Hawaii Renewable Energy Development Venture
Technology Assessment

Photovoltaic Electricity Production

1. Overview:

Photovoltaic (PV) cells are specialized semiconductor devices that directly convert sunlight into DC (direct current) electricity. PV-based solar-electric energy systems are becoming increasingly important as alternative sources of utility power, on residential, commercial and industrial power-production scales. For remote or standalone power generation, a PV system is typically coupled with a battery storage system and charge controller circuitry to sustain a DC electricity bus. Alternatively, the PV-generated DC electricity can be converted using power-inverter technology into AC (alternating current) electricity for powering conventional AC equipment or for feeding into utility grids.

Solar conversion technologies such as PV are particularly important to renewable energy development, especially considering the immense scope of the solar resource. The sun is continuously bombarding the earth with approximately 178,000x10^{12} or 178,000 TW of radiant power. Although a substantial fraction of this is immediately reflected to space, over 82,000 TW of the radiant energy reach the earth's surface- 36,000 TW of this falling over the world's collective land-masses. In comparison, our current human energy demand is on average about 13 TW (approximately 2 TW in electricity usage), with future projections up to 25 TW in the next 40 years. There is clearly an over-abundance of solar energy reaching earth. Although about half of this energy is vital for driving the planet's climate and life cycles, there is sufficient remainder for conversion to useable forms of energy for human consumption.

There are, however, certain logistical challenges in harnessing the vast solar resource. The sun is a constant power source, but at a given location on earth, the power delivery is variable based on the time of year, the time of day and on weather conditions. The sun is an immense power source, but the per area energy density is relatively low. The peak solar flux at the earth's surface is only slightly over 1 kW/m^2. In terms of the net solar energy received at the latitudes of the United States and Europe, typical insolation levels range from 4 kWh/m^2/day in northern regions to 8 kWh/m^2/day in the sunniest regions. Using an average value of 6 kWh/m^2/day, and assuming a 10% solar conversion efficiency, approximately 80,000 million m^2 of land area would be needed to supply our current net electric consumption levels of 48 TWh/day (i.e., 2 TW x 24h/day). This is a significant land mass, although the unpopulated area of the Sahara desert is significantly larger, at over 9,000,000 million m^2.

Covering the Sahara desert with solar cells could convert enough solar energy to meet mankind's electricity demands, but the physical cost of this endeavor would be enormous with current conversion technologies, and there would be significant problems in storing and transmitting the electricity for consumption in populated regions around the world. It is clear that in the long-term, practical solar-to-electric power generation will require not only efficient and cost-effective conversion technologies, but also practical large-scale storage and transmission schemes.

The two primary routes for viable solar-to-electric energy conversion include solar-thermal and PV. In solar-thermal electricity production, which utilizes solar energy to heat the working fluid in a thermodynamic cycle, the high-temperature operating conditions required for high efficiencies can be severely limiting. PV, on the other hand, is a direct solar-to-electricity conversion process that can achieve relatively high conversion efficiencies at low operating conditions, but its viability depends on the large-scale deployment of cost-effective semiconductor materials systems.

State of the art semiconductor materials systems for PV applications include silicon (in crystalline, multicrystalline/polyscrystalline, ribbon and amorphous forms), III-V crystalline compounds (such as gallium-arsenide and indium-gallium-phoshpide), and thin-film compounds such as cadmium-telluride (CdTe) and copper-indium-gallium-diselenide (CIGS). Material systems in the exploratory stages include organic semiconductors and dye-sensitized metal oxide systems. Demonstrated PV conversion efficiencies range from less than 1% in the exploratory systems up to 43% in the most sophisticated laboratory scale systems. PV efficiencies for commercially available silicon-based solar cells range from 6% in amorphous silicon to 20% in crystalline silicon; with efficiency values from 12%-18% in multicrystalline and ribbon silicon. Demonstrated PV efficiencies for thin-film CdTe and CIGS range from 14-20%. There remains, as in any technology, an inherent trade-off between performance and cost. 42% efficient PV cells based on multijunction III-V crystalline semiconductors can be up to 100 times more costly to product than their lower-efficiency silicon counterparts.

Materials performance and cost are critical to the long-term viability of PV electricity production, though balance of system, including possible solar-tracking, solar-concentration, as well as the power-inverter, maximum-power-tracking and grid-tie systems are also important considerations. Overall, there are advantages and disadvantages to large-scale PV deployment, as summarized below:

Advantages	Disadvantages
Vast power source (solar energy)	Low energy density of the solar resource, as well as local intermittency based on sun cycle and weather conditions
No emissions, no combustion, no radioactive waste as part of power generation	Energy consumption and environmental impact resulting from large-scale processing of PV-grade semiconductor materials
Low operating costs: - no moving parts (avoiding wear) - ambient temperature operations (avoiding materials degradation and safety issues)	High up-front installation costs
High reliability in demonstrated PV modules (20-30 years)	Reliability issues remain in balance of system components (such as storage, tracking and concentration systems), though power inverter technologies have recently demonstrated reliabilities rivaling PV modules.

2. Status of Commercial Readiness:

PV technology is commercially available today, though the high-cost of large-scale implementation remains a barrier. Nevertheless, the world PV market installations reached a record high of 5.95 gigawatts (GW) in 2008, representing growth of 110% over the previous year. Europe accounted for 82% of world demand last year, with Spain and Germany taking first and second place in the market ranking. The US advanced to number three, while rapid growth in Korea allowed it to become the fourth largest market, closely followed by Italy and Japan. In the US, the grid-tied PV market led the overall PV market with 292 MW installed in 2008, a growth rate of 81 percent from 2007. California was the leader among state grid-tied PV installations with 178.6 MW, New Jersey followed with 22.5 MW installed, Colorado was next at 21.6 MW, Nevada installed 13.9 MW and Hawaii with 11.3 MW.

On the supply side, world solar cell production reached a figure of 6.85 GW in 2008, up from 3.44 GW a year earlier. Overall capacity utilization rose to 67% in 2008 from 64% in 2007. China and Taiwan continued to increase their share of global solar cell production, rising to 44% in 2008 from 35% in 2007. Polysilicon supply to the solar industry grew by 127% in megawatt terms, sufficient to substantially ease supply limitations in 2008. United States polysilicon production accounted for 43% of the world's supplies. Average global wafering capacity grew to 8.30 GW (up 81%).

Meanwhile, thin film production also recorded solid growth, up 123% in 2008 to reach 0.89 GW.

In the US, new manufacturing facilities for solar cells and modules in Massachusetts, Michigan, Ohio, Oregon, and Texas are adding enough capacity to produce thousands of megawatts of solar devices per year within the next few years. In late 2008, for example, Sanyo Electric Company, Ltd. announced its decision to build a silicon-PV manufacturing plant in Salem, Oregon, which is planned to reach a full production capacity of 70 MW per year by April 2010. Also in late 2008, First Solar, Inc. broke ground on an expansion of its Perrysburg, OH facility that will add enough capacity to produce another 57 MW per year of Cd-Te-PV modules, bringing its total capacity to roughly 192 MW per year. Recent growth has been impressive, but not all the news is good for PV. Some market researchers expect a decline in the photovoltaics industry in 2009, due to overcapacity, plunging prices and weak demand for solar as a consequence of the global economic recession.

Bottom line, the cost of PV electricity is still too high to compete against fossil-fuel plants, despite rising fossil fuel prices. Semiconductor materials and processing costs are the primary reason. Silicon, which comprises over 90% of the current PV market share, is one of the earth’s most abundant elements; still the processing of PV-grade silicon is both energy and cost intensive. A common method used to express economic costs of electricity-generating systems is to calculate a price per delivered kilowatt-hour (kWh). For PV, the cell efficiency and lifetime in combination with the available irradiation will determine the electricity costs. Commercially available silicon solar cells have efficiencies ranging from 6 to 20% (for amorphous to crystalline silicon, respectively) and warranted lifetimes up to 30 years. As a result, current PV electricity generation costs range from ~0.60 US$/kWh down to ~0.30 US$/kWh in regions of high solar irradiation. This electricity is generally fed into the electrical grid on the customer's side of the meter. Compared with prevailing retail electric pricing, which varies from 0.04 US$/kWh in the US up to 0.50 US$/kWh worldwide, PV-generated electricity is relatively high-priced..

Until rising fossil fuel prices result in a fivefold increase in retail electric prices, the cost-competitiveness of PV-electricity will depend on development of lower-cost PV semiconductors, such as the thin-film CdTe or CIGS, with lifetimes rivaling silicon; or alternatively, on breakthroughs in lower-cost silicon manufacturing. In the meantime, the rise and fall of the PV industry is being fueled in substantial part by tax incentives and government subsidies.

3. Hawaii Photovoltaic Resources and Incentives

The use of solar energy via photovoltaic conversion to electricity is on the rise in Hawaii. The Hawaiian Islands' abundant sunshine in conjunction with heavy reliance on imported fuels for energy and high electricity cost (relative to the US mean) are providing strong incentives for accelerated investment in PV. The average solar resource in Hawaii is among the highest in the United States, and considerably higher than in most of the populated world. On average, approximately 5.7 kWh/m2 per day of solar energy is available in Hawaii for flat panel PV-conversion, while approximately 7kWh/m2 can be converted with tracking PV systems.

Even with the exceptional solar resource in Hawaii, PV development would not be possible without the considerable State and Federal incentives. The Hawaii Energy Tax Credits legislation enacted the Solar and Wind Energy Credit in 1990, according to which individuals or corporations could avail an income tax credit of 35% of the cost and installation charges for a solar thermal or photovoltaic system. In 2003 in Senate Bill (SB) 855, there was a revision in Tax Credit and also an extension through 2007. According to SB 3162 in 2004, a taxpayer was allowed to claim a credit exceeding his income tax liability which could be carried forward until it was exhausted. The State of Hawaii enacted House Bill (HB) 2957 in June 2006 which removed the credit's sunset date, and also announced the removal of new federal tax credits which were to be deducted from the cost of the system prior to the calculation of state tax credit. With SB 644, a single family residential property owner could avail a credit of 35% of a purchased PV system's cost or $5,000 whichever is less. The same for multi family residential property owner is 35% of system's cost or $350 per unit, whichever is less. Commercial property owners are eligible to claim a credit of 35% of the photovoltaic system's cost or $500,000, whichever is less. PV-equipped homes and businesses in Hawaii that produce more solar electric energy than they use and are connected to the utility grid can use surplus power to offset their electricity bills in a “net-metering” arrangement. “Feed-in-tariff” systems are also being considered by Hawaii. Federal tax credits are also available to partially subsidize PV systems, which can cost about $20,000 or more for a typical residential PV system without battery backup.

Hawaii’s favorable environmental and political climate has lead to a rapid rise in PV installations across the state in recent years. The state is among the leaders in the nation in grid-tied PV installations, with over 11MW installed. To accommodate this, dozens of Hawaii-based PV-installer companies are currently licensed. In the past few years, a number of commercial-scale PV installations have also been successfully completed, or are near completion. The 309 kW solar array at a US Naval facility on Ford Island, installed by PowerLight using Sharp Corporation polycrystalline-silicon modules, has been operational for over two years. During the daytime, this PV system generates energy equivalent to that normally used to power over 300 homes. Another good example is the Mauna Lani resort on the Island of Hawaii which since 2003 boasts the distinction of having the most solar electric generating capacity of any luxury resort in the world- over 500kW of SunPower silicon-based PV systems.

More recently, Castle & Cooke Inc. has built the largest solar photovoltaic energy farm in the state of Hawaii on 10 acres in Palawai Basin, Lanai. The Lanai solar farm, built with panels from California-based SunPower Corp., currently produces up to 500 kilowatts of energy, which is expected to rise to 1.2 megawatts upon completion in late 2009. This will be enough to provide up to 30 percent of the island's daily peak electrical needs. Under a 25-year power purchase agreement approved by the state Public Utilities Commission, Maui Electric will purchase Lanai PV-power from Castle & Cooke Solar Management, LLC for 27 cents a kilowatt hour for the first 10 years, 30 cents a kilowatt hour for the second 10 years, and 33 cents a kilowatt hour for the following five years. It is intended that the solar farm will provide financial relief to Lanai residents from the highest electric rates in the state, which now top 50 cents a kilowatt hour.

4. Overall Appropriateness of PV in Hawaii

In the big picture of “Hawaii’s Renewable Energy Development” it is extremely appropriate and important to foster the implementation of PV technologies for converting the state’s abundant solar resource to consumer electricity. Some general comments regarding PV which are consistent with the findings of the 2006 DBEDT report “Photovoltaic Electricity in Hawaii”, can be summarized:

- Hawaii is ideal for PV, based on its oil dependence, high electric costs and rich solar resource; research into the “best” PV for HI is ongoing;
- PV is cost-effective in parts of HI already, but up-front costs are high;
- Rooftop PV in Hawaii is attractive (non-competitive with other land use);
- Residential PV systems today are expensive, costing $15k-$25k up front for 2-3kW; policy & market forces will eventually improve this;
- Net-metering in the near-term is an attractive option for consumers & HECO;
- New grid infrastructures will be vital in the long-term for handling intermittent sources such as solar and wind
- Financial Incentives are also vital to spur growth in the PV market (including subsidies, tax-credits, ‘pay as you save’, etc.);
- PV performance & price data insufficient to define long term trends.

Regarding the final point in the bullet list above, important avenues of PV research are still needed to help identify the best pathways forward to practical large-scale PV implementation in Hawaii. These include:

- For different PV semiconductor technologies, identification of the specific temperature sensitivities in PV conversion efficiency- particularly related to the expected environmental operating conditions in Hawaii's different micro-climates;
- For different PV semiconductor technologies, identification of the specific spectral sensitivities in PV conversion efficiency- particularly related to the various atmospheric operating conditions in Hawaii's different micro climates;
- For different PV semiconductor technologies, quantification of the degradation rates and module lifetimes when subjected to Hawaii's different micro climates;
- Quantification of Hawaii's statewide variations in solar resource on a transient second-by-second basis resulting from weather patterns, which can have significantly influence the impact of PV on grid stability;
- Studies, on a sub-second transient level, on the grid impact of large-scale PV penetration;
- Identification of the most effective auxiliary system components in different scaled PV installations, including conventional power-inverters versus single-panel micro-inverters.

Names of PV Experts:

- Keith Emery, NREL
- Steve Hegedus, IEC Delaware
- Larry Kazmerski, NREL
- Martin Green, University of New South Wales
- Jim Fenton, Florida Solar Energy Center

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