

## Life Cycle Analysis of Photovoltaic Systems

Vasilis M. Fthenakis and Hyung-Chul Kim

PV EH&S Research Center

Brookhaven National Laboratory, NY, USA (vmf@bnl.gov);

### ABSTRACT

Life Cycle Analyses (LCA) at BNL show that: i) The BOS of an optimized installation has an energy payback time (EPBT) of only 0.4 years for average US insolation, which is 70% lower than previously reported estimates. ii) The EPBT of CdTe modules produced and used in the U.S. is 0.85 years. iii) The life-cycle CO<sub>2</sub> emissions of the nuclear fuel cycle in the U.S. are about the same as those in the PV cycle; this contrasts European studies showing CO<sub>2</sub> emissions from nuclear to be 10 lower than those from PV.

#### 1. Introduction/Objectives

Life Cycle Assessment (LCA) describes the possible lifespan environmental impacts of material and energy inputs and outputs of a product or process. Publications written to inform energy decision-makers in the European Community<sup>1</sup> and in Australia<sup>2</sup> showed photovoltaics to have relatively high life-cycle environmental impacts. These impacts result from fossil-fuel-based energy in the production of materials for solar cells and modules; however, the data used in these studies were outdated. Risk-based comparisons of PV with other technologies are also outdated and of limited scope.<sup>3</sup> The objective of our research is to accurately describe the environmental profile of PV for the concerned public and stakeholders. This is one of several PV-EH&S tasks designed to assist the public support and economic viability of current PV systems.

#### 2. LCA of PV BOS

We conducted a life-cycle analysis of the balance of system (BOS) components of the 3.5 MW<sub>p</sub> multi-crystalline PV installation at Tucson Electric Power's (TEP) Springerville, AZ, field PV plant.<sup>4</sup> TEP had accomplished a significant design optimization and cost minimization, and provided detailed records on materials, energy and personnel used in the construction and operation of the plant. Fig. 1 shows the results of our LCA for the various pieces of the BOS. The total primary energy in the BOS life cycle is 542 MJ/m<sup>2</sup> of installed PV modules. This finding contrasts sharply with the previous central PV plant BOS estimates (i.e., 1850 MJ/m<sup>2</sup>), corresponding to a PV plant in Serre, Italy. Using the average U.S. energy conversion efficiency of 33%, we obtained an

electricity equivalent of 50 kWh/m<sup>2</sup> that, after annualizing the administrative and disposal contributions, results in an EPBT of 0.21 years

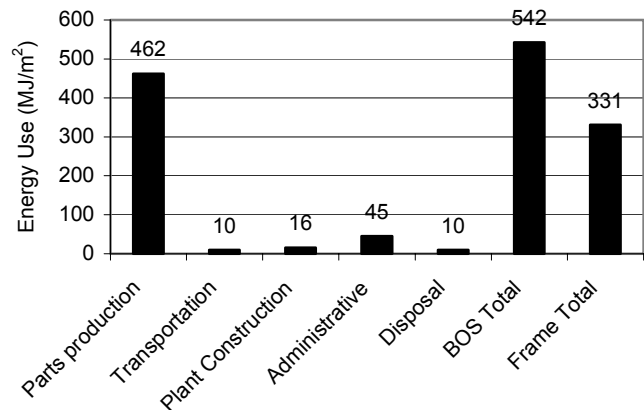


Fig. 1. Life Cycle Energy Consumption of BOS

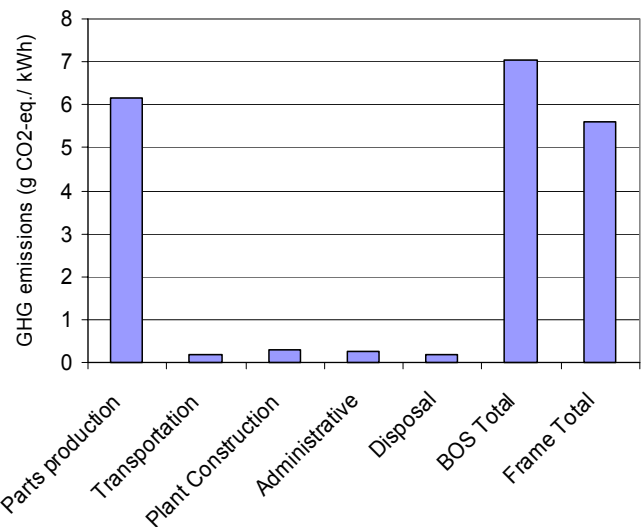


Fig. 2. Life-Cycle GHG Emissions of BOS

The Springerville site combines high insolation (e.g., ~2100 kWh/m<sup>2</sup>/yr) with relatively low ambient temperatures which increases the system's efficiency. The estimated EPBT of the BOS for average (1800 kWh/m<sup>2</sup>/yr), U.S. insolation is 0.37 years and the estimated CO<sub>2</sub> emissions are 7 g/kWh.<sup>4</sup> (Fig. 2)

### 3. LCA of CdTe PV Modules

We conducted the first phase of a LCA of the CdTe solar modules manufactured by First Solar, Perrysburg, Ohio. The life cycle stages of module materials production, module manufacturing, and transportation were considered. Further investigation is required for the LCA of CdTe recycling stage and to evaluate a new vapor transport deposition (VTD) system. Emissions and energy data associated with materials processing and manufacturing were obtained from the module manufacturer, material suppliers, and the USLCI and Ecoinvent databases. The LCA tool 'Simapro' was used for compiling life cycle inventories, calculating aggregated materials usages, and determining life cycle impact metrics. The results, based on U.S. average solar irradiation are: Life Cycle Energy: 1200 MJ/m<sup>2</sup> (Fig. 3);

EPBT: 0.85 yrs; GHG emissions: 18 g CO<sub>2-eq</sub> /kWh

Thus the total GHG emissions of CdTe PV modules coupled with the Springerville BOS design is only 25 g CO<sub>2-eq</sub> /kWh, for average US insolation, in contrast to the 180 g cited in the ExternE study for Germany<sup>1</sup> and the 100 g cited for Australia<sup>2</sup>.

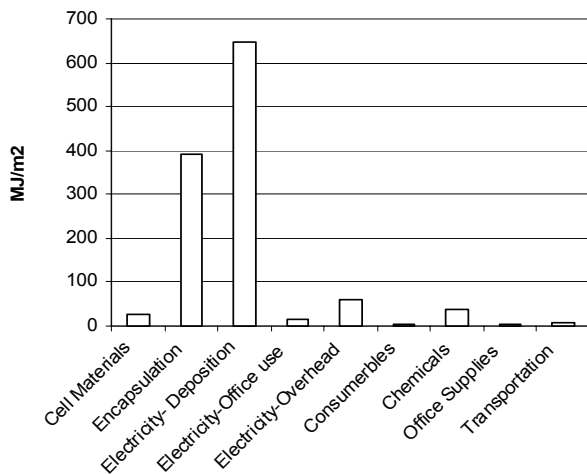


Fig. 3. Energy distribution across the life cycle stages of CdTe PV modules

### 4. LCA-Based Comparisons of PV and Nuclear Fuel Cycles

The well-publicized ExternE studies presented nuclear as having life-cycle carbon dioxide emissions 10 times lower than those of PV. Other more recent studies showed considerable variability due to the complexities of the nuclear fuel cycle. For well-balanced comparisons with PV, we conducted a critical review of LCA studies of GHG emissions in the nuclear fuel cycle. Often system boundaries were inconsistent and GHG emissions associated with disposal of nuclear waste were neglected or underestimated. We conducted an original analysis of GHG emissions associated with permanent nuclear waste storage in the Yucca Mountain repository. We estimated the total GHG emissions for a 1000 MW PWR plant in the US to be about 27 g/ CO<sub>2-eq</sub> /kWh.

Our results together with estimates from other sources are shown in Fig. 4.

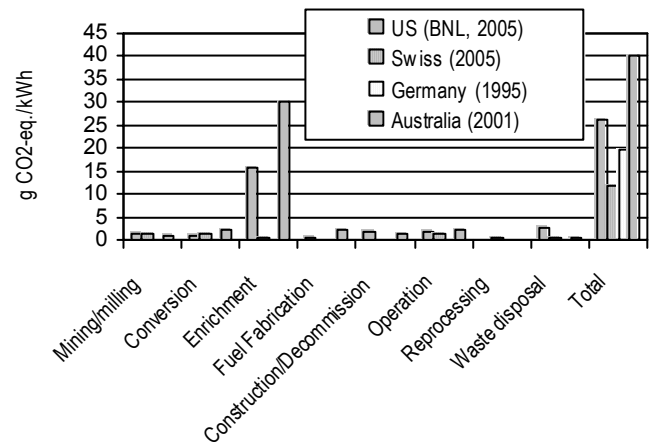


Fig. 4. GHG emissions in the nuclear fuel cycle

### 5. Discussion

The potential environmental impacts of energy technologies are being closely scrutinized as concerns for the environment increase and different technologies compete for the marketplace and for R&D funding. It is widely accepted that the total costs of electricity generation are their direct costs plus the external (environmental and societal) costs during all the stages of the system and the fuel cycles. Publications with high political impact present unbalanced and incomplete comparisons of nuclear energy against photovoltaics. We challenged such comparisons, engaged the concerned parties, and initiated efforts to correct and complete them. Our LCAs show that the nuclear cycle does not have any advantage over solar electricity based on GHG emissions in the life-cycle of current technologies. Comprehensive peer-reviewed studies covering the uncertainty of our estimates and risk-based assessments are under way. These studies will benefit PV industry in accurate projecting the environmental benefits of photovoltaics.

### REFERENCES

- European Commission, Directorate-General for Research (2003): "External costs"; Office for Official Publications of the EC, Luxembourg, EUR 20198.
- Australian Coal Industry Association, ACARP, "Coal in a Sustainable Society", 2004.
- Fthenakis V. and C. Kim, A Review of Life Cycle Risks in the Solar Electric Cycle, Submitted to the International Conference on Safety and Security of Energy Infrastructures, Brussels, Nov. 2005.
- Mason J., Fthenakis V.M., Hansen T. and Kim C. Energy Pay-Back and Life Cycle CO<sub>2</sub> Emissions of the BOS in an Optimized 3.5 MW PV Installation, Progress in Photovoltaics, in press.

