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CRYSTALLINE-SILICON PHOTOVOLTAICS: NECESSARY AND SUFFICIENT

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ABSTRACT

Photovoltaic (PV) energy systems have always been dominated by crystalline-silicon (c-Si) technology, and recent developments persuasively suggest that c-Si will continue to be the dominant technology well into the next century. We explain why c-Si technology is fairing much better than previously expected, and discuss the impact of improvements currently under development. We use a ground-up, engineering-based approach to predict the expected evolution of this type of PV system, and argue that c-Si PV will be in a position to compete for the US residential power market starting in about the year 2010. This market alone will provide the opportunity for PV to supply several percent of the electrical energy used in the United States. Crystalline-silicon technology is therefore not just necessary for building a near-term PV industry; it also offers a low-risk approach to meeting long-term goals for PV energy systems.

INTRODUCTION

The largest application for PV energy systems today is remote power. Crystalline silicon is the technology of choice for PV remote power because of its proven reliability and acceptable cost. However, for PV to become a major source of electrical energy, advancements in several areas will be required, including the following: (1) substantial cost reductions for PV products, (2) large-scale manufacturing of PV, and (3) development of large profitable markets for PV systems.

Crystalline-silicon PV technology has frequently been excluded as a viable candidate for supplying a significant fraction of the world's electrical energy because the cost of this technology was found to be prohibitive for central-station PV generation. This conclusion assumed that central-station generation was required to achieve large-scale deployment of PV in developed countries. This perception has led to the substantial investment by both public agencies and private firms in alternate PV technologies. While these alternate technologies do show progress, c-Si technology has demonstrated continuous

improvement and presents a rapidly moving target for competing approaches.

In this paper, we claim that c-Si PV technology is both necessary and sufficient to establish PV solar energy systems as a major electrical energy source. We first review the manufacturing cost of c-Si PV technology. We will, in particular, demonstrate that several commonly perceived limitations of c-Si technology (cost of polysilicon feedstock, module manufacturing costs, and energy payback) are not overriding issues.

We believe that expansion of PV into large-scale markets requires that the systems capture the value of several advantages that are unique to PV: distributed generation, user ownership, low maintenance, and low environmental impact. We present, as a specific example, homeowner-owned residential rooftop systems. From the understanding we have gained of the underlying scientific and manufacturing issues associated with c-Si technology, we can predict the expected evolution of the cost of this type of system. Our projections do not assume optimistic levels of public support; rather, they are based on a realistic continuation of current economic and technical trends. All costs have been adjusted to represent 1994 US dollars, and all component and system ratings are based on d.c. output under standard reporting conditions.

CRYSTALLINE-SILICON TECHNOLOGY

Crystalline-silicon PV technology benefits substantially from the huge investments that have been made and continue to be made in the integrated-circuit (IC) industry. Because large factories for purifying silicon have been built to supply the IC industry, top-grade polysilicon feedstock is available for \$45/kg [1], only one-fourth the inflation-adjusted price of twenty years ago [2]. Furthermore, reject silicon from the IC industry and excess silicon from Eastern Europe that are suitable for PV are available for less than \$10/kg. Due to inefficiencies in sawing and processing, only about one-third of the polysilicon feedstock purchased by today's vertically integrated PV manufacturing plants ends up in a module [1]. Still, at \$10/kg the cost of the polysilicon feedstock required to produce a flat-plate module is only \$0.14/W. Continuing growth in the IC industry will ensure an adequate supply of hyperpure silicon feedstock at low

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cost for years or even decades to come; and improvements in wafer, cell, and module technology will significantly reduce the amount of silicon required. The cost and availability of silicon feedstock is therefore not expected to be an issue, even for multi-gigawatt deployment of the technology.

A valid concern is the cost of forming the polysilicon feedstock into wafers suitable for processing into solar cells. This step currently costs about \$1.50/W. The methods used are not readily scaleable, so that a large number of crystal growers and saws must be installed to increase production capacity. However, there are three approaches that can reduce the cost of wafers by at least half: cut thinner wafers, grow planar crystals, or use concentrating optics. We expect that this diversity of approaches has a high probability of achieving a wafer cost below \$1/W in 5-10 years, approaching \$0.50/W over the next 15-20 years. The price of modules fabricated from these wafers will drop accordingly, from \$4-5/W today toward \$1.50/W over the next 20 years.

The most direct approach to wafer cost reduction is to cut thinner wafers with less kerf loss so that more cells can be produced from the same ingot of silicon. This approach can be applied to both Czochralski and cast-multicrystalline technologies. The current standard wafer thickness of 300-400 μm is limited primarily by the availability of techniques for handling thin cells without breaking them. Wafers as thin as 80 μm have been processed with high yield using automated equipment [3]. Using IPEG costing assumptions [4], each automated handling station costing \$100K adds less than \$0.01/W to the manufacturing cost at a production throughput of 10 MW/yr. Attempts to decrease wafer thickness below 250 μm will require improved technology for the back-surface electrical contact, or else cell efficiency will decrease as the wafer is made thinner. Promising potential solutions include the emitter wrap-through cell [5] and the double-sided buried-contact cell [6].

The second approach with the potential to reduce wafer cost significantly is to bypass ingot growth. Ribbon, spherul, sheet, and thin-layer technologies are all under development, using various forms of c-Si [7]. These technologies carry a higher technical risk than the ingot approach, but have the benefit of substantially reduced sawing cost. Ribbon growth from a crucible of molten silicon shares an advantage of ingot approaches in that it permits flexible silicon feedstock specifications, but the areal growth rate needs improvement. Spherul and sheet technologies produce low-cost wafers, but the material quality needs improvement to obtain adequate cell efficiency. Thin-layer c-Si on glass has the potential for very low module cost, but high manufacturing throughput at temperatures compatible with glass is problematic.

The third approach to reducing wafer cost is to concentrate sunlight onto smaller-area cells using reflection or refraction. Concentration up to a few suns

can be incorporated into fixed flat-plate modules without much loss of performance [8]; the challenge is to minimize losses while keeping a thin module profile. Concentration of more than a few suns requires a tracking structure and more sophisticated cell technology. These concentrators tend to be bulky and heavy, but in mass production they should have somewhat lower cost than flat-plate systems. Consequently, concentrators are a potentially viable option for large systems in sunny areas where purchase price is paramount and maintenance can be absorbed into existing infrastructure.

Energy Payback

Although manufacturing cost is the ultimate test of feasibility for large-scale deployment of photovoltaics, it is also important that a PV technology not require more energy than it produces during its life. The amount of energy required to convert readily available raw materials into a turnkey flat-plate photovoltaic system based on crystalline silicon is approximately 400 kWh/m² [9]. Of this total energy input, only 40% is in the form of electricity consumed at the PV module manufacturing plant. The rest is energy required to fabricate the balance-of-system components, construct the factory, and to refine the aluminum, glass, and chemicals used in manufacturing the system. This total energy input is returned by the system in just 24 months of outdoor operation. A PV system with a service life of 20 years returns ten times the energy used to manufacture it.

The energy required to purify polysilicon feedstock from quartz sand (200 kWh/kg [10]) is not included in our estimate, because polysilicon material is available as a reject byproduct of the IC industry, and thus qualifies as a raw material for photovoltaic applications. If, in the future, the supply of reject IC material becomes inadequate to meet PV demand, then the energy required to refine the polysilicon should be considered. By the time this might happen, the amount of silicon required per wafer will be less than half what it is today, so that silicon purification would add at most 18 additional months to the energy payback time for the system.

PV APPLICATIONS

Photovoltaic energy systems based on crystalline silicon are currently used wherever relatively small electrical loads cannot be conveniently powered by an existing utility grid. Most of these systems require less than 100 kWh/month, although PV is also the preferred source for telecommunication repeaters requiring up to 1000 kWh/month. Virtually all of these systems use flat-plate c-Si technology because it is rugged, reliable, and proven. Unlike conventional technologies for producing electricity, photovoltaic systems can be installed in sizes ranging from 100 W to 10 MW with relatively little variation in the cost per unit energy produced. This flexibility permits PV systems to be installed wherever the demand is greatest, allowing the technology to fill a continuum of niche

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applications as it matures toward ever-larger markets. Throughout this evolution, the unique advantage of photovoltaics – its modularity – is expected to remain the cornerstone for cost-effective applications.

The most profound benefit expected from PV is its impact in developing countries. Electrification using renewable energy in these countries will reduce stress on the global environment while allowing continued economic development. But financial resources in developing countries are limited. Without a huge increase in support from international development banks, this market cannot justify the large capital investment needed to expand PV production facilities to the scale needed to impact global energy use. However, the profitable deployment of grid-connected PV systems in industrialized countries would have enough market impact to encourage this investment [11]. There are several scenarios for grid-tied PV systems, including central stations (>1 MW), support for overloaded distribution lines (100 - 500 kW), commercial building rooftops (10-50 kW), and residential rooftops (1-5 kW). A recent utility-sponsored study identified a market of 9 GW in the US for distributed grid-tied PV with an installed cost of \$3/W [12]. Another study sponsored by EPRI identified an even greater market potential for residential and commercial rooftop systems [13].

RESIDENTIAL ROOFTOP SYSTEMS

The grid-tied application that takes maximum advantage of the modularity of PV is the deployment of PV modules on residential rooftops. A 20-m^2 , 3-kW installation as illustrated in Fig. 1 is representative. No energy storage is required for this type of system, at least for the PV penetration levels envisioned here, although storage may nevertheless prove to be economical. The photovoltaic modules mounted to the roof are wired to a dc-to-ac inverter which is tied to the grid through protective switches. In the future, each module may come equipped with its own inverter, thus eliminating the need for a separate inverter and switchgear and greatly simplifying compliance with applicable electrical codes. The system economics we present assume that the roof and building structure already exist. Incorporation of PV into new building construction can be even more economical, but the initial market is much smaller.

Fig. 1. Typical Residential Rooftop PV Installation

There are 10-million single-family homes located in regions of the United States that have above-average

sunshine and that have suitably tilted roofs with unshaded access to direct sunlight, and this number is expected to grow by 1%/yr [13]. This represents approximately 15% of the single-family homes in the US. The annual solar energy incident on these roofs ranges from 1.6 to 2.4 MWh/m^2 . The annual d.c. operating efficiency of a c-Si PV system of this type is 10% using current technology, and can be expected to increase to 15% over the next 20 years, even as the price of the system drops. The a.c. output of these 20-m^2 systems averages 300 kWh/month with current technology, increasing toward 500 kWh/month over this period. This is sufficient to supply the total annual electrical consumption in the home on which the system is deployed, provided common cost-effective conservation measures are employed and the home's space heating is provided by fossil fuel, solar thermal, or other means.

The subset of homes in the US suitable for PV represents a 40-GW market through the year 2020. This deployment alone could feed 70 TWh/yr into the utility grid, supplying 2.5% of the current total US electrical consumption [14]. The fraction of US consumption this would represent in the year 2020 depends on what conservation measures are implemented to reduce electrical demand, and whether a significant fraction of the transportation system converts to electric power.

A residential PV system based on c-Si modules can be installed today at a cost to the user of \$8-10/W [12,15]. Fig. 2 illustrates the expected evolution of the key system cost components through the year 2020. The wafer costs in Fig. 2 are greater than those previously discussed because here they include profits for the manufacturer. About \$3.50/W of the current system price is for balance-of-system hardware and installation, because each installation is custom-designed. As the market for these systems increases, installation will become more routine with standard components and connectors. The total cost to the homeowner can be expected to drop below \$6/W by the end of this decade through improved manufacturing processes, standardization, and increased conversion efficiency. Installed c-Si PV system cost should eventually approach \$3/W for residential rooftop systems capable of lasting 30 years

Fig. 2. Predicted Evolution of c-Si PV System Cost

The cost of the energy delivered by these systems depends strongly on the service life of the system. Each component has a different life expectancy, but the net effect on cost using currently available products is as if the entire system had a service life of about 15 years. This is expected to increase toward 30 years as mass production produces more reliable system components. Maintenance costs must also be considered. These include an annual checkup and module removal and reinstallation after 15 years to accommodate roof repair.

We assume a levelized constant-dollar capital cost factor of 7%/yr [16]. This includes an investment value of money 4%/yr above inflation for 30 years, plus 1%/yr for insurance and taxes. No additional capital recovery is included, because the decision to lease or purchase the PV system is being made by individual homeowners, who are not required to generate profit for investors.

The expected cost of energy from these residential PV systems is as illustrated in Fig. 3. Also shown is the expected cost to the homeowner of energy from the electric utility. We expect utility prices to rise over this period despite an increased diversity of generation sources, but improvements in energy efficiency will keep the homeowner's annual utility bill nearly constant. The average cost of electricity delivered to residential customers in the region of the US analyzed here was \$0.08/kWh in 1992 [13]. The power delivered by PV frequently coincides with peak-demand periods, when the value of this energy to the utility can exceed \$0.12/kWh. This provides some incentive for the utility to cooperate with the residential owner in the installation of the PV system. We anticipate that most utilities will allow net-energy billing for these systems, so that the energy cost of PV can be directly compared to the price of energy purchased from the utility.

Fig. 3. Predicted Residential Energy Costs

The cost of energy from the utility is expected to increase as environmental protection measures are implemented and efficiency improvements reduce energy consumption per customer. If the average cost of electricity to the residential customer is assumed to double over the next 20 years, as shown in Fig. 3, the residential PV system becomes cost-effective in about the year 2010. Demand

for these systems will then grow rapidly. Forty gigawatts could be installed over the following ten-year period by a c-Si PV manufacturing industry that, by continuing to maintain an average annual growth rate of at least 16% [17], will be 50 times larger in 2020 than it is today.

CONCLUSION

Crystalline-silicon technology is necessary for the success of photovoltaics in this century; and with expected engineering improvements, this technology will be sufficient to meet expanding market demands well into the next century.

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Introduction

- Crystalline-silicon technology is not perceived by some as a long-term player in the PV marketplace
- Our study of this issue shows that it is!
 - Silicon wafer costs are low and decreasing
 - Distributed, user-owned PV is a huge market that will be accessible to c-Si technology starting in about the year 2010

Crystalline-Silicon Technology

- Technology of choice for today's systems
- Beneficiary of IC industry investment
- Uniquely positioned to expand capacity
- Is the cost of silicon wafers too high?

Cost of Silicon Material

- Hyperpure Si \$45/kg, remelt <\$10/kg
- Si feedstock only 14¢/W today
- If PV does outgrow IC industry, will only need half as much silicon as today
- Cost and availability of Si feedstock is not expected to be an issue, even for multi-GW deployment

Cost of Silicon Wafers

- Current cost of wafers \$1.50/W
- Cut thinner wafers with less kerf
 - Module manufacturing <\$2/W in 5-10 yrs
- Bypass ingot growth (ribbon, spherul, sheet, thin-layer)
 - Module manufacturing <\$1/W in 20 yrs
- Concentrators (low-X or tracking)
 - Large systems in sunny regions

Energy Payback Time

- Energy used for system: 400 kWh/m²
 - Electricity at PV manufacturing plant (40%)
 - PV Factory construction
 - Refine aluminum, glass, chemicals
 - Balance-of-system components
- Energy payback time = 24 months
 - Si feedstock today would add 36 months
 - Si feedstock will add <18 months in future

Residential Rooftop PV Systems

- Takes maximum advantage of PV modularity
- 10 million suitable homes in the US (15%)
 - 40 GW market through the year 2020
 - 70 TWh/yr, 2.5% of current US consumption

Utility Connection

- PV power frequently coincides with the utility's peak-demand periods
 - PV value to utility during these periods can exceed 12 ¢/kWh, well above the average price charged to homeowners
- Net energy billing anticipated
- PV energy cost can be compared directly to utility energy price

Evolution of c-Si Residential PV System Price

Energy Cost Calculation

- Effective PV service life increases from 15 years toward 30 years after 2010
- Constant-dollar capital cost 7% per year
 - 4%/yr over inflation, 30-year loan, +1%/yr
- Utility costs will double over 20 years
 - Energy efficiency improvements will keep annual utility bill nearly constant

Predicted Residential Energy Costs

CONCLUSION

- Crystalline-silicon technology is necessary for the success of PV in this century
- Crystalline-silicon technology is sufficient to meet expanding market demands well into the next century