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Short communication

Energy payback time and carbon footprint of commercial photovoltaic systems

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ABSTRACT

Energy payback time and carbon footprint of commercial roof-top photovoltaic systems are calculated based on new 2011 manufacturers' data; and on 2013 equipment manufacturers' estimates of "micromorph" silicon photovoltaic modules. The energy payback times and carbon footprints are 1.96, 1.24, 1.39, 0.92, 0.68, and 1.02 years and 38.1, 27.2, 34.8, 22.8, 15.8, and 21.4 g CO_2-eq/kWh for monocrystalline silicon, multicrystalline silicon, amorphous silicon, "micromorph" silicon, cadmium telluride and CIGS roof-top photovoltaic systems, respectively, assuming a poly-silicon production with hydropower; ingot-, wafer-, solar cell and module production with UCTE electricity; an irradiation on an optimized-angle of 1700 kWh/($m^2 \times$ year); excluding installation, operation and maintenance and end-of-life phase. Shifting production of poly-silicon, ingots, wafers, cells and modules to China results in similar energy payback times but increases the carbon footprint by a factor 1.3–2.1, depending on the electricity intensity of manufacturing.

1. Introduction

The increase in scale of production of PV modules goes hand in hand with economies of scale of manufacturing and optimized designs. This work shows the latest results for energy payback time and carbon footprint based on new data for commercial scale manufacturing of PV modules and updates of several data sets of ecoinvent 2.2+ [1].

2. *Methodology*

Life Cycle Assessment (LCA) methodology was used to calculate the cumulative energy demand and global warming potential of PV modules and Balance-of-System components. Energy payback time and carbon footprint were calculated using the IEA PVPS task 12 guidelines [2]. The ecoinvent 2.2 database was used for background data, and calculations were performed with Simapro 7.3.3 software.

Data for PV systems and its components are described in [3] and are based on: (1) manufacturers' data collected by SmartGreenScans, (2) International Technology Roadmap for Photovoltaics (ITRPV) [4], (3) crystalline silicon solar cell data in [5], (3) market surveys of equipment in Photon International, and (4) Estimated data of "micromorph" silicon PV module with Oerlikon Solar THINFAB 120 MWp [6].

The roof-top balance-of-system amounts of a PV system with crystalline silicon modules on a typical Dutch house is described in [7]. The cable diameter for modules with lower module efficiency is smaller but no data are available so far, for thin film modules; therefore the same cabling is assumed here as for crystalline silicon. Inverter sizing values are taken from Stetz [8].

The IEA PVPS task 12 guidelines [2] recommend assuming a performance ratio of 0.75 for roof-top systems. In this study we used a performance ratio of 0.77 which is the average of Belgian and French residential PV systems investigated by Leloux in 2010 [9].

The IEA PVPS task 12 guidelines [2] recommend taking into account a linear power degradation of 20% after 30 years (0.67%/year) for all module technologies. A typical power guarantee on nominal module power is 80% after 25 years [10]. In this study we used system power degradation values of PV systems installed after the year 2000 from a recent literature review by Jordon [11].

To be able to compare the LCA results, the electricity mix to produce solar grade poly-silicon is taken to be hydropower, whereas for the ingots, wafers, cells and modules UCTE electricity mix is assumed. The efficiency of the UCTE electricity grid is 11.4 MJ/kWh (ecoinvent 2.2). The system analyzed is a roof-top PV system with PV modules with optimized-angle. Excluded are installation, operation, maintenance and end-of-life phase. Key parameters are shown in Table 1. High module efficiencies are

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Table 1
Key parameters and LCA results for commercial PV systems.

Technology:		mono-Si	mono-Si	multi-Si	multi-Si	a-Si
Product name/description:		average	average	average	average	average
Scale of production:						33–45 MWp
Status:		2011	2011	2011	2011	2008–2011
Electricity mix:		hydro/UCTE	China/China	hydro/UCTE	China/China	UCTE
Installation type:		roof-top	roof-top	roof-top	roof-top	roof-top
DATA SOURCES						
Data source poly-Si:		ecoinvent 2.2: "Silicon, solar grade, modified Siemens process, at plant/ RER U"	ecoinvent 2.2: "Silicon, solar grade, modified Siemens process, at plant/ RER U"	ecoinvent 2.2: "Silicon, solar grade, modified Siemens process, at plant/ RER U"	ecoinvent 2.2: "Silicon, solar grade, modified Siemens process, at plant/ RER U"	not applicable
Data source ingots:		various	various	various	various	not applicable
Data source wafers:		various	various	various	various	not applicable
Data source solar cells:		various	various	various	various	not applicable
Data source modules:		various	various	various	various	2: Germany, T-Solar (Spain)
Data source mounting:		Schletter Eco05/EcoG	Schletter Eco05/EcoG	Schletter Eco05/EcoG	Schletter Eco05/EcoG	Inventux fiX
Data source inverter:		ecoinvent 2.2	ecoinvent 2.2	ecoinvent 2.2	ecoinvent 2.2	ecoinvent 2.2
Background data:	ecoinvent	ecoinvent 2.2	ecoinvent 2.2	ecoinvent 2.2	ecoinvent 2.2	ecoinvent 2.2
KEY PARAMETERS						
POLY-SILICON						
Technology:		solar grade Siemens	solar grade Siemens	solar grade Siemens	solar grade Siemens	not applicable
Feedstock	kg virgin/ m^2 module	1.192	1.192	0.625	0.625	not applicable
INGOTS & WAFERS	*"as grown" crystal/ingot*					
Wafer size:		156 mm × 156 mm	156 mm × 156 mm	156 mm × 156 mm	156 mm × 156 mm	not applicable
Wafer thickness:		180–200 μm	180–200 μm	180–200 μm	180–200 μm	not applicable
Virgin Si charging of crucible:	kg virgin/kg crystal	0.781	0.781	0.700	0.700	not applicable
Ingot/wafer	kg crystal/ wafer	0.0385	0.0385	0.0224	0.0224	not applicable
Wafers/module	wafers/m^2 module	39.66	39.66	39.85	39.85	not applicable
FAB electricity consumption:	kWh/kg crystal	68.18	68.18	15.49	15.49	not applicable
FAB electricity consumption:	kWh/wafer	0.62	0.62	0.51	0.51	not applicable
SOLAR CELLS						
Solar cell size:		156 mm × 156 mm	156 mm × 156 mm	156 mm × 156 mm	156 mm × 156 mm	not applicable
Wafers/cell	wafers/cell	1.030	1.030	1.035	1.035	not applicable
Cells/module:	cells/m^2 module	38.50	38.50	38.50	38.50	not applicable
FAB electricity consumption:	kWh/cell	0.35	0.35	0.35	0.35	not applicable
MODULES						
Cells in one module:		6 × 10	6 × 10	6 × 10	6 × 10	not applicable
Cells/module:	cells/ module	61.5	61.5	61.5	61.5	not applicable
Glass length:	mm	986	986	986	986	2200
Glass width:	mm	1620	1620	1620	1620	2600
Glass area:	m^2	1.6	1.6	1.6	1.6	5.72
Module	modules/ m^2	0.626	0.626	0.626	0.626	0.175
Module weight:	kg	20	20	20	20	118
Module weight/area:	kg/m^2	12.5	12.5	12.5	12.5	21
Module efficiency:	%	14.8%	14.8%	14.1%	14.1%	7.0%
Module power/area:	Wp/m^2	148	148	141	141	70
Module area/power:	m^2/kWp	6.76	6.76	7.09	7.09	14.29
Module composition:		glass-EVA-backsheet	glass-EVA-backsheet	glass-EVA-backsheet	glass-EVA-backsheet	glass-PVB-glass
Glass:		single	single	single	single	double
Glass thickness:	mm	3.2	3.2	3.2	3.2	3.2
Glass density:	kg/m^3	2500	2500	2500	2500	2500
Encapsulation material:		ethylvinylacetate (EVA)	ethylvinylacetate (EVA)	ethylvinylacetate (EVA)	ethylvinylacetate (EVA)	polyvinylbutyral (PVB)
Encapsulation thickness:	μm	450	450	450	450	760
Encapsulation density:	kg/m^3	955	955	955	955	1079
Encapsulation cutting loss:		1%	1%	1%	1%	6%
Backsheet thickness:	μm	330	330	330	330	none
Backsheet cutting loss:		6%	6%	6%	6%	
Frame material:		aluminum	aluminum	aluminum	aluminum	none
Frame weight:	kg/m^2 module	2.13	2.13	2.13	2.13	0