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Broader Perspectives

SHORT COMMUNICATION: ACCELERATED PUBLICATION

Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status

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Life cycle assessments and external cost estimates of photovoltaics have been often based on old data that do not reflect the extensive technological progress made over the past decade. Our assessment uses current (2004–early 2005) manufacturing data, from twelve European and US photovoltaic companies, and establishes the Energy Payback Times (EPBT), Greenhouse Gas (GHG) emissions and external environmental costs of current commercial PV technologies. Estimates of external costs are about 70% lower than those in recent high-impact publications which were derived from the old data. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: photovoltaics; energy payback; external costs; greenhouse emissions; life cycle

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INTRODUCTION

It is well understood that production of energy by burning of fossil fuels generates a number of pollutants and carbon dioxide. What is less known is that any anthropogenic means of energy production, including solar, generate pollutants when their entire life cycle is accounted for. A life cycle starts from the mining and processing of materials that comprise solar cells, modules and balance of system, and ends to their final decommissioning, disposal and/or recycling. Costs associated with the environmental, health and societal impacts that are not included in the direct cost of electricity, are called external costs of electricity production. While societal external costs are difficult to quantify, external costs associated with environmental and health protection or damage have been quantified in monetary terms. Perhaps the most well-known effort to quantify environmental and health damages due to electricity production, is the European Union's series of ExternE (External Costs of Energy) projects. The ExternE methodology starts from emissions generated at specific sources and follows their impact to receptors through atmospheric dispersion and dose-response functions. In general, this type of environmental impact assessment is well accepted, although assumptions related to

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the monetary valuation of estimated impacts, especially green-house related impacts, are debateable. 'The ExternE methodology has been applied in a large number of European and national studies to give advice for environmental, energy and transport policies.'[1] Photovoltaic installations in Germany were presented in the latest ExternE report to the European Commission[1] as having 30% higher health impacts than natural gas and GHG emissions of 180 g CO_2-eq./kWh which would be 10 times higher than those for the nuclear fuel cycle (Figure 1). These results were based on 15-years old PV systems and even older data on module production technology.[‡] Also based on outdated PV technology data a life cycle-based comparison of energy technologies in Australia[2] showed that PV emits about 100 g CO_2/kWh during its life cycle (Figure 1). The results from these two studies were widely circulated and especially the ExternE publication with its official status is likely to have influenced policy decisions with regard to energy technology. More recent (i.e., 2000) data are included in the Ecoinvent data base[12] and these are expected to be used in future updates of the ExternE project. Our present paper updates all these estimates and shows the energy payback times of current (i.e., 2004–2005) PV systems, based on actual manufacturers data from several independent sources.

CRYSTALLINE SILICON PV MODULES ON ROOFTOP

Crystalline silicon modules constitute about 94% of the 1250 MW of PV system capacity installed in 2004. With the cooperation of 11 European and US photovoltaic companies, an extensive effort was made to collect Life Cycle Inventory data that represent the current status of production technology for crystalline silicon modules; this was part of the European Commission's CrystalClear project. The new data cover all processes from the producing of silicon feedstock to manufacturing cells and modules. For each step in the production process, going from silica mining up to PV system installation, all significant inputs of materials and energy were accounted for in the Life Cycle Inventory. Moreover, all commercial Si-wafer technologies are covered i.e., multi- and mono-crystalline wafers and ribbon technology. These data can be considered representative of the status of technology in 2004, at least for Europe and the US. The data set has been published in a separate paper[3] and is also publicly available on the web.[10]

With this information, we analyzed the environmental impacts of PV electricity generation,[4] and demonstrated that the life-cycle greenhouse gas emission of complete rooftop PV systems based on multicrystalline silicon and under average Southern-Europe insolation (1700 kWh/m^2/yr) is only 37 g $CO_{2\text{-eq}}$/kWh (Figure 2). For silicon ribbon and monocrystaline silicon technologies the respective numbers are 30 and 45 g/kWh (not shown in figure). The Energy Pay-Back Times (EPBT) of such systems are, respectively, 1·7, 2·2, and 2·7 years for ribbon, multi-, and mono-Si technology. Figure 3 shows the EPBT estimates for multi-Si PV modules and systems, in comparison with those for CdTe thin film PV modules and systems). Note that a Performance Ratio of 75% (accounting for the effects of shading, snow cover, heat loss and DC–AC conversion loss)[11] was assumed for the roof-top systems, a value which might be somewhat conservative.

Furthermore, we estimated external costs using the baseline damage factor method developed within the ExternE-Pol project (see Table 1). For Southern Europe average conditions (i.e., 1700 kWh/m^2/yr insolation), the health and environmental external cost would be 0·18 €c/kWh. For a system in South Germany with optimal latitude insolation (i.e., 1300 kWh/m^2/yr)[9] the external cost will be 0·23 €c/kWh.

BALANCE OF SYSTEM FOR GROUND INSTALLATIONS

A detailed study was done on the Balance of System (BOS) for the Tucson Electric Power (TEP) Springerville, Arizona, PV plant.[5] Actual 3-year performance data from the 3·5 MW crystalline silicon section of the plant were used, along with detailed mass and energy inventories. A Performance Ratio[11] of 83·5% was measured at the grid connection on the 480 V side of the isolation transformer; this performance efficiency accounts for all

‡It is noted that results from an ExternE follow-up project (ExternE-Pol),[8] show lower external costs for PV technology, but these results are still based on incomplete and partly outdated technology data.

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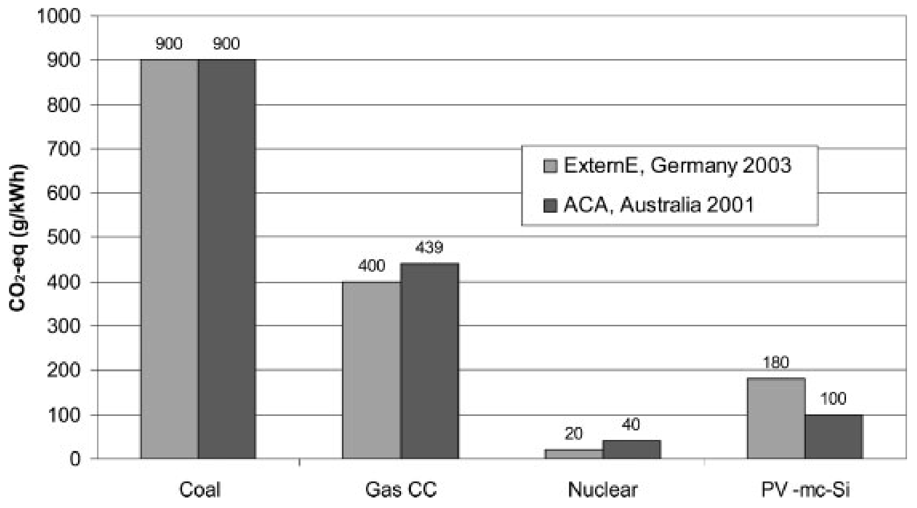

Figure 1. GHG emissions from life cycle energy of electricity production; -ExternE & Australian Coal Association research programs[1,2]

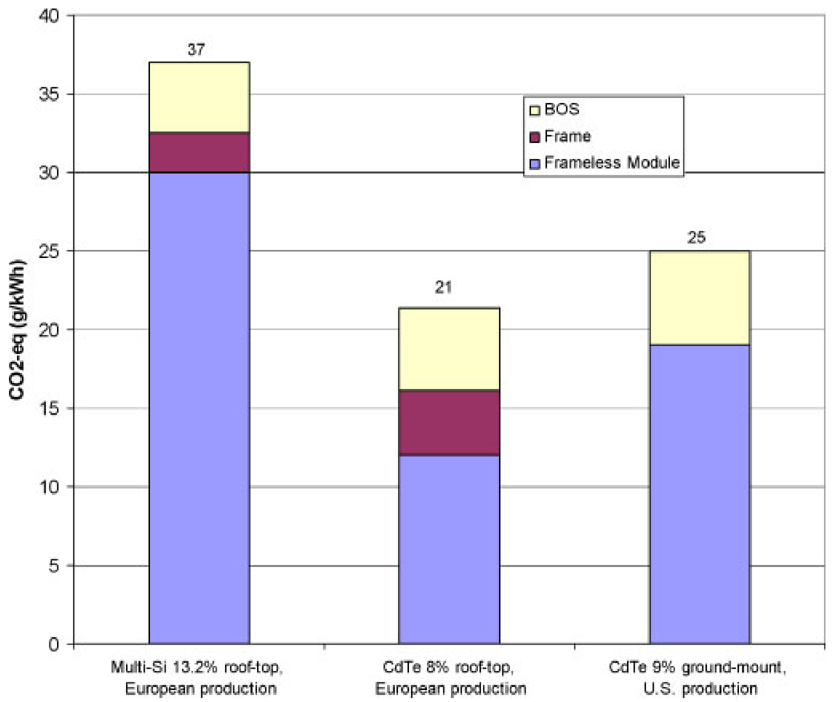

Figure 2. Updated GHG emissions from the life cycle photovoltaic electricity production for average southern European insolation (1700 kWh/m^2/yr), 30 years lifetime, 75% performance ratio for roof-top installations, 80% performance ratio for utility ground-mount installations.[4–7] The place of production is indicated because CO_2 emissions of the average US electricity supply are higher than those of the average European supply, resulting in relatively higher CO_2 emissions for US produced modules

the losses of the PV module-wiring-inverter-transformer system. TEP instituted an innovative PV installation program guided by optimizing the design and minimizing cost. The resulting advanced PV structure incorporated the weight of the PV modules as an element of support design, thereby eliminating the need for concrete foundations. The estimate of the life-cycle energy requirements embodied in the BOS is 542 MJ/m^2, a 71%

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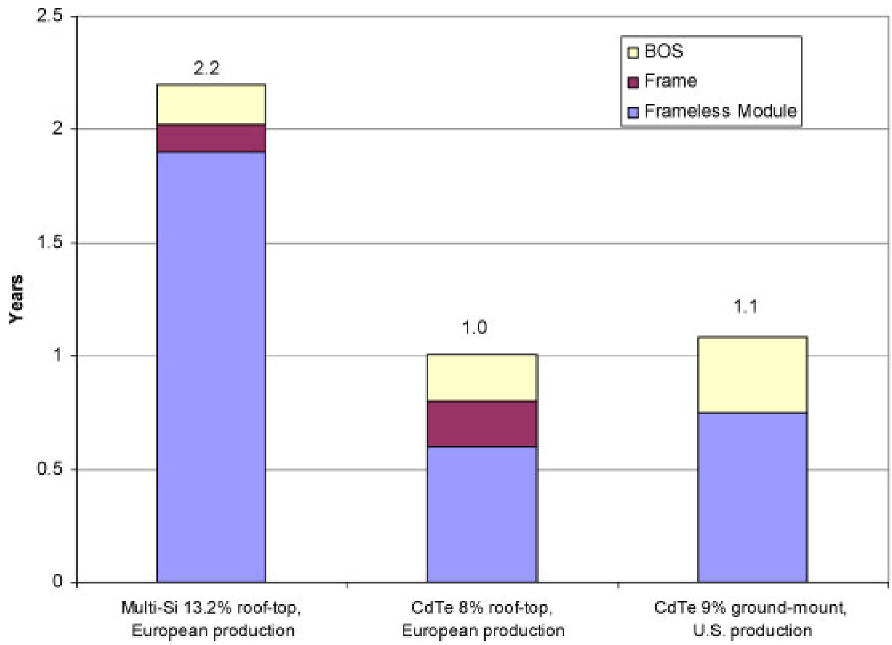

Figure 3. PV energy payback times of 2004 PV technologies for average southern Europe insolation (1700 kWh/m^2/yr), 75% performance ratio for roof-top installations, 80% performance ratio for utility ground-mount installations[4–7]

Table I. Evaluation of external costs of photovoltaics in southern-Europe, based on the damage factor approach

		Multi-Si roof-top PV system		CdTe utility PV system		
				Emission factors		
	Damage factor (€-/ton)	Emission factor Modules + BOS (kg/kWh)	External cost (€c/kWh)	modules* (kg/kWh)	BOS* (kg/kWh)	External cost* (€c/kWh)
CO2-eq	19	3·64E-02	6·93E-02	1·94E-02	7·49E-03	5·10E-02
As	80 000	3·27E-08	2·62E-04	1·46E-09	9·94E-09	9·12E-05
Cd	39 000	1·12E-08	4·35E-05	1·40E-09	2·55E-09	1·54E-05
Cr	31 500	4·39E-08	1·39E-04	3·55E-09	4·00E-08	1·37E-04
Cr-IV	240 000	1·08E-09	2·58E-05	5·98E-11	9·40E-10	2·40E-05
Cr-other	0	0·00E + 00	0·00E + 00	0·00E + 00	0·00E + 00	0·00E + 00
Formaldehyde	120	4·61E-08	5·55E-07	1·29E-08	1·03E-07	1·39E-06
Ni	3800	7·38E-08	2·80E-05	4·18E-09	1·91E-08	8·83E-06
Nitrates, primary	5862	1·10E-10	6·43E-08	9·86E-11	3·78E-10	2·80E-07
NMVOC	1124	1·49E-05	1·68E-03	1·94E-05	1·22E-05	3·55E-03
NOx	2908	7·16E-08	2·09E-05	1·46E-12	4·72E-05	1·37E-02
Pb	1 600 000	3·32E-07	5·32E-02	7·56E-08	6·08E-08	2·18E-02
PM10	11 723	0·00E + 00	0·00E + 00	7·06E-11	3·74E-08	4·39E-05
PM2·5	19 539	1·02E-05	2·00E-02	3·16E-06	5·08E-08	6·27E-03
PM2·5–10	0	9·07E-06	0·00E + 00	1·16E-06	1·19E-05	0·00E + 00
SO2	2939	1·08E-04	3·18E-02	1·03E-05	8·96E-05	2·94E-02
Sulfates, primary	11 723	2·87E-07	3·37E-04	2·67E-07	8·24E-08	4·10E-04
Radionuclide emissions	5000	1·05E-11	5·26E-09	2·80E-10	0·00E + 00	1·40E-07
Total			**0·177**			**0·126**

Note: The damage factor (in €/ton) gives an economic valuation of the total health and environmental damages caused by a certain emission. Multiplication of the damage factor with the corresponding life-cycle emission factor for modules and BOS (in kg/kWh) results in the external costs (in €-cents/kWh) of that specific emission. The total external costs of PV electricity of 0·177 respectively 0·126 €c/kWh for multi-Si and CdTe module technology can be compared with external costs evaluated for other energy technologies [8]. Damage factors are based on [8]; emission factors are from [4] and [7]).
*Emissions related to utility CdTe PV correspond to the US average electricity mix and are expected to be lower in average European conditions.

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reduction from those of an older central plant; the corresponding life-cycle greenhouse gas emissions are 29 kg CO_2-eq./m^2. Using the system performance data from field measurements, the energy payback time (EPT) of the BOS is 0·21 years at the actual location of this plant, and 0.33 years for average southern Europe insolation conditions (1700 kWh/m^2-yr). The calculated CO_2-eq. emissions during the life cycle of the BOS are 6 g/kWh for 1700 kWh/m^2-yr solar inputs and 8 g/kWh for South Germany (1300 kWh/m^2-yr insolation[9]). Note that these emissions correspond to the US average electricity mix and are expected to be lower in average European production conditions.

CADMIUM TELLURIDE PV GROUND INSTALLATIONS

A detailed analysis of the CdTe PV lifecycle was conducted based on materials and energy data from FirstSolar's 25 MW_p/yr module production facility in Perrysburg, Ohio.[7] The energy payback time of a CdTe PV module is 0·8 years, and the total life cycle GHG emissions are 19 g CO_2-eq./kWh, based on the current module efficiency of 9%, a Performance Ratio of 80%, Southern Europe insolation conditions (1700 kWh/m^2/yr), and a system lifetime of 30 years. These estimates are higher than the estimates presented by Raugei *et al.* which were based on Antec Solar's CdTe PV module production data in Germany, the later result in an EPBT of 0·6 years and a GHG emission of 12 g CO_2-eq./kWh (see Figures 2 and 3). The EPBT and GHG indicators for modules from the Perrysburg plant are expected to improve further upon optimization of the CdTe vapour transport deposition equipment. However, CO_2 emissions of the average US electricity supply are higher than those of the average European supply, resulting in higher CO_2 emissions for US produced modules.

In combination with the BOS for the Springerville, TEP, ground-mount installation, the energy payback time and GHG emissions for the CdTe PV fuel cycle would be 1 to 1·25 years and 19 to 25 g CO_2-eq./kWh, respectively, for average European (1700 kWh/m^2/yr), conditions. The low estimate corresponds to the data from the production line in Germany and the high corresponds to the US production data. The external costs of the whole system are about 0·13 €c/kWh, based on ExternE-Pol[8] base case damage factors (Table 1). For South Germany (1300 kWh/m^2-yr insolation)[9] the calculated CO_2 emissions during the life cycle of the whole system are 23 to 32 g/kWh, for the German and the US production data correspondingly.

CONCLUSION

An update is given on energy pay-back times, greenhouse gas emissions and external costs of PV technology, based on up-to-date data from real production processes. For average South European solar irradiation (1700 kWh/m^2-yr) the energy pay-back time for complete installed PV systems range from 1 years to 2·7 years depending on the module technology. The corresponding GHG emissions range from 21 g CO_2-eq./kWh to 45 g CO_2-eq./kWh for South Europe and 27–59 g CO_2-eq./kWh for Southern Germany conditions (1300 kWh/m^2-yr). These emissions are 60 to 85% lower than the GHG emission estimates shown in the latest ExternE report to the European Commission.[1] Based on the ExternE damage factors, the external costs of PV associated with health and environmental impacts during their life-cycle are about 0·15 €c/kWh.

More progress is expected in the energy and emission factors of photovoltaic systems as production lines are optimized and scaled up; thus, new prospective life cycle analyses would be necessary.

While these estimates can be used for comparing the externalities of PV with those of conventional energy technologies (e.g., fossil and nuclear fuels), one should note that the externalities associated with fuels' depletion (fossil and nuclear), severe accident consequences, risks from nuclear waste storage, nuclear proliferation, and security protection and risks, are not fully captured in the described monetarization.

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