CRITICAL NATIONAL NEED IDEA

Developing Manufacturing Innovations Needed to Achieve Solar Photovoltaic Grid Parity

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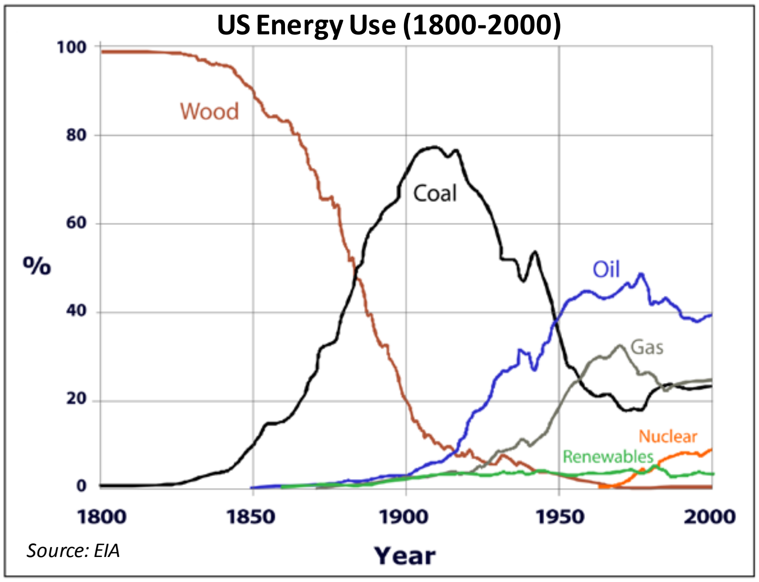
Overview

Energy is the foundation of our economy and our lives. As technologies have evolved over the last two hundred years the amounts and sources of the energy we consume have shifted dramatically. The 1800s were primarily fueled by wood, which in turn gave way to coal during the industrial revolution. With the invention of the internal combustion engine and meteoric rise of modern transportation, petroleum came to dominate energy sources. Other fuels, such as cleaner burning natural gas, nuclear, and hydro, emerged in the last half of the 20th century. The question persists: what fuel sources will best serve the evolving needs of our society?



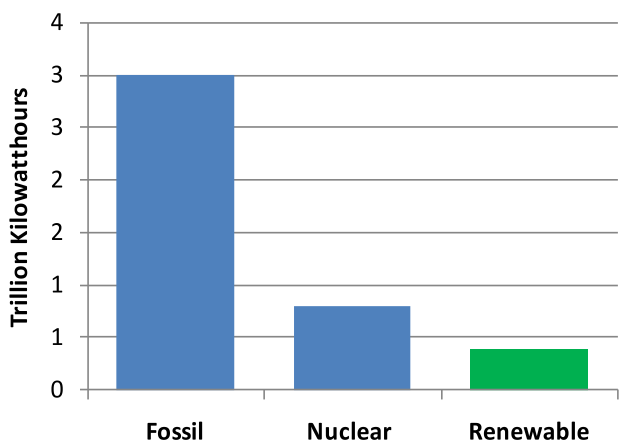
As the global economy has surged in recent years we have witnessed historically high prices and volatilities for key fuel sources such as oil and natural gas. As we build new factories, buildings, and methods of transportation to meet the needs of a growing population, we put increasing demands on our existing energy infrastructure. One of the most important energy networks is our electric generation, transmission, and distribution infrastructure. Electric generation accounts for over 40% of total US primary energy consumption and is responsible for satisfying the majority of non-transportation energy demand.[1] The Energy Information Association (EIA) estimates that from 2007-2030, United States GDP will grow at an annualized rate of 2.5%. Despite declines in our energy use per capita, demand for electricity is projected to grow at approximately 1% per year.[2]

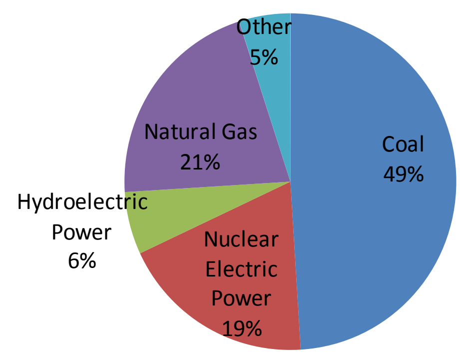
There is intense public debate about how best to meet the growing electricity needs of our nation. Renewed concerns about energy independence and emerging evidence of the negative effects of climate change are increasing government and private sector interest in developing alternative electric generation sources. Traditional fossil fuel based technologies, especially coal, have faced scrutiny over greenhouse gas emissions and other environmental impacts. The prices of major commodities have fluctuated dramatically over the last five years, resulting in wild swings in energy prices.

Emerging renewable technologies are providing an opportunity to rethink our approach to electric generation. One of the most promising is solar photovoltaics (PV). PV has the potential to solve many of the supply, environmental, and pricing problems that existing technologies face. The cost of PV has dropped dramatically over the last 30 years and is within reach of the cost of traditional electric generation. However, there are key manufacturing and engineering obstacles that are limiting cost reductions. Potential manufacturing innovations geared to overcome these obstacles are not being funded by the private sector or government. This funding gap exists between basic research and prototype-stage development. This paper focuses on the national benefits and technical challenges of making PV a viable electricity source, and the critical need for government support for pre-prototype research and development.

The Current State of Electric Generation and Transmission

The US has approximately 1 TW of installed electric generating capacity of different fuel types to meet existing electricity demand. The dominant technology is coal which represents 49% of net electric generation. Coal is followed by natural gas with 21%, which includes both combined cycle and single-cycle turbine technologies. Nuclear plants represent 19% of net electric generation, followed by hydroelectric power with 6%. Oil generation is less than 2%.[3]





Source: EIA

As electricity demand has grown rapidly over the last fifty years, electricity generation has accounted for greater proportions of total domestic coal and natural gas demand. Coal-based electricity generation now represents 93% of US coal demand, compared to 17% in 1950. Natural gas-based electricity generation represents 30% of US natural gas demand, compared to 11% in 1950.[4] The increased demand electricity generation has placed on fossil-fuel supplies has led to coal and natural gas price increases and supply constraints in the last 10 years. The price of the electricity generated by fossil fuels also tends to rise and fall with the price of the underlying input fuels. The EIA estimates natural gas and coal prices will rise over the next 20 years driving average electricity prices from $0.085/kWh to $0.14/kWh.[5]

Demand for electricity is expected to continue to grow over the coming decades, with the EIA estimating demand increases of 1% per year from 2007-2030. With the retirement of 45GW of installed capacity, the EIA estimates an additional 263GW of new capacity is required by 2030.[6] The amount of new capacity is also highly dependent on the future of the electric car. A wide-scale adoption of the electric car could put increased demands on existing electric infrastructure, which would take years to develop.

If projected capacity increases come from centralized sources (traditional coal, natural gas, nuclear, and large-scale wind) they will strain our electric transmission and distribution network. Transmission and distribution lines are the key link that connects power sources to our homes and businesses. There have been few major investments in transmission in the last 15 years.[7] According to the American Public

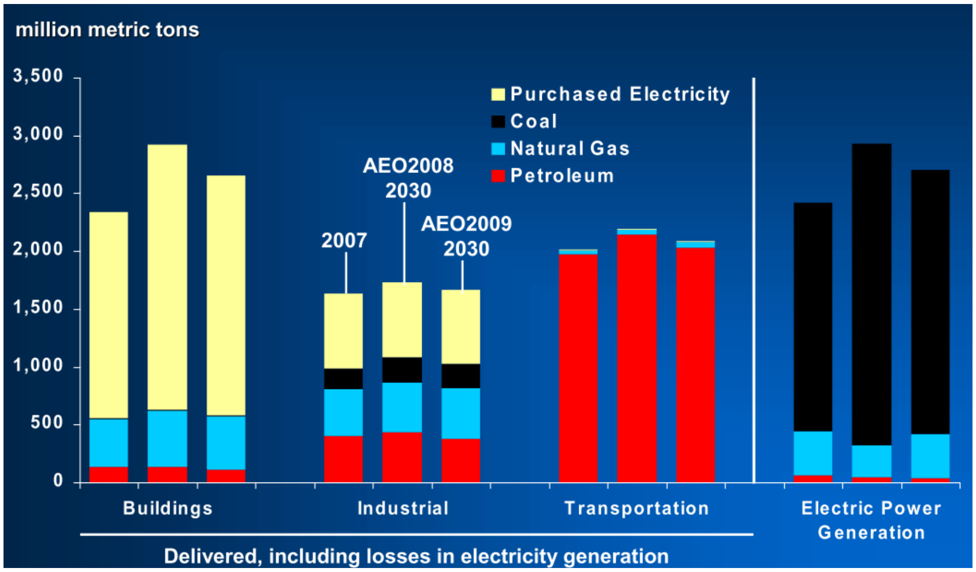
Power Association (APPA), siting is the biggest obstacle for developing new transmission and distribution networks.[8] Transmission and distribution projects often face local opposition as governments and businesses struggle with how to allocate costs.

The US Climate Change Technology Program (CCTP) estimates that over the next decade demand for transmission and distribution will remain dangerously higher than supply. Transmission line miles are projected to increase by 6% by 2012, with demand up by 20%. This means more power will be forced through the same lines, leading to higher system losses and reduced reliability.[9] It is already estimated that transmission system losses average about 7% of total electric generation and that the cost of blackouts exceeds $100 billion per year.[10] New surges in capacity and demand will exacerbate current problems and increase costs.

The Problems with Today's Dominant Technologies

The ideal electric generation technology would be distributed and produce renewable, clean, reliable electricity at a low, stable price. Most of the traditional electric generation technologies (coal, natural gas, nuclear, oil) fall decidedly short of this ideal. Traditional generation technologies also have complex supply chains that require years to decades to develop and high capital costs. Supply chain development requires extensive coordination to build the natural gas wells, pipelines, or coal railcars needed for each new MW added. Often new sources depend on foreign supplies; such is the case with natural gas which relies on imports to satisfy 16% of total demand.[11] Over 98% of existing generation also originates from centralized sources, requiring complex transmission and distribution networks. Unless distributed generation technologies, such as PV, gain broader traction each new MW of capacity added with traditional technologies will require either greater investment in transmission and distribution or greater system losses and reliability issues.

United States CO_2 Emissions



Source: EIA

Traditional electric generation technologies, especially coal and natural gas (which make up 70% of US generation), face environmental issues and transmission and distribution constraints. Approximately 40%

of US CO_2, 23% of NO_x, and 67% of SO_x emissions come from existing electricity generation with the bulk from coal plants.[12] Natural gas plants emit about half of the CO_2 emissions per kWh as compared to coal plants, but natural gas generation is still responsible for approximately 500 million metric tons of CO_2 emissions per year.[13] Nuclear energy, which generates 19% of our electricity, has historically faced strong opposition. There is renewed interest in nuclear energy, but waste disposal continues to be a major obstacle. Proliferation concerns, lengthy licensure processes, and supply chain bottlenecks add to the large-scale implementation struggles of nuclear energy. There has not been a construction permit issued to build a nuclear plant since 1979.[14]

Despite the limitations of natural gas generation, fuel switching to natural gas is already underway to meet growing electricity demand.[15] Natural gas has emerged as the favored technology due to its superior environmental and capital requirement characteristics relative to coal and nuclear. Natural gas has shorter construction times than coal and nuclear (3 years versus 4-5 years for coal and 6-7 for nuclear) and 50% of the CO_2 emissions as coal.[16] Clean coal technologies, in comparison, are still far from commercialization and present their own challenges.[17] Carbon capture and sequestration equipment could absorb up to 10-50% of installed capacity, which would require the installation of an additional 320,000MW of capacity at existing coal plants to meet parasitic losses associated with CO_2 capture and compression systems. Clean coal technologies would also have higher forced outage rates and require the development of substantial non-electric infrastructure such as advanced communications, coal gasification, pipelines, and storage facilities.[18]

The shift towards natural gas generation, however, is not a long-term solution. Natural gas still emits significant amounts of greenhouse gases and faces some of the same supply and price stability issues of other fossil fuels. The EIA also projects that the cost to build and operate a natural gas plant will *increase* over the next 20 years. According to the National American Electric Reliability Council (NERC) this “dash to gas” is the most immediate concern for electric grid reliability.[19] NERC’s concern highlights the challenge of coordinating all stakeholders to efficiently develop centralized generation sources. There remains a real opportunity to develop and commercialize new distributed technologies that have greater economic, environmental, and social benefits than those offered by natural gas.

Natural Gas and Coal Construction and Operating Costs

Costs	2015 Advanced coal	2015 Advanced combined cycle	2030 Advanced coal	2030 Advanced combined cycle
	2006 mills per kilowatthour			
Capital	35.83	13.44	32.91	12.50
Fixed	5.05	1.49	5.05	1.49
Variable	17.93	43.87	17.94	47.41
Incremental Trans.	3.50	3.62	3.54	3.54
Total	**62.31**	**62.42**	**59.44**	**64.94**

Source: EIA

Why PV is Part of the Solution

Past and current administrations have supported the development and deployment of solar technology. In 2006 President Bush announced the Advanced Energy Initiative (AEI) in his State of the Union address to accelerate the technical and cost viability of alternative energy technologies. The AEI focused on the development of nuclear power, clean coal, wind, and solar in an effort to transform the way we power our homes and businesses. The President Bush's 2009 budget included $936 million for research and development in the Energy Efficiency and Renewable Energy (EERE) programs, of which solar claimed $156 million compared to $53 million for wind and $30 million for geothermal. The 2009 budget also included an additional $37 million for basic research on solar.[20] The current administration has built on past efforts and recently enacted the Economic Recovery and Reinvestment Act, which includes numerous provisions to encourage the development of solar power sources, including investment and manufacturing tax credits and federal procurement provisions. President Obama has specifically highlighted the need to focus on solar in numerous public announcements.

Solar power, and PV in particular, holds unique promise to meet our long-term need for renewable, clean electricity. PV shares positive attributes with other renewable energy sources like wind and geothermal: zero emissions generation, reduced waste, lower water use, and price stability. However, PV has specific attributes that make it preferable for long-term development. PV has more resource potential than any other renewable fuel, is not as geographically limited, and has no moving parts. PV has the power to supply all of the energy needs of the US (up to 500GW of rooftop power potential) and virtually eliminate emissions from the power sector.[21] Solar systems can be installed anywhere the sun shines and require less maintenance than all other renewable technologies. The natural supply profile for PV also fits demand load profiles well, with high levels of solar radiation coinciding with peak daily demand.[22] The Union of Concerned Scientists reports that for each 1% of PV generation added natural gas prices would drop 1.4%. This small reduction in natural gas prices would have a wide, beneficial impact on electricity prices to consumers.[23]

One of the most important benefits of PV is the ability to distribute energy generation and thus avoid transmission and distribution costs and system losses. The transmission and distribution infrastructure requires constant capital investment and maintenance. These costs can range from $0.03 to $0.08 per kWh, depending on the region. Distributed generation also minimizes the 7% of electricity lost in transmission.[24] A centralized natural gas plant would have to generate 7% more electricity for the same peak power capacity to compensate for system losses. Finally, distributed generation can also serve as a hedge against power outages and reduce the cost of blackouts. NREL estimates that 500MW of installed PV may be enough to avoid annual blackouts which are estimated to cost $100bn.[25]

Despite the government's support, electric generation from PV and all renewable sources are still only 0.01% and 2.5%, respectively. Since 2000, renewable installations (excluding hydropower) have doubled, reaching 33GW of capacity, the majority of which came from wind. Wind and solar installations have grown the fastest at 45% and 40%, respectively, in 2007.[26] Electricity from biomass, geothermal, and hydropower, in comparison, has remained stable since 2000.[27] The EIA estimates that nonhydro renewable power will represent 33% of generation growth between 2007-2030. The Department of

Energy's (DOE) Solar America Initiative (SAI) has set a goal of PV grid parity by 2015 with 5-10GW of PV installations by 2015 and 70-100GW by 2030.

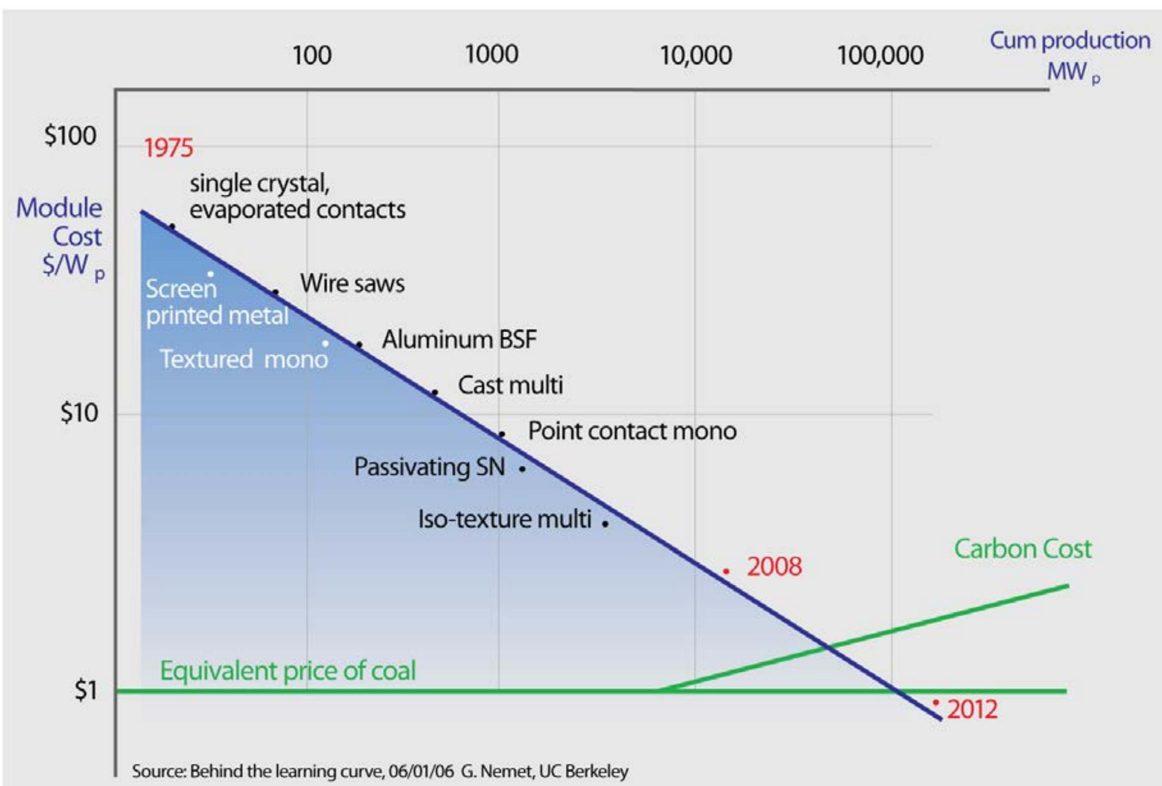
The government has set ambitious goals for PV and renewable deployment, but significant manufacturing and engineering work remains. The amount of PV generation that is installed over the next 20 years is heavily dependent on technological development and cost reductions.

A Roadmap to Bring Down the Cost of PV

Wafer-based silicon solar cells are the dominant PV technology, representing over 90% of manufacturing capacity.[28] The DOE estimates that wafer-based silicon PV will remain dominant for at least the next 10 years until 2017.[29] Wafer-based silicon dominates the PV market because silicon is a safe, scalable feedstock that is well understood after decades of research. As for installations, wafer-based silicon PV panels have proven to be the most reliable and longest lasting of all PV technologies.[30] Any roadmap for wide scale PV adoption must address current manufacturing challenges in wafer-based silicon PV production.

The cost of wafer-based silicon PV has declined dramatically over the last 30 years, from a module manufacturing cost of $100 per watt in the early 1970s to approximately $2 per watt today. For PV to become a viable power source wafer-based silicon PV module manufacturing costs must be brought below $1 per watt, which will allow total system installation prices to reach the SAI's 2030 cost target of $2.5/watt.[31] Scale, and more importantly, innovative manufacturing techniques are critical to reaching these cost targets.

Multicrystalline PV Module Manufacturing Costs

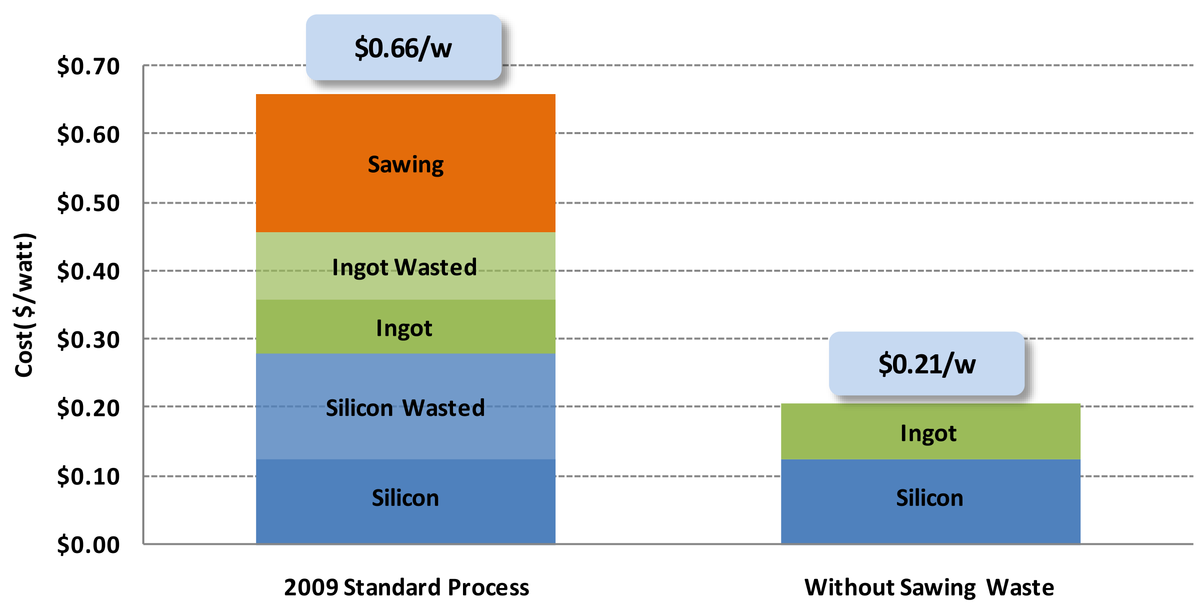


There are key processes in the wafer-based silicon PV supply chain that require innovation and cost reduction to meet national PV cost targets. The wafering process is the most critical. Historically, the cost of the wafer has been the largest of the three components of wafer-based silicon PV manufacturing cost (wafer, cell, module), accounting for over 40% of the total module cost. Over time, all three cost components have come down. However, wafer manufacturing cost has been the slowest to decline, due to the rising cost of silicon and limited innovation in the core crystal growth technology.

Over 98% of the wafers in the world are produced using the "cast" multicrystalline and monocrystalline technologies. These processes were adopted in the 1960s and 1970s as adaptations of techniques designed for the microelectronics industry. They are multi-step processes that require massive amounts of capital and energy. Incredible effort is exerted and cost incurred to generate a wafer with the right purity (part-per-billion levels) and crystal structure, only to waste over 50% of the silicon ingot material as sawdust in the final sawing step. These wafering processes were suitable for the semiconductor industry due to the drive towards compaction and the low cost of wafering as a percentage of the products' end value (<0.005%). In contrast, the cost of the wafer in solar modules is the largest single contributor to up-front capital costs. As long as wafer production incurs the high expense of sawing, and as long as half of the high-value-added silicon is lost as kerf, PV cost goals will be near impossible to achieve.

Conceptually, the bar chart illustrates the benefits of kerfless wafering. A kerfless process saves the $0.45/wafer lost in silicon and ingot wasted and sawing costs. Additionally, and not captured in the bar chart, kerfless wafering removes the waste stream of cutting fluid, grit, used wire saw blades, and silicon dust that sawing generates.

Multicrystalline PV Wafer Manufacturing Costs



Source: Centrotherm, Photon International

In the last 30 years, several companies and institutes have attempted to capture the 50% of silicon that is wasted in ingot sawing by designing direct silicon casting methods. Past attempts at such innovation have tried growing sheets or ribbons of silicon, (e.g., Ribbon Growth on Substrate), but they have had limited success. Companies consistently faced a tradeoff between throughput and quality, often settling for faster processes with lower quality wafers. This history of failed innovation has made raising private funding for new wafering approaches even more challenging.

Despite the historical challenges, a redoubled effort is needed to find ways to redesign the costly wafering process. Major manufacturing breakthroughs, not incremental process changes, are essential. Many of these key solar technologies remain stranded in the “valley of death,” too risky for private markets, too focused for basic research, and too early-stage for government commercialization programs. A coordinated effort between private enterprise and the government is needed to address this funding gap and overcome the technical and cost hurdles of wafering so that affordable PV can become a reality.

The Need for Increased Government Funding

The payoff of a kerfless process for manufacturing silicon PV wafers is potentially huge. With wafer costs cut by over 50%, incremental improvements in other aspects of cell and module technologies can bring solar to parity with existing sources. At grid parity the landscape of electricity production and usage in the US will be transformed, with clean power being generated at (or near) the point of consumption across the nation. However, the cost of going from laboratory setting to pilot production is large. This cost is driven by the extreme purity requirements (part-per-billion levels) and (for many processes) the high melting point of silicon (1414 C). This combination of a high-risk, high-payoff technology, a high cost of working with PV grade material, and the history of “almost-but-not-quite-successful” kerfless projects, means that private funding is not available to bridge the gap.

On the Federal side, there are two main government funding sources for solar: the Office of Science and the Office of Energy Efficiency and Renewable Energy (EERE) in the Department of Energy. The Office of Science manages “fundamental research programs in basic energy sciences, biological and environmental sciences, and computational science.” The 2009 budget for the Office of Science dedicated $69 million to solar. The EERE’s mission is to “strengthen the United States' energy security, environmental quality, and economic vitality in public-private partnerships.” The 2009 budget for the EERE dedicated $156 million to solar. The key initiative within EERE for solar is the SAI, whose goal is to “make solar electricity from photovoltaics (PV) cost-competitive with conventional forms of electricity from the utility grid by 2015.” The SAI has a series of programs that offer contracts and grants to help fund research and development. Three of the main programs are the SAI PV Incubator, the SAI PV Pre-Incubator, and the PV Supply Chain and Cross-Cutting Technologies.

None of the existing government programs bridge the “valley of death” that early-stage, major manufacturing innovations face. The current Office of Science programs focus on basic research proposals. The SAI programs either focus on later stage technologies or offer inadequate funding for earlier stage manufacturing innovations. The SAI PV Incubator’s objective is to “explore the commercial potential of new manufacturing processes.” The PV Supply Chain and Cross-Cutting Technologies objective is to “accelerate the development of unique products or processes with the potential to have a large impact on industry.” Both of these programs offer contracts of up to $3 million, but they target developed technologies, not higher risk, proof-of-concept technologies. The SAI Pre-Incubator is the only program that has a mandate to target these types of technologies, but it is underfunded. The SAI Pre-Incubator’s objective is to “accelerate the development of innovative PV module related concepts to the prototype stage of technology development.” The mission is noble, but the funding only amounts to

$500,000 over 12 months. This level of funding is wholly inadequate to spur the development of innovative, risky, technologies in such a capital-intensive area as manufacturing.

There are at least 5 US companies we are aware of that are pursuing new wafering processes. The problems of wafering are a well known throughout the industry and are the topic of frequent conversation. If a new program dedicated to solving this manufacturing problem were established there would be a high level of industry interest, from both startups and established players. The development of a wafering solution in the US would also be a boon for US manufacturing and solar industry competitiveness. In the last 10 years, the PV market has been led by German and Japanese companies that benefited from local government support. Supporting key innovations in solar would allow the US to reclaim its technological and manufacturing leadership in the solar industry and pave the way for sustained job creation and economic growth in a critical industry of national interest.

Desired Outcome

On its home page (http://www.nist.gov/tip/), the NIST clearly states the goals of TIP.

> *The Technology Innovation Program (TIP) supports, promotes, and accelerates innovation in the United States through high-risk, high-reward research in areas of critical national need. TIP has the agility and flexibility to make targeted investments in transformational R&D that will ensure our Nation's future through sustained technological leadership.*

We have demonstrated that there is a critical national need for cost-competitive manufacture of photovoltaic energy systems in the United States. Furthermore, we have shown that there is a single technology innovation, kerfless silicon wafers, which can transform PV from a niche source of electricity to a major source of electricity for the country. A TIP program targeting the creation of manufacturing processes for kerfless silicon wafers is exactly the type of high-risk, high-reward research Congress envisioned in creating the program. We urge NIST to create such a program under its TIP.

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[1] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Review 2007.* Retrieved March 1, 2009 from http://www.eia.doe.gov/aer/

[2] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Outlook 2009, Early Release.* Retrieved March 3, 2009 from http://www.eia.doe.gov/oiaf/aeo/

[3] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Review 2007.* Retrieved March 1, 2009 from http://www.eia.doe.gov/aer/

[4] Ibid.

[5] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Outlook 2009, Early Release.* Retrieved March 3, 2009 from http://www.eia.doe.gov/oiaf/aeo/

[6] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Review 2007.* Retrieved March 1, 2009 from http://www.eia.doe.gov/aer/

[7] US Climate Change Technology Program. (2006). *Strategic Plan.* Retrieved March 1, 2009 from http://www.climatetechnology.gov/stratplan/final/index.htm

[8] American Public Power Association. (2009). *Electric Transmission*. http://www.appanet.org/utility/index.cfm?ItemNumber=13707

[9] Grover, S. (2007). National Renewable Energy Lab. *Energy, Economic, and Environmental Benefits of the Solar America Initiative.* Retrieved March 1, 2009 from http://www.nrel.gov/analysis/news_archive2007.html

[10] Ibid.
[11] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Outlook 2009, Early Release.* Retrieved March 3, 2009 from http://www.eia.doe.gov/oiaf/aeo/
[12] Grover, S. (2007). National Renewable Energy Lab. *Energy, Economic, and Environmental Benefits of the Solar America Initiative.* Retrieved March 1, 2009 from http://www.nrel.gov/analysis/news_archive2007.html
[13] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Outlook 2009, Early Release.* Retrieved March 3, 2009 from http://www.eia.doe.gov/oiaf/aeo/
[14] Energy Information Administration, U.S. Department of Energy. (2008). *Annual Energy Review 2007.* Retrieved March 1, 2009 from http://www.eia.doe.gov/aer/
[15] North American Electric Reliability Corporation. (2008). *Special Report: Reliability Impacts of Climate Change Initiatives*. Retrieved from http://www.nerc.com/elibrary.php
[16] Energy Information Administration, U.S. Department of Energy. (2008).*Electricity Market Module*. Retrieved March 1, 2009 from http://www.eia.doe.gov/fuelelectric.html
[17] North American Electric Reliability Corporation. (2008). *Special Report: Reliability Impacts of Climate Change Initiatives*. Retrieved from http://www.nerc.com/elibrary.php
[18] Ibid.
[19] Ibid.
[20] Office of Science and Technology Policy. (2008). *Advanced Energy Initiative: Research and Development in the President's 2009 Budget.* Retrieved March 1, 2009 from http://www.ostp.gov/cs/initiatives/advanced_energy
[21] Denholm, P., and Margolis, R. (2006). National Renewable Energy Lab. Very Large-Scale Deployment Grid-Connected Solar Photovoltaics in The United States: Challenges and Opportunities*.* Retrieved March 1, 2009 from http://www.nrel.gov/pv/publications.html
[22] Ibid.
[23] Ibid.
[24] Ibid.
[25] Ibid.
[26] U.S. Department of Energy. (2008). *Renewable Energy Data Book*. Retrieved March 1, 2009 from http://www1.eere.energy.gov/maps_data/renewable_energy.html
[27] Ibid.
[28] "The Q Factor, Sharp and the Market; Cell Technology Shares (%)." *Photon International*, March 2008.
[29] U.S. Department of Energy. (2007). *National Solar Technology Roadmap: Wafer-Silicon PV*. Retrieved March 1, 2009 from http://www.nrel.gov/pv/publications.html
[30] Ibid.
[31] Grover, S. (2007). National Renewable Energy Lab. *Energy, Economic, and Environmental Benefits of the Solar America Initiative.* Retrieved March 1, 2009 from http://www.nrel.gov/analysis/news_archive2007.html