Moore's Law of Photovoltaics

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Abstract

Advanced civilizations require energy – commonly produced today from fossil fuels using *yesterday's sunshine* in the form of vegetation converted to unsustainable coal, oil and gas, and subsequently converted into electricity via electromechanical machinery. The convergence of environmental, social and technical issues highlights the need for new approaches to electricity generation. Photovoltaics (PV) uses *today's unlimited sunshine* to generate energy that is sustainable in perpetuity. However, despite PV's many advantages, today it contributes only a small fraction to total electricity generation. In order for PV to contribute substantially to total electricity generation, it must achieve sustained growth rates of over 40 percent over four orders of magnitude in production volume. Integrated circuits (IC) have achieved such sustained growth rates, famously expressed as Moore's Law. Recasting Moore's Law for photovoltaics shows that PV has the technical characteristics to achieve similar sustained growth rates as the IC industry.

Introduction

Most electricity is generated today with electromechanical machinery, much as it has been since the concept of the electric generator by Faraday in 1832 and the first AC generator by Tesla in 1892. Such generators have served us well, but little has changed in the fundamentals. It was not until 1941 that solid state physics and quantum mechanics were applied to electricity generation through the invention of silicon solar cells at Bell Labs.[1]

Quantum mechanics, the major scientific advance of the 20th century, and semiconductor devices (diodes, transistors, integrated circuits), have had an enormous, transformative impact on society. Lighting, almost entirely controlled by incandescence in the past, has been partially replaced by fluorescence and will be replaced by electroluminescence through light-emitting diodes (LEDs). Displays, which previously used cathodoluminescence in cathode ray tubes, are now almost entirely based on flat panel displays with pixels controlled by thin-film transistors and backlighting by LEDs. The field of communications is controlled by semiconductor devices, through the use of lasers and photodetectors in fiber optics and ICs in wireless communications. While PV is central to satellite power generation, it has made only a minor contribution to terrestrial power generation.

Our present energy systems face “a series of great opportunities disguised as insoluble problems”:[2] climate change, uneven geographical distribution, national security and long-term resource supply. PV offers many benefits as a sustainable energy source, including large solar resource, high efficiency and low environmental impact (both in terms of emissions and of water use). Further, PV has high-ideal efficiencies (higher than cogeneration, thermal cycles or solar thermal systems). PV is a robust and reliable technology, and the Bell Labs cell of 1954 still generates power.

Contrary to popular view, solar cells have a **higher energy density** (energy delivered over the lifetime of a device per unit mass of material) than most other energy technologies.[3] The energy density is an important parameter for power generation as it relates the necessary material quantity to generate a given amount of power. It is also a measure of how much material needs to be mined to generate today’s and tomorrow’s power. Figure 1 shows the energy density of the most common “fuels” used today for power generation. Coal, oil and natural gas have a density of 30-50 MJ/kg. Reactor

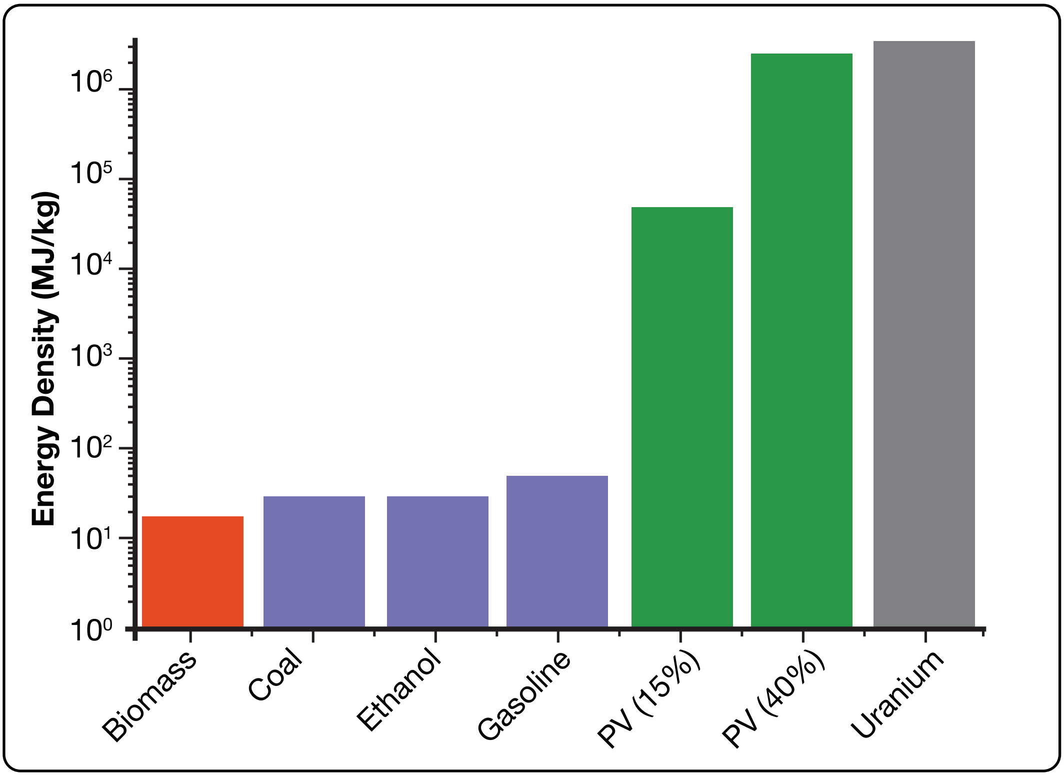

Figure 1 – Energy Density for Common Energy Technologies[4]

grade uranium has a significantly higher density of 3.46x10^6 MJ/kg. Solar cells come in at a surprisingly high value in the mid 10^4 to the 10^5 MJ/kg range. The high-energy density of solar cells is due to their small volume and their expected life of 20 years. The calculation for the solar cell power density use is – cell efficiency of 15 and 40 percent, cell thickness 200 µm and 2 µm, sunshine for 6 hours/day and 20-year life – all lead to the high values of 5.05x10^4 MJ/kg and 1.35x10^5 MJ/kg.

PV Growth Rates

As shown in Figure 2, photovoltaics has grown at an average compound annual growth rate (CAGR) of 40 percent for over a decade,[5] and even with recent economic setbacks causing slowed growth, it is expected to grow again at 40

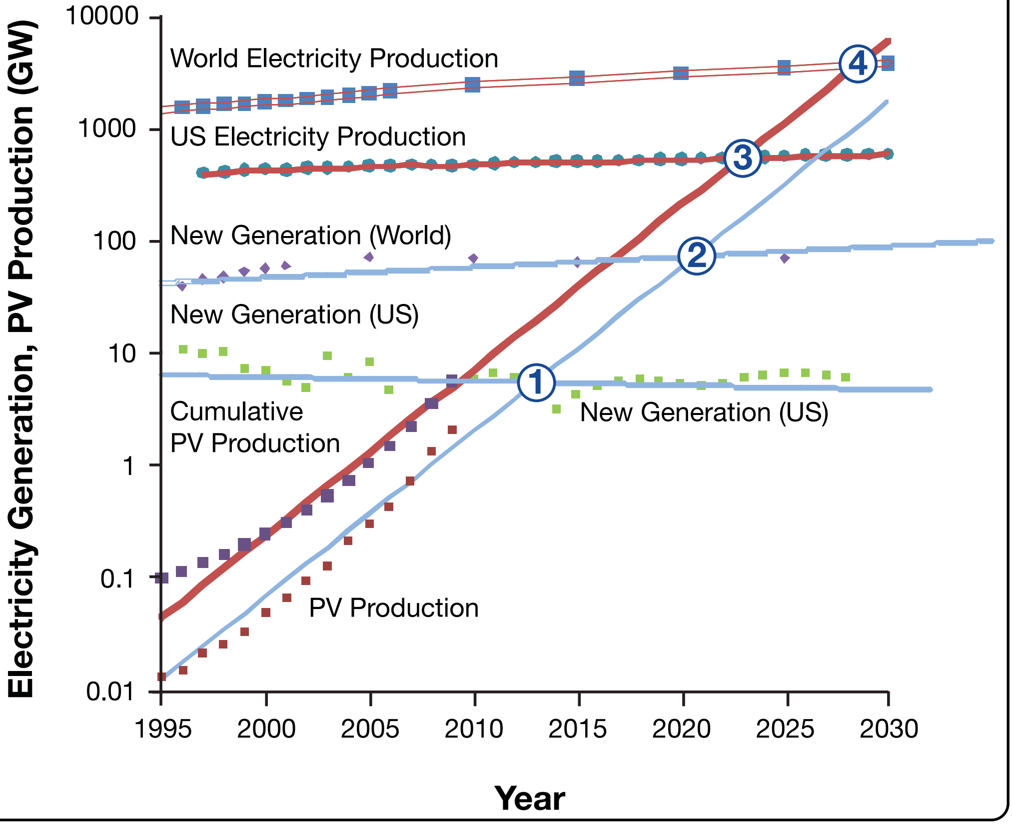

Figure 2 – The rapid growth of photovoltaics of 40 percent CAGR and the slower growth of electricity production of 1.5 percent in the U.S. and 3.5 percent worldwide.[7] The numbered points are described in the text.

percent CAGR in 2010.[6] The photovoltaic experience-cost curve shows the cost of modules decreasing by 20 percent for every doubling of cumulative volume, resulting in many photovoltaic technologies achieving the long-standing cost target of \$1/W_p. The present challenge is to continue the photovoltaic growth rate of 40 percent so that photovoltaics can make a significant contribution to world electrical production.

A 40 percent growth rate is a necessary and sufficient condition to allow large-scale contributions of photovoltaics to the world electricity grid. Figure 2 illustrates the impact of 40 percent growth curves. Because the PV industry is growing more rapidly than the electricity market, sustained growth allows substantial contributions to the electricity industry in a short time frame. To allow for a direct comparison between photovoltaic production and conventional electricity sources, the photovoltaic production figures normally given in terms of watts peak (W_p) have been divided by a factor of six, corresponding to a yearly production of 1500 kWh/kW, which is typical of the continental U.S. The numbered points in Figure 2 show:

1. In the next five years all ***new*** U.S. electricity production capacity could be met with photovoltaics (although it requires the U.S. to absorb world production).
2. In 10 years, all ***new*** world electricity production could be photovoltaics.
3. Within 15 years, photovoltaic production could meet the entire electrical generation of the U.S.
4. In just over 20 years, the entire world electricity production could be met by photovoltaics.

In practice, the development of an affordable, practical, large-scale photovoltaics industry would increase the electricity market. For example, shifting some of the transport sector to electricity, using electricity to address water issues, or increasing electricity access to the 1.5 billion people (one-fourth of the world's population) presently without access to electricity.[7]

Achieving Rapid Growth and Continuous Improvements: Moore's Law

While PV has demonstrated continuous cost reductions and growth rates of over 40 percent for two decades, it must continue to do so in a broad range of locations sustained over five orders of magnitude change in cumulative production capacity. Cost alone is not a predicator of growth, since it ignores many issues, such as the impact of efficiency and unforeseen barriers related to large-scale production. For example, historical 40 percent growth rates are not predominantly limited by cost; subsidies have maintained the market to the point where manufacturers are challenged to provide PV modules, and even resulted in short-term price increases as manufacturers were sold out several years in advance. "…buying out the experience curve" (i.e., providing subsidies until PV reaches grid parity) is estimated at a total worldwide cost of \$60 billion to \$160 billion over a 10-year period.[8,9]

The rapid development of ICs is famously expressed as Moore's Law, which describes the doubling every 18 months of the transistor count per unit area. The enabling feature of Moore's Law is the existence of a parameter that drives both improved performance *and* reduced cost, circumventing the nearly ubiquitous trade-off between performance and cost in many industries. In ICs, the enabling technical parameter is the gate length, where a shorter gate both improves computer speed and reduces costs by allowing more transistors on a silicon wafer. As formulated for ICs, Moore's Law does not translate to PV[10] since neither efficiency nor module area scale by large factors. While the PV experience curve is often cited as evidence of a "Moore's Law" effect,[11-13] the experience curve does not by itself demonstrate the positive feedback between higher efficiency and reduced cost.

While not directly translatable, the technical features that made Moore's Law possible have analogs in photovoltaics. For example, the analog to transistors/cm^2 is W/cm^3 (where cm^3 corresponds to the volume of material in the solar cell). The volume is the relevant parameter rather than surface area (as in transistors) both

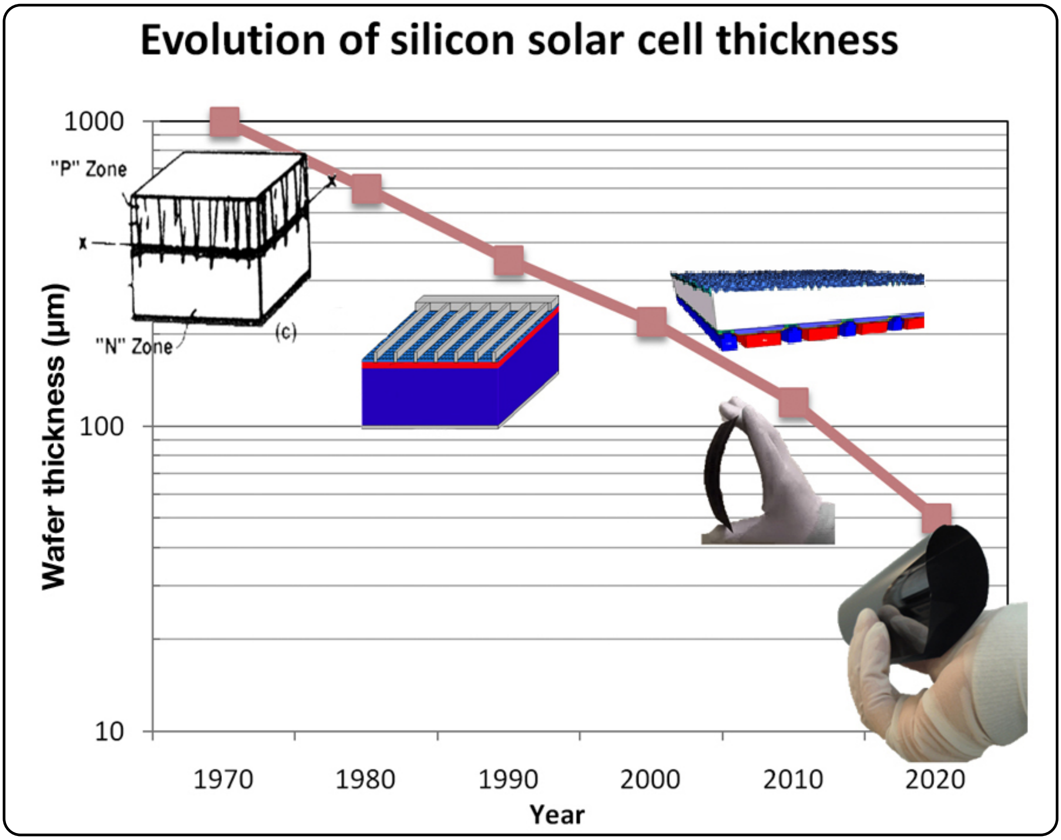

Figure 3 – Evolution of Solar Cell Thickness, Showing Move From 1000 μm to Ultra-Thin Wafers

because PV costs are dominated by material volume in large-scale production and because performance relates to material volume (e.g., in real devices, both absorption and recombination relate to material volume). There are two approaches to decreasing material volume while increasing efficiency: decreasing solar cell thickness and increasing concentration. A thinner solar cell enables higher W/cm^3 by increasing the efficiency (assuming light trapping) and by decreasing material use, making solar cell thickness an analog to gate length in transistors. Plotting the evolution of silicon solar cell thickness (Figure 2) shows the beginning of a "Moore's Law" for PV, where silicon solar cell thickness has decreased from 1,000 µm in early solar cells, to a typical value of 200 µm today, with new wafer technologies as thin as 20 µm,[14] and some solar cells as thin as 2 µm.[15] Interestingly, the change in thickness is numerically similar to the change in gate length in ICs, which decreased from about 5 µm in 1975 to under 50nm today. The combination of increased efficiency, thinner wafers, concentration and other effects will enable a five-order of magnitude improvement in W/cm^3, similar to that experienced in transistors/cm^2 in Moore's Law.

In PV, as in the IC industry, Moore's Law represents *potential* for growth through intensive, focused collaboration and innovation, rather than an intrinsic property realized through evolution. In ICs, speed is not improved by smaller gates unless parasitics are controlled, voltages are scaled and photolithography allows shorter for transistors. Similarly, in solar cells, efficiencies will decrease unless surfaces are improved, yields are maintained and wafer handling and defects are addressed. While the industry is still in its early stages, gains in performance and affordability are achieved through optimization and economies of scale, but continual advances – even beyond those originally predicted possible – are achieved through innovation. The PV industry is at a critical juncture, reaching the limit of evolutionary improvements. Its need for the next decade is collaborative, innovative solutions, driven by a roadmap.

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