ANALYSING THE EFFECT OF GEOGRAPHIC LOCATION ON THE ENVIRONMENTAL PERFORMANCE OF A HIGH CONCENTRATION PHOTOVOLTAIC POWER PLANT

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ABSTRACT

High Concentration Photovoltaic (HCPV) technology uses multi-junction solar cells made of different layers of semiconducting materials (GaInP2/GaAs/Ge) to produce electricity from solar radiation in a sustainable and efficient manner. The environmental performance of this technology has been investigated using Life Cycle Analysis (LCA) methodology (ISO14040) using a complete inventory of a commercial 1.008 MWp HCPV plant. The analysis has been conducted in six geographic locations with potential for this technology (Morocco, Peru, South Africa, United States, Mexico and Brazil) but showing differences in terms of availability of solar resource, nature of the national electricity mix, technology capacity to produce plant components, location and availability of natural resources for the manufacturing of these components, and average transportation distance of components and resources. The origin of power consumed on-site (either from the grid or self-consumption) has given rise to two analytical scenarios.The ReCiPe Midpoint World (H) method was used for the characterization and normalization of environmental impacts in climate change, human toxicity, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and terrestrial acidification. The Cumulative Energy Demand (CED) and Energy Payback Time (EPBT) were used to evaluate the energy performance of the system.

The results showed significant differences depending on the electricity consumption scenario considered for the plant (self or grid). This is due to the fact that electricity from the grid has a much higher impact than that obtained from the HCPV plant. This effect was more marked in countries where their electricity mix is highly depending on fossil fuels (such as South Africa) and less notable in countries with a higher contribution of renewable energies (like Brazil). The HCPV plant located in Peru exhibited the best environmental and energy performance, both in the grid and the self-consumption scenarios. This was followed by South Africa when considering environmental impacts and Brazil when considering the CED indicator. Morocco showed the worst environmental performance, with impacts nearly doubling those calculated in Peru. The results suggest that the most important parameter in the environmental performance of the HCPV plant is the amount of electricity produced (related to solar resource), followed by the share of renewable energies in the national electricity mix. This latter item plays a significant role only when assuming that the grid consumption scenario. The effect of other items, like manufacturing location and transportation of plant components, is not significant.

Keywords: LCA, Cumulative Energy Demand, Energy Payback time, HCPV, photovoltaic.

1. Introduction

High Concentrated Photovoltaic (HCPV) is an emerging technology capable of producing electricity at high efficiency. HCPV systems use Fresnel lenses to concentrate direct solar radiation onto III-V multijunction cells (typically by a factor of around 1000) (Xie *et al*., 2011), which are constructed using superimposed layers of semiconducting materials that allow the absorbance of a broader range of wavelengths (Polman and Atwater, 2012). Commercial HCPV systems use two-axis tracking to optimize the use of the solar resource, which results in comparatively higher investment costs than conventional PV. However, this is compensated by superior generation capacities per unit area. Although the penetration of this technology is still limited, the commercial viability of HCPV systems has been proven in various sites of Morocco, China, US, Spain, Portugal and Italy (Law *et al*., 2010, Padovani *et al*., 2010).

The improved efficiency of HCPV has a strong influence not only on the economics of the technology but also on its environmental performance, as reported in various investigations based on Life Cycle Analysis (LCA) methodology (Fthenakis and Kim, 2013, Kammen *et al*., 2011, Nishimura *et al*., 2010, 2005). Carbon emissions reported in the literature range between 18 and 45 g CO2 eq/kWh, depending on several factors including scope and methodology of the LCA analysis, characteristics and scale of the plant, energy efficiency and solar radiation availability. Energy Pay Back Times (EPBT) were in all cases below two years (de Wild-Scholten *et al*., 2010, Fthenakis and Kim, 2013, Nishimura *et al*., 2010, Peharz and Dimroth, 2005).

An aspect not fully investigated in the literature involves the effect of geographical location on the environmental performance of commercial HCPV plants. This location has an influence not only on the availability of the solar resource, and therefore generation capacity of the plant, but also on impacts associated with the fabrication and transportation of components and utilization of natural resources. This paper investigates the environmental performance of a commercial 1 MWe HCPV plant based on six locations in Mexico, Brazil, Morocco, USA, Peru and South Africa. These countries benefit not only from optimum solar resource and land availability, but also from favourable national policies that promote the deployment of renewable energies (IEA, 2015). A detailed life cycle inventory has been gathered using information from a commercial HCPV plant. This inventory has been adapted to the specific conditions of the six geographic locations considered. The origin of power consumed on-site (either from the grid or self-consumption) has given rise to two analytical scenarios.

2. Methods, objectives and scope

2.1. Objectives and scope

The aim of this study is to evaluate the environmental and energy performance of a commercial HCPV power plant in six locations around the world. The life cycle of the plant consists of 5 life phases, including:

- Material extraction and manufacturing (E&M): This includes materials extraction and fabrication of plant components.The elements considered include HCPV modules, electronic components, cables, inverters and a control building.
- Transportation (Transp): shipping of the modules, from Spain to the plant location. Transportation of solar trackers and plant components manufactured locally.
- Construction (Const): use of machinery and energy for the construction of the plant.
- Operation and maintenance (O&M): vehicles for maintenance operations, water for cleaning, lubricating oil and electricity consumed for plant operation.
- Dismantling and disposal (D&D): Due to lack of data for dismantling operation, energy and machinery requirements in this stage have been assumed to be the same as in the construction phase. This phase also comprises management of plant components at the end of their lives.

2.2. Description of the HCPV plant and plant locations

The characteristics of the power plant are shared for all the locations and scenarios considered in this analysis. The nominal capacity of the plant is 1008 kWp and consists of 75 solar trackers with azimuth and elevation drivers. Each solar tracker contains 4 mega-modules, each one made up of 12 modules with a nominal power of 280 Wp. Each module contains 25 focal points totalling 90000 multi-junction III-V GaInP2/GaAs/Ge individual solar cells in the HCPV plant. Gross electricity generation has been calculated using PVSyst software, considering the availability of solar resource at each location and assuming 28 % conversion efficiency for the multi-junction III-V solar cells. The efficiency of the plant is reduced by 0.4 %/yr (0.6 % first year) during the lifetime of the plant (30 years) due to deterioration of components. The plant consumes 19.05 MWh/yr for operation and maintenance. Two different scenarios have been considered where this power is obtained from the grid or directly from the plant (self-consumption). In the latter case, net electricity generation has been calculated by subtracting total on-site consumption from gross generation.

Table 1 illustrates the solar resource in the locations considered in terms of Direct Normal Irradiation (DNI) and also the annual generation capacity of the plant in such conditions.

Table 1: Characteristics of the HCPV plant analysed in each location

Location		Morocco	USA	Peru	Brazil	Mexico	SA
		Casablanca (33.6°N 7.7°W)	Tucson (32.1°N 110.9°W)	Ashua (15.9°S 72.2°W)	San Joao do Piaui (8.4°S 42.2°W)	Zacatecas (22.8°N 102.6°W)	Upington (28.4°S 21.3°E)
Direct Normal Irradiation (kWh/m²)		1834	2571	2920	2164	2044	2950
Electricity produced* (MWh/yr)		1503	2151	2460	1821	1702	2486
Performance ratio (%)		81.3	83.0	83.6	83.5	82.6	83.6
Electricity injected into the grid	Electricity grid supply scenario (MWh/yr)	1378	1975	2326	1672	1562	2282
	Self-consumption scenario (MWh/yr)	1361	1955	2307	1653	1544	2263

*First year, without considering components deterioration losses

The electricity mix has been gathered and modelled for each location (IEA, 2015, Itten *et al*., 2014, US EIA, 2014). The technical inventory of the HCPV plant was supplied by BSQ Solar, a company dedicated to the manufacturing, distribution and promotion of this technology. EcoInvent v.3 was used to obtain generic environmental information about the following elements: processing of raw materials, manufacturing of plant components, construction activities, operation and maintenance of the HCPV plant, transport processes, and manufacturing of inverters and electronic components in control units. Due to lack of data, the following information was obtained and extrapolated from the scientific literature: the energy consumed in the manufacturing of the multi-junction solar cells was obtained from Fthenakis *et al*. (2013) and the water consumption for cleaning the modules (15 l/MWh) was obtained from Fthenakis *et al*. (2011).It has been assumed that all modules are manufactured in Spain, transported by ship to the port nearest to the HCPV plant, and by lorry from the port to the plant.

2.3. Methods

The LCA was conducted using standard ISO 14040-4 methodology. The functional unit to which all the impacts are referred to is the generation of 1 MWh of net electricity. The lifetime of the plant has been assumed to be 30 years, with 0.5 % yearly reduction in power output due to deterioration of components. Simapro 8.0.3 software was used for calculations. Recipe Midpoint World (H perspective) was used for aggregation of environmental impacts. The Cumulative Energy Demand (CED) method (Hischier *et al*., 2010) was applied to determine input data for EPBT calculations and Equation 1 was used to determine EPBT in each case.

$$EPBT = \frac{E_{E\&M} + E_{transp} + E_{const} + E_{D\&D}}{\left(\frac{E_{agen}}{n_g}\right) - E_{O\&M}} \qquad (1)$$

$E_{E\&M}$, E_{transp}, E_{const},, $E_{D\&D}$ = Primary energy demand during E&M, modules transportation, Construction and D&D phases (MJ). E_{agen} = Annual electricity generation (MJ/yr). $E_{O\&M}$ = Annual energy demand for O&M phase (MJ/yr). n_g = Grid efficiency (an average 0.3 value has been chosen in every case).

3. Results and discussion

Table 2 shows the characterized impacts of the HCPV plant in the six locations considered. The calculation has been conducted for in two scenarios: grid consumption and self-consumption of onsite electricity requirements. The environmental categories shown in the analysis (climate change, human toxicity, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and terrestrial acidification) have been selected considering their significance, according to previous publications.

Table 2: Characterized impacts of the HCPV plant in 6 geographic locations

Impact category	Morocco		Brazil		Mexico		Peru		S.Africa		USA	
	GC	SC	GC	SC	GC	SC	GC	SC	GC	SC	GC	SC
Climate change, kg CO_2 eq/MWh	40.0	29.6	27.0	24.2	34.4	26.1	20.3	17.9	27.0	17.9	27.4	20.6
Terrestrial acidification, g SO_2 eq/MWh	0.25	0.17	0.15	0.14	0.20	0.15	0.12	0.10	0.19	0.11	0.15	0.12
Freshwater eutrophication, kg P eq/MWh	0.020	0.018	0.015	0.014	0.017	0.016	0.011	0.011	0.017	0.011	0.015	0.012
Human toxicity, kg 1.4-DB eq/MWh	30.8	28.7	24.4	23.6	26.9	25.3	17.9	17.4	21.6	17.3	22.7	20.0
Freshwater ecotoxicity, kg 1.4-DB eq/MWh	0.84	0.79	0.67	0.65	0.73	0.70	0.49	0.48	0.57	0.48	0.63	0.55
Marine ecotoxicity, g 1.4-DB eq/MWh	0.84	0.79	0.67	0.65	0.73	0.69	0.49	0.48	0.57	0.48	0.61	0.55

*GC: Grid consumption. SC: Self-consumption.

In the self-consumption scenario, the environmental classification of the selected locations in order of impacts is: Peru = South Africa > USA > Brazil > Mexico > Morocco. This classification follows a direct correspondence with the availability of solar resources (higher DNI results in lower impacts). In the grid consumption scenario, the environmental classification is as follows: Peru > South Africa > Brazil > USA > Mexico > Morocco. In this scenario, Brazil has a better classification at the expense of USA location, even though USA's DNI is higher. The improved performance of the HCPV plant in Brazil derives from its lower emission electricity mix, whose share of renewable energies reaches the 74%. Despite the similar irradiation levels, the environmental impacts of the HCPV plant in Peru are significantly lower than in South Africa, which may be attributable primarily to the high contribution of hydropower in the electricity mix in the former and the high dependence of coal in the latter. The differences in terms of carbon footprint between Peru and South Africa, two locations with very similar irradiation levels, are significant (33 % higher in the latter). The results evidence that the environmental performance of the HCPV plant highly depends on the nature of the electricity mix in the country of location. This is due primarily to onsite consumption.

The climate change impact for Morocco (grid consumption scenario) is 40.0 kg CO_2 eq/MWh. This value almost doubles that of Peru (20.3 kg CO_2 eq/MWh) for this category. This range of variation is similar for the other studied impact categories: 113 % for terrestrial acidification; 72 % in freshwater eutrophication category and human toxicity, and 71 % in freshwater and marine ecotoxicity. The impacts of the HCPV plant in Morocco location in the self-consumption scenario are between 64%-65% higher with respect to the Peruvian results for every studied category. The impact variation in the self-consumption scenario is associated with the different solar resources in each location, while the variation in the grid-consumption scenario is strongly affected by the nature of the national electricity mix.

The CED and EPBT results are described in Table 3. The grid consumption shows higher energy intensity than the self consumption scenario in terms of CED. The classification of locations for grid consumption scenario, in order of energy demand per functional unit is as follows: Peru < Brazil < South Africa < USA < Mexico < Morocco. In the case of self-consumption, the order is as follows: Peru < South Africa < USA < Brazil < Mexico < Morocco. The differences in each scenario classification (mainly Brazil position) are derived from the electricity mix origin, which in Brazil has a high share of hydroelectric power. Since the CED calculations do not take into account the primary energy coming from the renewable resources, the primary energy demand for technologies using fossil fuels is considerably higher. Table 3 describes the CED results for O&M and E&M (including transport) phases. The results evidence that the life cycle phase most affected by the geographical location of the plant is O&M. This life cycle phase is also highly influenced by the power consumption scenario (self or grid). In contrast, other life cycle phases like E&M, Construction and D&D remain essentially unaffected by the location of the plant.

Table 3: Cumulative Energy Demand and EPBT of the HCPV plant during its 30 years lifetime in all the scenarios.

		Total CED per functional unit (MJ/MWh)	CED O&M (TJ)	CED E&M(TJ)	EPBT[2] (years)
Morocco	GC	444.8	5.947	24.47	0.772
	SC	315.3	0.2539	24.47	0.774
Brazil	GC	279.3	1.554	24.34	0.624
	SC	256.94	0.2539	24.34	0.630
Mexico	GC	413.3	6.847	24.56	0.687
	SC	279.9	0.2539	24.56	0.69
Peru	GC	230.2	3.092	24.44	0.466
	SC	191.1	0.2539	24.44	0.469
South Africa	GC	295.2	7.694	24.58	0.469
	SC	191.1	0.2539	24.58	0.469
USA	GC	337.9	7.457	24.61	0.544
	SC	221.7	0.2539	24.61	0.544

*GC: Grid consumption. SC: Self-consumption.[1] Transport of components included in this phase
[2] Including disposal benefits due to recycling and energy recovery

4. Conclusions

The environmental performance of HCPV technology is significantly affected by the geographic location of the plant and also by the origin of the electricity consumed onsite (self or grid consumption). In the grid consumption scenario, environmental impacts varied by up to 103 %, depending on the location. The climate change category doubled its value when comparing the Moroccan location (highest impact due to lower irradiation levels) with the Peruvian location (lowest impact due to higher irradiation and higher renewable share in the electricity mix). Assuming a self-consumption scenario, where the electricity for O&M activities is self-consumed from the power plant production, the impact increase between the most polluting location and the least is lower (approximately 65% higher). The results suggest that the availability of solar radiation, and therefore electricity production capacity, is the most important factor in the environmental and energy performance of the plant. The second most important factor is the share of renewable sources in the national electricity mix, especially in the grid consumption scenario. Therefore, the location with the best environmental performance (in Peru) is due to a favourable combination of higher electricity productivity (due to a higher DNI) and a low-emissions electricity mix.

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