing two different photovoltaic plants, 10 MW installed each, to a traditional coal fuelled thermoelectric power plant (emitting 1000 kg_{CO_2}/MWh). Both operation and materials and construction emissions have been considered. For a photovoltaic plant producing 11830 GWh/year the return time is 3.85 years, corresponding to 148 kg_{CO_2}/MWh, while it is 4.91 years if the annual production is 8640 GWh/year, corresponding to 187 kg_{CO_2}/MWh. Both the results are highly smaller than plant operation life. Finally, the PCM has been evaluated, which is defined as the equivalent CO_2 emissions avoided using a particular system. It is calculated by means of the equation

$$\text{PCM} = \text{Annual Energy Output} * (28\ \text{years} - \text{EPBT}) * CO_2\ \text{national content}$$

and depends not only on PV technology, but even on local energetic mix for the electricity generation summarised in Table 7 [5].

Table 8 summarises the results. The CO_2 average content for each country has been calculated considering 0 the content for renewable and nuclear energy, 0.999 kg CO_2/kWh for coal, 0.942 kg CO_2/kWh for oil and 0.439 kg CO_2/kWh for natural gas thermoelectric power plants.

The highest value of PCM is the Australian (1.11 CO_2 tons annually avoided for each PV pick kW installed) due to both high solar radiation and an energetic mix based on fossil fuels; the lowest is the Norwegian, whose electricity generation is nearly clean. These results are interesting to evaluate the convenience of installing PV plants to reduce the CO_2 production of a country.

5. Comments and improvements

Some possible improvements in the panel production process have been supposed and their influence on EPBT has been analyzed, as reported also in [23]: a reduction of

Table 8
PCM for different photovoltaic plant location

Country	Town	Solar radiation (kWh/m^2)	Latitude	Altitude (m)	CO_2 content ($kgCO_2/kWh$)	PCM (tCO_2/kWp)
Australia	Sydney	1614	−33.55	1	0.841	1.1093
Austria	Vienna	1108	48.20	186	0.211	0.1912
Belgium	Brussels	946	50.50	77	0.248	0.1954
Canada	Ottawa	1377	45.25	75	0.243	0.2887
Czech Republic	Prague	1000	50.06	261	0.517	0.4229
Denmark	Copenhagen	985	55.75	1	0.536	0.4556
Finland	Helsinki	956	60.13	0	0.315	0.2599
France	Paris	1057	48.52	32	0.080	0.0698
France	Marseille	1540	43.18	7	0.080	0.1054
Germany	Berlin	999	52.32	35	0.574	0.4816
Germany	Munich	1143	48.21	515	0.574	0.5510
Greece	Athens	1563	38.00	139	0.801	1.0237
Hungary	Budapest	1198	47.30	103	0.409	0.4041
Ireland	Dublin	948	53.20	9	0.642	0.5207
Italy	Rome	1552	41.53	15	0.569	0.7482
Italy	Milan	1251	45.28	103	0.569	0.5872
Japan	Tokyo	1168	35.40	14	0.508	0.4851
Republic of Korea	Seoul	1215	37.30	30	0.498	0.4990
Luxembourg	Luxembourg	1035	49.62	295	0.295	0.2543
The Netherlands	Amsterdam	1045	52.21	−1	0.512	0.4536
New Zealand	Wellington	1412	−41.17	21	0.187	0.2197
Norway	Oslo	967	59.56	13	0.002	0.0017
Portugal	Lisbon	1682	35.44	16	0.491	0.6815
Spain	Madrid	1660	40.25	589	0.444	0.6189
Spain	Seville	1754	37.24	5	0.444	0.6482
Sweden	Stockholm	980	59.21	16	0.042	0.0361
Switzerland	Bern	1117	46.57	524	0.007	0.0065
Turkey	Ankara	1697	39.55	1102	0.489	0.6846
United Kingdom	London	955	51.30	20	0.532	0.4192
United Kingdom	Edinburgh	890	55.57	32	0.532	0.4011
United States	Washington	1487	38.52	14	0.609	0.7606

wafer thickness from 300 to 200 (in 2010) and 150 μm (in 2020); new processes to produce wafers (the edge-defined film-fed growth has been supposed in 2010 and 2020, which allows to save silicon rejection during cutting phase); a technology to produce solar grade silicon outside from electronic silicon process. In the best hypotheses, an EPBT of 2 years has been calculated. A conversion efficiency of 13% in 2004, 17% in 2010 and 18% in 2020 has been assumed. Fig. 4 summarises these results for three different geographic locations.

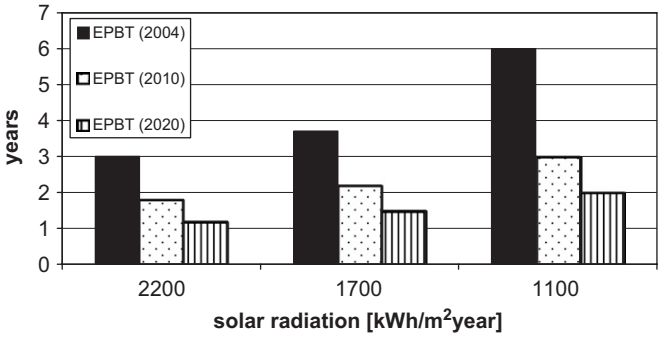

Fig. 4. EPBT evolution for different solar radiation values.

6. Conclusion

Briefly, the most important results of the analysis are the calculation of a gross energy requirement (GER) of 1494 MJ/panel (0.65 m^2 surface) and of a global warming potential (GWP) of 80 kg of equivalent CO_2/panel. The most critical phases are the transformation of metallic silicon into solar silicon and the panel assembling.

Moreover, the energy pay back time (EPBT) has been evaluated. It is estimated to be shorter than the panel operation life even in the worst geographic conditions.

So the results of the LCA support the idea that the photovoltaic electric production is advantageous for the environment, also considering the panel production process.

At present, the impact of PV module transport from factory to utilisation on EPBT and PCM is being studied. This could be interesting to evaluate the real PV impact when long distances must be covered (for example, in Italy

the PV production is very lower than the demand and they must be imported from abroad).

The disposal phase is also under analysis to evaluate its influence on the energy and emissions analysis.

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