PV ENERGY ROI
Tracks Efficiency Gains

SOUTHERN ENERGY MANAGEMENT

Energy payback time (EPBT) is the time it takes for a photovoltaic (PV) system to produce all the energy used throughout its life cycle. A short EPBT corresponds to a high energy return on energy investment (EROI); these two indicators are metrics of sustainability often used in comparative evaluations of different power-generation technologies. Early assessments in the 1970s and '80s showed high EPBT (low EROI) values for prototype systems utilizing large amounts of steel and aluminum and thick silicon wafers produced in small, inefficient production lines. Now, current commercial PV technologies "pay back" the energy used in only six months to two years (depending on the location/solar irradiation and the technology). With their expected life times of 30 years, their EROIs range from 15:1 to 60:1, signifying that they return 15 to 60 times more energy than that used during their fabrication and lifetime.

Accounting for All Energy Inputs, Outputs

Photovoltaics need no fuel to produce electricity, but energy is needed for generating their materials, cells, modules and systems. As in all types of products and systems, a complete evaluation of their environmental profile must be done under the framework of a life-cycle analysis [1]. The life cycle of photovoltaics starts from the extraction of raw materials ("cradle") and ends with the disposal ("grave") or the recycling and recovery ("cradle") of the PV's components (figure 1, facing page). The mining of the raw materials — for example, quartz sand for silicon PVs; copper, zinc and aluminum ores for mounting

The EROI of conventional thermal generation from fossil fuels has been viewed as much higher than those of photovoltaics; this recently was shown to be a misconception. Here, the 1.5-megawatt Sandy Cross Solar Farm was under construction this spring to serve Elm City, N.C.

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Think photovoltaic systems return less on the energy investment than fossil fuel generation over their lifetimes? Not anymore.

By **VASILIS FTHENAKIS**

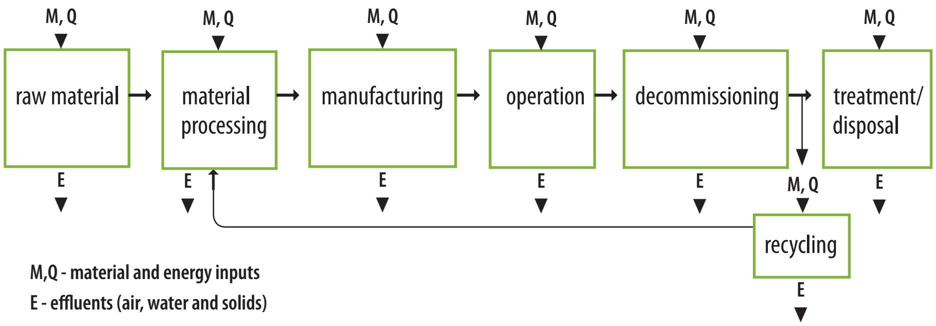

Figure 1. Flow of the life-cycle stages, energy, materials and effluents for PV systems

Vasilis Fthenakis is a tenured senior chemical engineer and director of the Photovoltaics Environmental Research Center at Brookhaven National Laboratory, and, in a joint appointment with Columbia University, is a professor of Earth and environmental engineering and the founder and director of the Center for Life Cycle Analysis. He is the author of 300 publications, member of the editorial boards of *Progress in Photovoltaics and the Journal of Loss Prevention*. He also a Fellow of the American Institute of Chemical Engineers, a Fellow of the International Energy Foundation and member of several panels of energy and sustainability experts. He can be reached at vmf@bnl.gov.

structures and thin-film semiconductors — is followed by the multiple stages of separation and purification. The silica in the quartz sand is reduced in an arc furnace to metallurgical-grade silicon that must be purified further into solar-grade silicon (i.e., 99.999 percent purity). That requires significant amounts of energy. Metallurgical-grade cadmium, tellurium, indium, gallium and selenium for cadmium telluride (CdTe) and copper indium gallium (di)selenide PV primarily are obtained as byproducts of zinc, copper and lead-smelting, and then further purified to solar grades.

The raw materials include those for encapsulations and balance-of-system components — for example, silica for glass, copper ore for cables, and iron and zinc ores for mounting structures. The production of all these materials requires large amounts of energy, as does the manufacture of the solar cells, modules, electronics and structures, their installation and operation, and eventually their dismantling and recycling [2] or disposal.

Thus, the EPBT is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of primary-energy equivalent) that was used to produce the system itself.

Energy Payback Time =

$$(E_{mat}+E_{manuf}+E_{trans}+E_{inst}+E_{EOL}) / (E_{agen} - E_{aoper}),$$

where —

E_{mat} = Primary energy demand to produce materials comprising the PV system

E_{manuf} = Primary energy demand to manufacture the PV system

E_{trans} = Primary energy demand to transport materials used during the life cycle

E_{inst} = Primary energy demand to install the system

E_{EOL} = Primary energy demand for end-of-life management

E_{agen} = Annual electricity generation in primary energy terms

E_{aoper} = Annual energy demand for operation and maintenance in primary energy terms

An indicator more commonly used for comparing different types of energy-production technologies is the energy return on energy investment, which quantifies the benefit the user gets out of exploiting an energy source. Usually, it is expressed as the dimensionless ratio of the energy generated from a system over that energy, or its equivalent from some other source, that is "invested" in extracting, growing or processing a new unit of the energy in question. Thus, EROI even can be used for fuel-based power production that never pays back its energy requirement, as it continuously needs

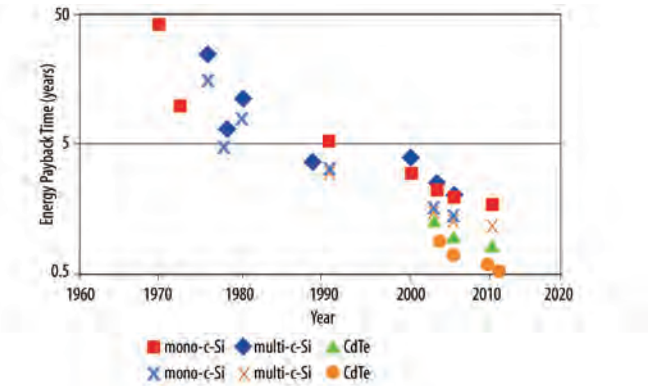

Figure 2. Energy payback times of various PV systems were reduced from about 40 years to 0.5 years from 1970 to 2010. The low numbers correspond to insolation of 2,400 kilowatt-hours per square meter per year (US-SW) and the high numbers correspond to insolation of 1,700 kilowatt-hours per square meter per year (Southern Europe).

energy in the form of depletable fuel to operate.

The traditional way of calculating the EROI of PV is EROI = lifetime/EPBT; thus, an EPBT of one year and a life expectancy of 30 years corresponds to EROI of 30:1. The EROI of conventional thermal generation from fossil fuels has been viewed as much higher than those of photovoltaics; this recently was shown to be a misconception fostered by using outdated data in and a lack of consistency among calculation methods [3].

Correcting Outdated Estimates

Several published studies on PV life-cycle assessments (LCAs) give differing estimates of the EROI. Such divergence reflects the varied assumptions about key parameters, like product design, solar irradiation, performance ratio and lifetime. These assessments also deviate because of the different types of installation used, such as ground mounts, rooftops and façades. Also, assessments continue to be calculated based on outdated information from antiquated PV systems. As an example of such misrepresentation, a recent *PE* magazine article stated that "… photovoltaic electricity generation cannot be an energy source for the future because photovoltaics require more energy than they produce during their lifetime." Statements to this effect were not uncommon in the 1970s based on some early PV prototypes. However, today's PVs return far more energy than that embodied in the life cycle of a solar system; figure 2 (see page 25) illustrates this historical trend.

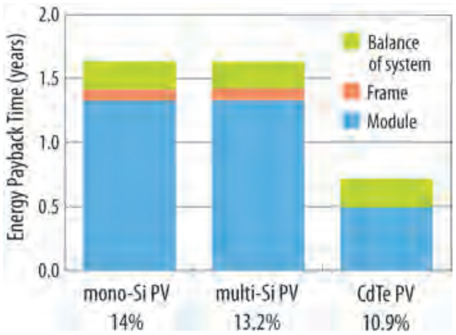

Figure 3. Energy payback times (EPBT) of roof-mounted PV systems for U.S. and European production and installation under average U.S. irradiation of 1,800 kilowatt-hours per square meter per year (4.9 kilowatt-hours per square meter per day), a performance ratio of 0.75, and the module efficiencies shown above. Data adapted from de Wild Scholten (2009) and Fthenakis et al. (2009); note that module efficiencies have increased since 2009, and, correspondingly, EPBTs have decreased.

To resolve these inconsistencies in the estimates, the International Energy Agency Photovoltaic Power Systems Program Task 12 published "Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity" for conducting balanced, transparent and accurate LCAs [5]. Following these guidelines, which represent consensus among LCA experts from the 10 member countries of Task 12, the author calculated the EPBTs of today's PV technologies.

Figure 3 (left) plots the EPBTs of three major types of commercial PV modules: monocrystalline silicon, multicyrstalline silicon and CdTe. These results are based on detailed process data obtained through collaborations with 13 European and U.S. PV manufacturers [4]. Of course, the effectiveness of solar modules depends on the amount of sunlight they absorb, which varies by region. Therefore EPBTs for the same types of systems installed in the U.S. southwest were shorter in proportion to the solar irradiation ratio (1,800/2,380) between the U.S. average and southwest solar conditions (see figure 4, left). Thus, for southwest irradiation, the EPBTs for the three PV technologies shown in figure 3 are 1.3, 1.3 and 0.5 years, and their corresponding EROIs are 23:1, 23:1 and 60:1. **ST**

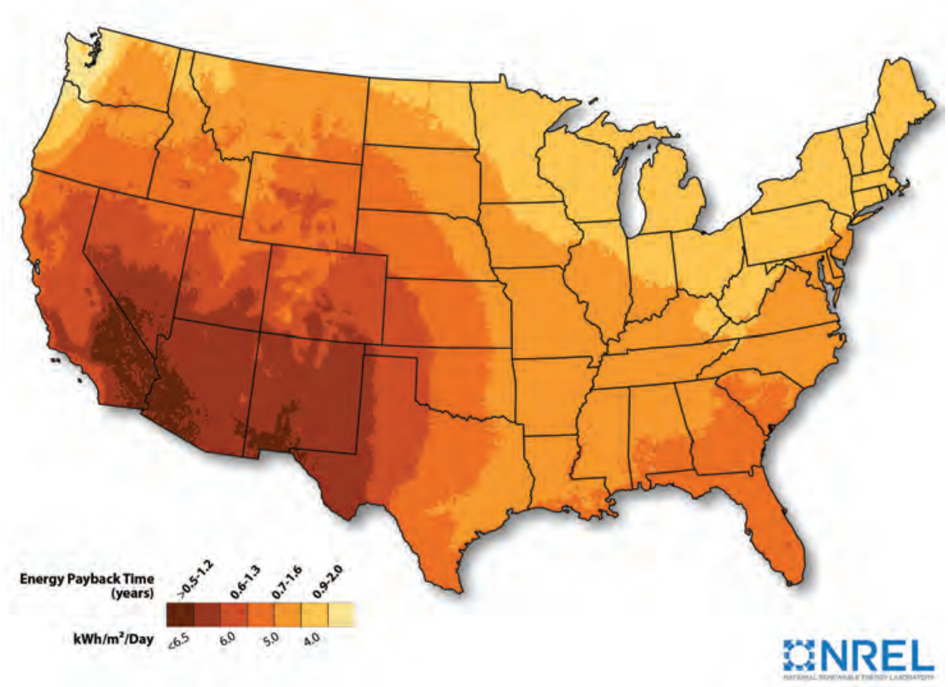

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Figure 4. Energy payback times (EPBTs) for different insolation levels in the United States. This solar resource map was produced by B. Roberts, National Renewable Energy Laboratory for the U.S. Department of Energy; the colors show annual averages of daily insolation for the south-facing latitude-tilt plane. The EPBTs were estimated by V. Fthenakis, Brookhaven National Laboratory.

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