IEEE 4th World Conference on Photovoltaic Conversion, Hawaii, May 8-12, 2006

QUANTIFYING THE LIFE-CYCLE ENVIRONMENTAL PROFILE OF PHOTOVOLTAICS AND COMPARISONS WITH OTHER ELECTRICITY-GENERATING TECHNOLOGIES

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ABSTRACT

The various detrimental environmental and health effects of conventional electricity generation have long been recognized. Renewable technologies offer the opportunity for reducing such impacts, but, during their entire life cycle, their use is not without effects. Indeed, some major European and Australian studies portrayed photovoltaic systems as causing significant life-cycle environmental and health impacts, due to the fossil energy used in the production of cell and module materials. However, the most recent studies on the life-cycle impacts of c-Si and thin film photovoltaics show that they are drastically lower than the ones earlier reported. Such improvements reflect the more effective use of material, thinner layers, improvements in the balance-of-systems components and installation, frameless modules, and higher conversion efficiencies. This paper summarizes a comparison of the greenhouse gas emissions (GHG) from the life-cycle of PV, nuclear, fossil and biomass electricity generation in the U.S.

INTRODUCTION

Current generations of photovoltaics are more expensive than conventional forms of energy. Then, why people are buying them? The major reason is that subsidies from governments and utilities reduce their price to acceptable levels; nevertheless in most cases there still is a cost differential or up-front investment that the consumer is willing to absorb or bear. The fundamental reason why governments and the people they represent support photovoltaics and other renewable clean technologies is their environmental advantages over fossil-fuel technologies. Accurately representing these advantages is paramount to ensure the continuation of this support.

Life Cycle Assessment (LCA) is a framework for describing the possible lifespan environmental impacts of material/energy inputs and outputs of a product or process [1]. LCA is used in evaluating the environmental impacts of energy technologies, and its results are increasingly used in decisions about R&D funding and energy policies. Publications written to inform energy decision-makers in the European Community [2] and in Australia [3] portrayed photovoltaics as having much higher environmental impacts than the nuclear fuel cycle. Although solar electric is peak power and nuclear is a base-load one, the potential use of nuclear and solar technologies for electrolytic generation of hydrogen fuel puts them on the same frame, and makes a comparative evaluation pertinent. Life-cycle environmental impacts result from the fossil-fuel-based energy currently used in the production of materials for solar cells, modules and systems. One issue with these comparisons is that the photovoltaic systems were assessed based on old data. Another issue is that these comparisons are based entirely on material- and energy-flows; they ignore the external costs and risks related to water and land use, fuel depletion, energy security, and accidents in fuel mining, transportation, use and disposal.

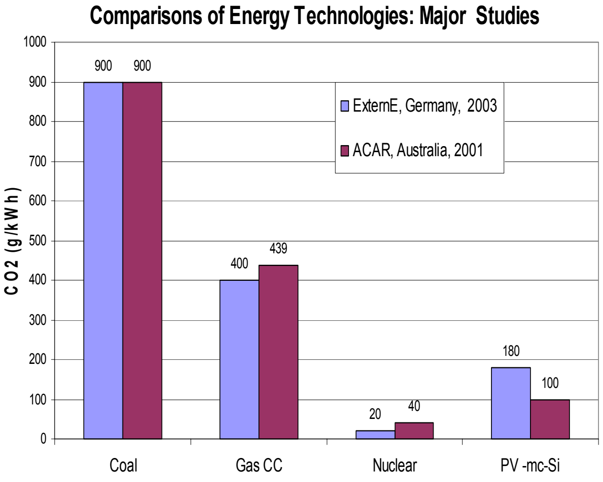

Figure 1. Current but Outdated High-Impact Studies

GHG EMISSIONS DURING THE LIFE CYCLE OF PHOTOVOLTAICS

Recent LCA studies on PV modules present up-to-date figures of the GHG emissions during the entire life cycle of bulk and thin-film PVs. The framework used for the PV LCA studies is typically process-based that includes the stages of materials production, module production, transportation, module installation, operation and end-of-life management. Material and energy inputs to the cell and module production are gathered from PV industries to the extent possible, and PV electricity generation efficiencies are obtained from actual field data.

Crystalline Silicon PV Modules on Rooftop Applications

This module type contributes to about 90% of the 1200 MW of PV system capacity installed in 2004. New data were collected from 11 European and US photovoltaic companies, representative of the current status of production technology for crystalline silicon modules. These data cover all commercial wafer technologies (e.g., multi- and mono-crystalline wafers and ribbon technology). From them, an analysis was made of the environmental impacts of PV electricity generation [4]. The results show life-cycle greenhouse gas emissions of only 35g/kWh from a rooftop PV system based on multicrystalline silicon and located in Southern-Europe (i.e., under 1700 kWh/m^2-yr insolation conditions). For silicon ribbon and monocrystalline silicon technology, the respective numbers are 30 and 43 g/kWh. The energy payback times (EPBTs) of such systems are, respectively, 1.6, 2.1, and 2.5 years for ribbon-, multi-, and mono-Si technology.

For fast evolving technologies like PV, a prospective LCA is also of interest. Alsema and de Wild see trends towards 40-50% lower GHG emissions in the crystalline-Si PV cycle within the next 5 years [5] based on the reduction in the wafer's thickness, and the increase in electric-conversion efficiency underway within the Crystal Clear project. Corresponding to these targets, GHG emissions with the current Western European average electricity mixture (UTCE) will be 19 g CO_2-eq./kWh for c-Si PV (higher in the U.S. electricity mix). Another potential for significant future decrease of GHG emissions include the new fluidized bed reactor (FBR) for producing solar-grade Si which may cut electricity consumption in Si-purification by up to 90%. On the other hand, about half of c-Si PV manufacturing facilities employ CF_4, a potent GHG, for dry etching of Si wafers. We determined that the current use of this gas is 30 kg CO_2-eq./ m^2 of manufactured solar cells. If unabated, this usage could add up to 6 g CO_2-eq./kWh to the GHG emissions of the c-Si PV lifecycle; however, commercial point-of-use abatement systems with higher than 90% destruction efficiencies are available.

Balance of System for Utility Plant (on-ground installation)

A detailed study was made of the Balance of System (BOS) for the Tucson Electric Power (TEP) Springerville, Arizona, PV plant [6]. Three-year performance data and detailed mass and energy inventories were used. The TEP instituted an innovative installation program guided by optimum design and cost minimization, wherein the resulting advanced PV structure incorporated the weight of the PV modules as an element of support, thereby eliminating the need for concrete foundations. The estimated the life-cycle energy requirements embodied in the BOS was 542 MJ/m^2, a 71% reduction from those of an older central plant; the corresponding life-cycle greenhouse gas emissions were 29 kg $CO_{2\text{-eq.}}$ /m^2. From field measurements, the energy payback time of the BOS is 0.21 years at the actual location of this plant, and 0.4 years for average Southern Europe insolation (1700 kWh/m2-yr). The calculated CO_2 emissions during the life cycle of the BOS are 6 g/kWh for 1700 kWh/m2-yr solar inputs.

CdTe PV Modules and On-ground Utility Installations

Fthenakis and Kim [7] presented a detailed analysis of the CdTe PV lifecycle based on materials and energy data from a commercial 25- MW$_p$ plant in Perrysburg, Ohio, producing. Its energy payback time was 0.8 years and the life-cycle GHG emissions factor was 19 g CO_2-eq./kWh based on the current rated electric conversion efficiency of 9%, Southern Europe insolation conditions, a 30-year lifetime, and a system efficiency of 80%. Combined with the BOS for a central (utility) up-to-date system, the energy payback time and GHG emissions for the CdTe PV fuel cycle under study would be 1.25 years and 25 g CO_2-eq./kWh, respectively, for the U.S. electrical

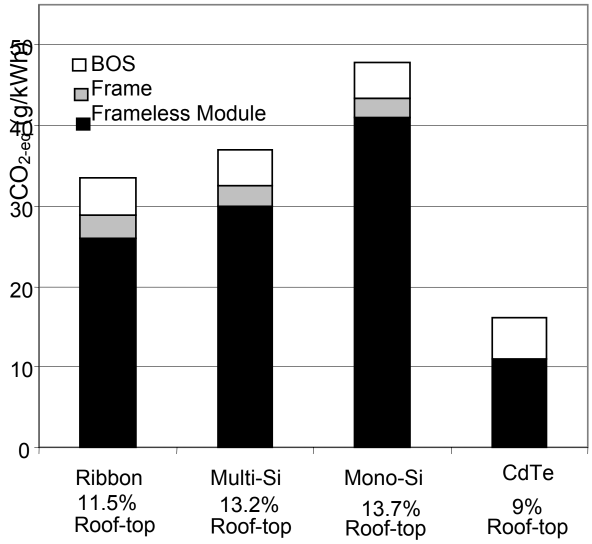

Figure 2. Current Status of GHG Emissions from c-Si and CdTe PV systems [8]

The current status of GHG emissions in the life cycle of c-Si and CdTe PV systems is shown in Fig. 2. More progress is expected in reducing the energy and corresponding emissions of photovoltaic systems as production lines are optimized and scaled up. The U.S. manufacturer of CdTe PV projects a linear increase in electrical-conversion efficiency of their module from the current 9% to 12% by 2010; today's laboratory record is 16.5%. Also, tested optimization of the deposition processes in CdTe lines is expected to reduce electricity requirements by about 25% within a couple of years; the corresponding emissions of this cycle will be 11 g CO_2-eq./kWh by 2010 in the current average U.S. electricity supply.

GHG EMISSIONS DURING THE NUCLEAR FUEL CYCLE

Widely varying estimates of life cycle greenhouse gas emissions were presented in recent LCA studies, ranging from 3.5 to 70 g CO_2-eq./kWh. The biggest differences occur during enrichment, NPP construction, and operation (Figure 3). These large differences in GHG emissions during enrichment reflect its type (diffusion vs. centrifuge), as well as country-specific background electricity mixtures. The energy requirement for gaseous centrifuge enrichment ranges from 40-100 kWh per Separative Work Unit (SWU), whereas gaseous diffusion requires 2400-3000 kWh per SWU [9,10]. The U.S., Australian, Japanese, and the 2nd of the Swiss cases in Figure 3 include diffusion-enriched uranium fuel [9,11,12]. Upstream electric energy sources also affect the GHG emissions during enrichment. The best possible case is that of Vattenfall, of a Swedish utility combining 94% fossil-fuel-free electricity and 80% of centrifugal enrichment [13]. The worst published cases correspond to the United States where mainly diffusion is used for enrichment and a hypothetical Australian case [9,3]. The dramatic difference in the GHG estimates during the construction and operation stages stem from employing different methodologies. Hondo's estimates of 2.8 g CO_2-eq./kWh for construction is based on process data and of 3.2 g CO_2-eq./kWh for operation, is partially based on EIO analysis [11], whereas Dones' corresponding estimates of 0.7 and 0.5 g CO_2-eq./kWh, and Vattenfall's estimates of 0.3 and 0.25 g CO_2-eq./kWh result from process-based analyses [12,13].

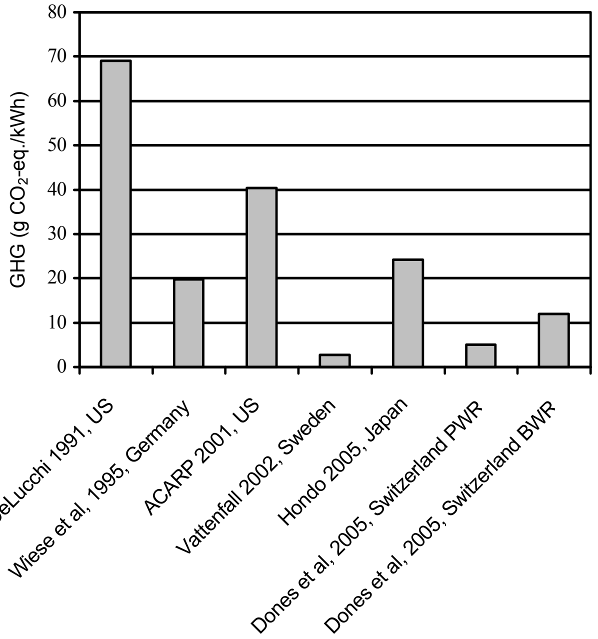

Figure 3. Estimates of GHG emission in the nuclear fuel cycle from main studies

GHG EMISSIONS IN THE FOSSIL AND BIOMASS LIFE CYCLES

A recent study by Kim and Dale examines the life cycle GHG emission profiles from US fossil fuel cycles based on the year 2000 data [14]. The included stages encompass extraction of raw materials (crude oil, natural gas, and coal), petroleum refining, transportation of petroleum oil, natural gas, and coal to power plants, and operation of power plants. The majority (78–96%) of the greenhouse gases are generated during operation from burning fossil fuels at the power plant. The GHG emissions estimate for the US coal cycle is higher than the European coal cycle reported by the ExternE study, probably due to the difference in coal type and system boundary selection.

Biomass is also envisioned as an important renewable energy sources for the future. Heller et al. conducted an LCA for willow biomass energy cycle based on demonstration-scale field data in New York [15]. GHG and toxic pollutant emissions were investigated from electricity generation of co-firing with coal, biomass gasification, and direct firing. Their study concluded that the local pollution and GHG emissions prevented by willow biomass cycle-growing, harvesting, and energy extracting are comparable to those of the solar electric life cycle. However, the latest data on photovoltaic material and energy inventories show PV to have environmental advantages over biomass based electricity generation. Comparisons of different fuel cycles in the U.S. are shown in Figure 4.

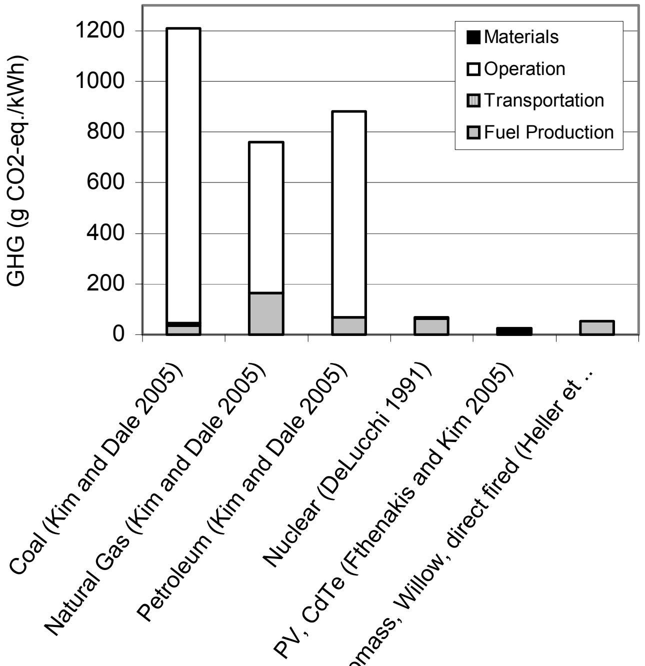

Figure 4. GHG Emissions in the US Electricity Generation Technologies

CONCLUSION

An evaluation of alternative energy technologies for their potential to decrease GHG emissions requires careful analyses of all the stages in the life of the fuels and devices. Quantifying such emissions in both present-day and prospective contexts is paramount for comparing the environmental profiles of different electricity-generation options. GHG emissions in the lifecycles of solar electric- and nuclear-fuel- technologies vary, depending on the efficiencies of upstream energy, local conditions, and other assumptions. Previous studies showing nuclear technology to have a clear GHG advantage over PV are greatly outdated; the emissions from the life-cycles of the two cycles are comparable under today's average U.S. conditions. Also GHG emissions during the life-cycle of PV are lower than those from a biomass direct-firing cycle and an order of magnitude lower than those from coal, petroleum and natural gas burning. Established trends in the PV cycles of current PV technologies are expected to keep further reducing emissions in the solar-electric cycle.

ACKNOWLEDGMENT

This work was funded by the Solar Technologies Program, Conservation and Renewable Energy, United States Department of Energy under contract DE-AEC02-76CH000016.

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