SOLAR ELECTRICITY: PROBLEM, CONSTRAINTS AND SOLUTIONS

The United States generates over 4,110 TWh of electricity each year, costing $400 billion and emitting 2.5 billion metric tons of carbon dioxide (Yildiz, 2010). Additionally, the United States' total electricity consumption has increased annually by an average of one percent over the past ten years (U.S. Total Electricity Consumption, 2010). This presents a major problem for the United States since the majority of electricity generation is based on polluting and nonrenewable fossil fuels. (Electricity in the United States, 2010) As the prices and environmental impacts of fossil fuels increase, it will become impractical to maintain our current electricity generation scheme.

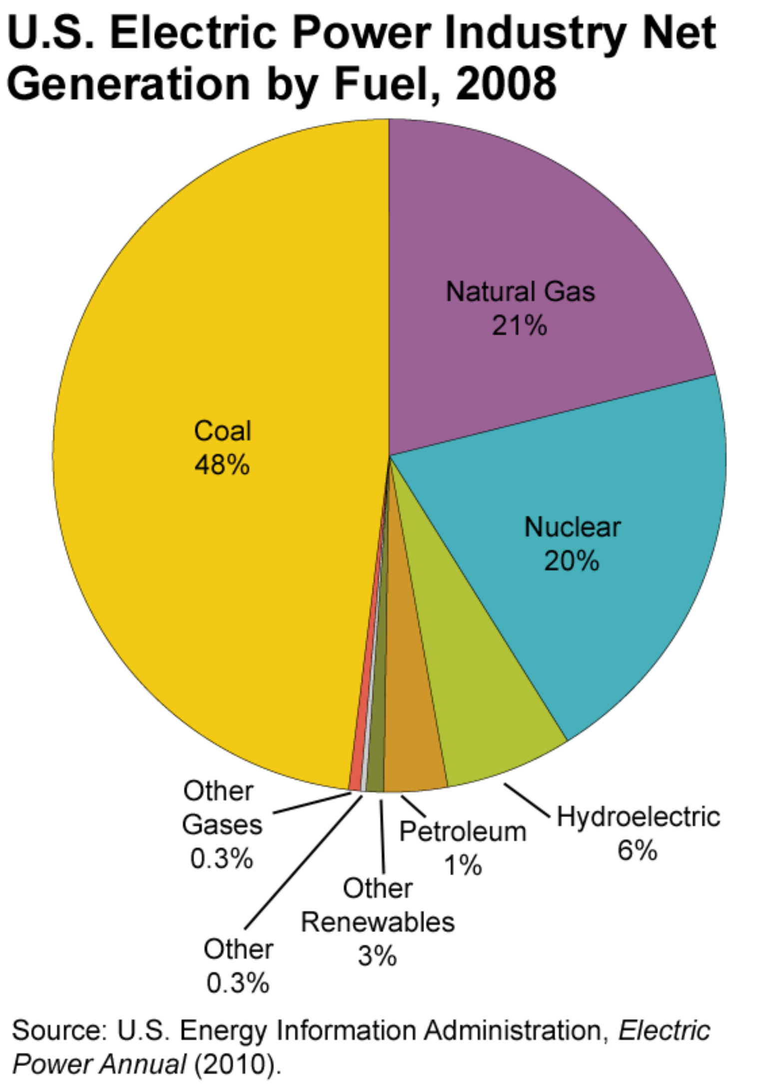

Figure I.1: The chart above depicts the various types of energy sources used for electricity generation and their shares of the U.S. power industry.

Solar photovoltaics present a unique opportunity to alleviate the United States' energy problem. Once solar cells are manufactured, they produce no waste emissions and utilize the abundant produced by the sun. Current crystalline silicon cells take about four years to collect enough energy payback, while newer thin film cells will be able to reduce the energy payback period to a year or less (Learning About PV: The Myths of Solar Electricity, 2008). After this payback period, solar cells become net positive energy generators and can offset the pollution and carbon emissions produced by fossil fuels. Photovoltaic cells also can reduce transmission losses through local power generation. Installing solar cells on rooftops puts electricity generation right next to consumers, as opposed to centralized power plants that must transmit electricity over long distances. The problem that we face is how to properly implement solar energy in the United States in a way that minimizes costs and promotes sustainable growth in the future. In our solution, we determined that grid-scale power generation will rely on Cadmium Telluride thin-film panels, while local power generation will rely on amorphous silicon panels.

In 2008, solar power's summer capacity is only 536 MW, less than 0.1% of the United States' 752,420 MW peak load. (Existing Net Summer Capacity of Other Renewables by Producer Type, 2010) The net generation for solar power in 2008 was 0.843 TWh, much less than 0.1% of the total electricity generated in the U.S. (Total Renewable Net Generation by Energy Source and State, 2009) However, the U.S. photovoltaics industry has been growing by an average cumulative growth rate of 35% per year. (Learning About PV: The Myths of Solar Electricity, 2008) If the industry maintains this growth and manages to cater to the domestic market, solar can become an important player in U.S. electricity generation.

The principle behind solar photovoltaics is actually quite elegant. The core of every PV panel is a simple p-n semiconductor junction. Incident photons from sunlight excite electrons in the p-type semiconductor and cause them to migrate across the junction, creating a net voltage and current. For typical silicon wafer panels, these p-n junctions are created by diffusing subvalent and supervalent atomic elements into the bulk material. The result is a solid-state power generating device with no moving parts.

Diagram of a photovoltaic cell removed due to copyright restrictions.

Figure I.2: A diagram of a typical silicon photovoltaic cell. (Harris, 2008)

Factors such as the band gap of the semiconductor, carrier lifetime, semiconductor thickness and texture, and the anti-reflective (AR) coating affect the efficiency of photovoltaic cells. The band gap of the semiconductors used determines the wavelengths of light that the cell can absorb. Incident photons must have energies greater than the band gap of the material, or it cannot excite electron carriers. Silicon has a band gap of approximately 1.1 eV, allowing it to absorb much of the solar spectrum. However, certain semiconductors like Cadmium Telluride have slightly higher band gaps that allow them to utilize more of the energy from solar radiation. These higher band gap materials absorb more energy per electron carrier at shorter wavelengths than silicon, which would dissipate this energy as heat. More advanced and expensive solar panels use several p-n junctions to more efficiently capture energy at different wavelengths. Next, carrier lifetime plays an important role in efficiency. Carrier lifetimes must be long enough for charge carriers to migrate across the semi-conductor and produce current. In single crystalline silicon wafer cells, carrier lifetimes are relatively high because of the purity of the material. The lower purities and enhanced surface effects of thin-film cells lower carrier lifetimes. Nonetheless, this is balanced by the thinness of the semiconductor, which allows carriers with shorter lifetimes to cross the material. The last three factors, thickness, texture, and AR coating allow solar panels to absorb more light. A thicker material provides a longer path length for light, providing more absorption of photons. Texture diffracts light at oblique angles through the semiconductor, increasing path length. AR coatings utilize destructive interference to prevent light from reflecting on the surface of the solar panel. Finally, new advances in distributed Bragg reflectors (DBR) and diffraction gratings will contribute to cell efficiencies. DBR coatings can be placed underneath semiconductor material to reflect unabsorbed light back into the panel, while diffraction gratings bend light to increase path lengths.

There is a myriad of technologies for photovoltaics, ranging from the ubiquitous crystalline silicon wafer to thin-film Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) panels. In general, thin-film photovoltaics are cheaper than wafer silicon, but wafer silicon is more efficient. As stated previously, multi-junction panels are more efficient, but cost much more. Solar panels must be relatively efficient in order to reduce land requirements and installation costs. However, since there is much available land area in brown fields (Learning About PV: The Myths of Solar Electricity, 2008) and on rooftops, the costs of cell production mostly needs to be compared to the installation costs.

Projected Costs for Thin Film Cells

2016 projections										
	Existing technology (Deutsche Bank)				With grating + DBR					
Technology	Efficiency	Installation cost per Watt	Module cost per Watt	System cost per Watt (1MW)	Efficiency improvement	Change in installation cost per Watt	Change in material cost per Watt	Change in capitol cost per Watt	Change in system cost per Watt	New system cost per Watt (1MW)
Organics	7%	$2.80	$0.60	$3.40	4%	($0.81)	$0.01	$0.10	($0.70)	$2.70
a-Si	9.1%	$2.08	$1.08	$3.16	2%	($0.35)	$0.01	$0.10	($0.24)	$2.92
CdTe	12.2%	$2.03	$0.71	$2.74	0%	$0.00	$0.01	$0.10	$0.11	$2.85
CIGS	13.2%	$1.99	$0.81	$2.80	0%	$0.00	$0.01	$0.10	$0.11	$2.91
thin film c-Si	13.0%	$1.99	$1.00	$2.99	1%	($0.12)	$0.01	$0.10	($0.01)	$2.98
p-Si	14.0%	$1.89	$1.00	$2.89	0%	$0.00	($0.15)	$0.10	($0.05)	$2.84
c-Si	15.4%	$1.78	$1.31	$3.09	-1%	$0.11	($0.31)	$0.10	($0.10)	$2.99

Numbers in green are taken from either Prometheus or Deutsche Bank as indicated
Numbers in light green are estimates by Thin Film Si Team
Numbers in blue are estimates by Thin Film Si Team
Numbers in black are calculated values

Figure I.3: The table above lists the costs for different thin film PV technologies in 2016 with and without grating/DBR enhancements. (Data taken from the 2008 Harvard-MIT iteams report on High Efficiency thin film solar cells)

As seen above, thin-film cells (organics, a-Si, CdTe, CIGS, and thin film c-Si) are the leaders in terms of both module production costs and total system costs. The reason why thin-film solar cells can be so cheap lies in their manufacturing platform. Most thin-film solar panel production can be automated. Amorphous silicon and Cadmium Telluride panels are manufactured by deposition of semiconductor material on substrates, while new CIGS systems can use open-air printing. (Harris, 2008) Manufacturers can also deposit transparent conductive oxide layers on top of the semiconductor material as an electrical contact. In contrast, traditional wafer silicon panels contain many components that must be hand assembled by workers. For our plan of solar panel deployment, CdTe will provide grid-scale power generation because of its relative cheapness, while thin film amorphous silicon (a-Si) will provide local rooftop generation because of the abundance of raw material and its nontoxicity.

One of the major issues for photovoltaics is that PV panels cannot produce power at night. Without energy storage or back-up generators, the United States cannot completely rely on solar photovoltaics for electricity generation. In order to determine the right application for solar energy, one must look at the electricity demands of the U.S. over a typical day. Below is a graph of the electricity consumption for New York City on April 18, 2010. (NYISO Hourly Loads, 2010)

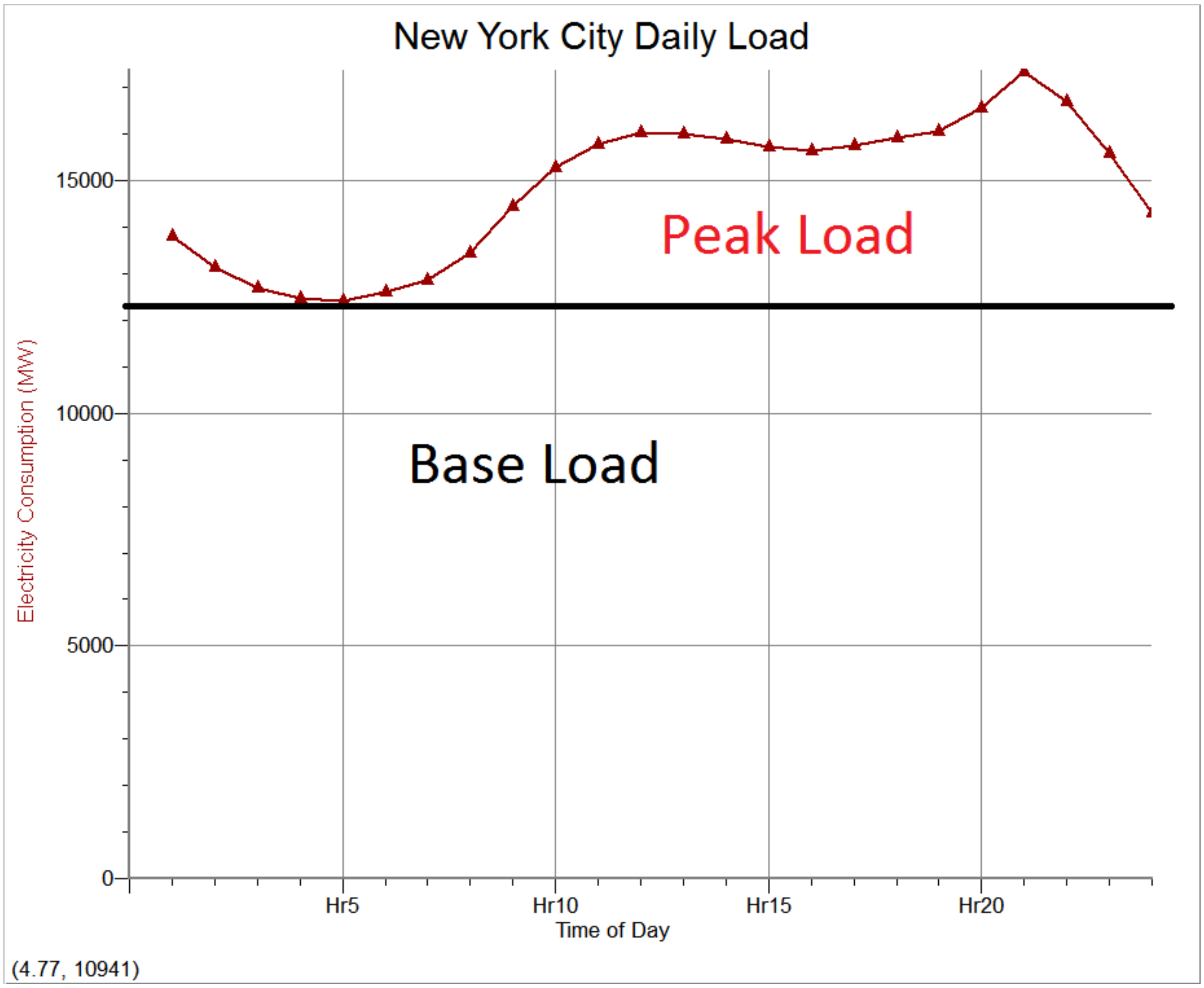

Figure I.4: Electricity consumption in NYC on 4/18/2010. There is a peak load of about 17 GW and a base load of 12 GW. (NYISO Hourly Loads, 2010)

In our current power generation scheme, cheaper static generators like coal-fired power plants, nuclear plants and hydropower dams handle the base load, while expensive and dynamic natural gas turbines address the peak load. Solar panels can work in conjunction with natural gas turbines to provide electricity to satisfy peak load demands. Looking at load data from California and Texas (see Appendix), the difference between the peak load and base load ranges from 22% to 36% of the maximum load. For simplicity, let us assume that we should install enough solar panels to make up 30% of our peak capacity for the United States. This would enable us to level peak loads during the day. We should not aim for a higher deployment percentage because then solar generation would cut into the base load. The static-generators used for the base load are cheaper than solar generation and cannot be easily varied (for example, it takes several days for a coal power plant to ramp up to full production from a cold start).

In order to calculate the total amount of energy generated, we should take 30% of the 752 GW peak capacity of the United States. (Yildiz, 2010) This gives 225.6 GW capacity. Multiplying this by 5 (the average daily insolation for much of the United States in kWh/day/m^2, essentially

Map of U.S. solar resource removed due to copyright restrictions.

Figure I.5: A map of the average daily insolation throughout the United States. (Source: National Renewable Energy Laboratory, 10/20/2008)

the normalized number of hours of maximum incident sunlight per day) and 365 days gives 411.720 TWh. Since the total electricity usage in the U.S. was 4,110 TWh in 2008, solar panels would generate approximately 10% of the total electric energy needs of the U.S if we deploy enough panels to provide 30% of our peak capacity.

The question then becomes: when will solar cell production reach our target capacity? For simplicity, let us ignore the use of amorphous silicon for local generation and concentrate on CdTe grid power since CdTe is the more dominant technology. First Solar is the largest manufacturer of CdTe photovoltaic panels in the United States.

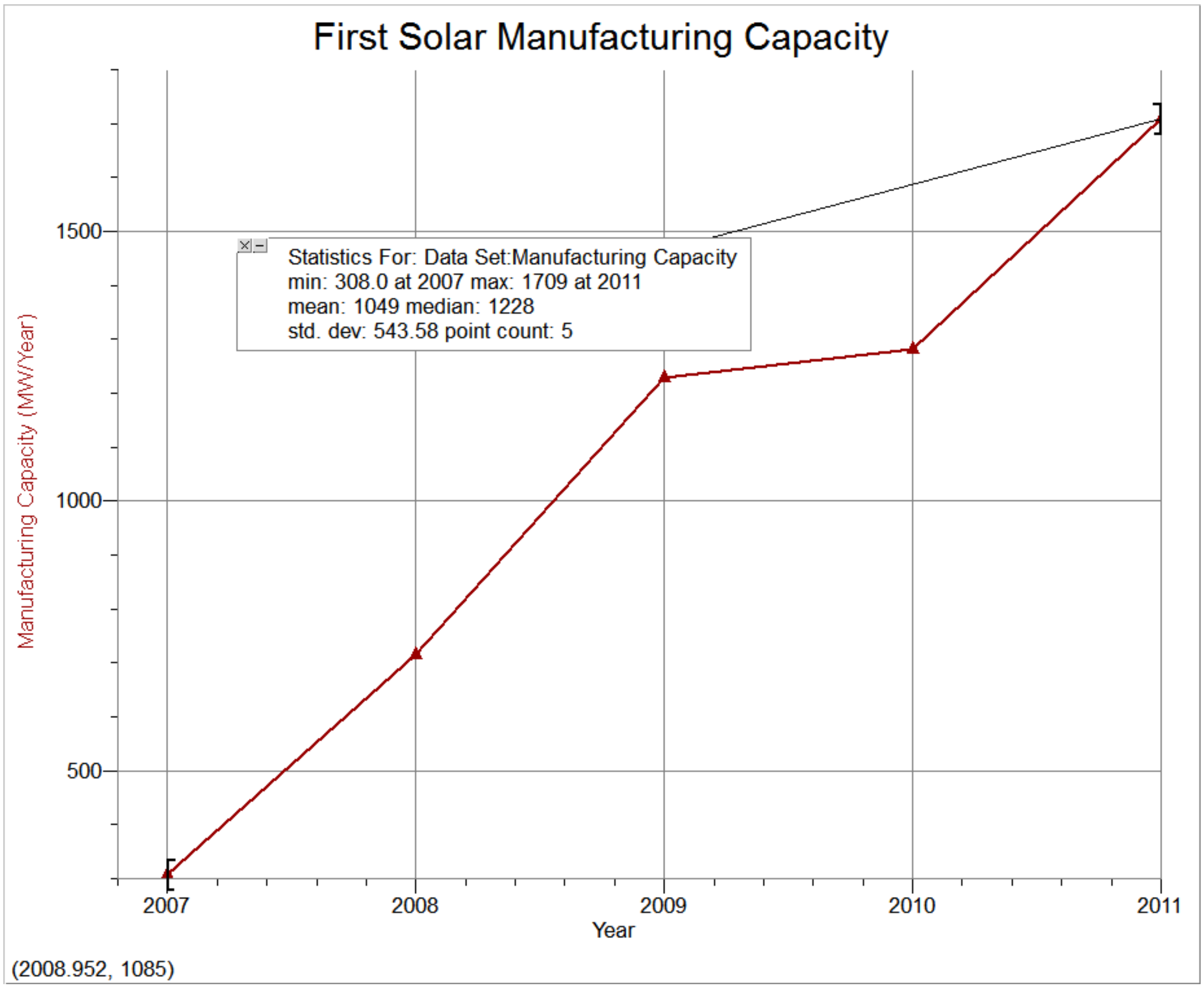

Figure I.6: A graph of First Solar's current manufacturing capacity in MW of panels produced per year. (Fast Facts: Company Overview, 2010)

First Solar projects that it will reach 1,709 MW of solar panels produced per year by 2011. Taking the average of its growth rate over the past 5 years, its manufacturing capacity has increased by 60.4% per year. If we integrate this production over time, we will get the total accumulated capacity.

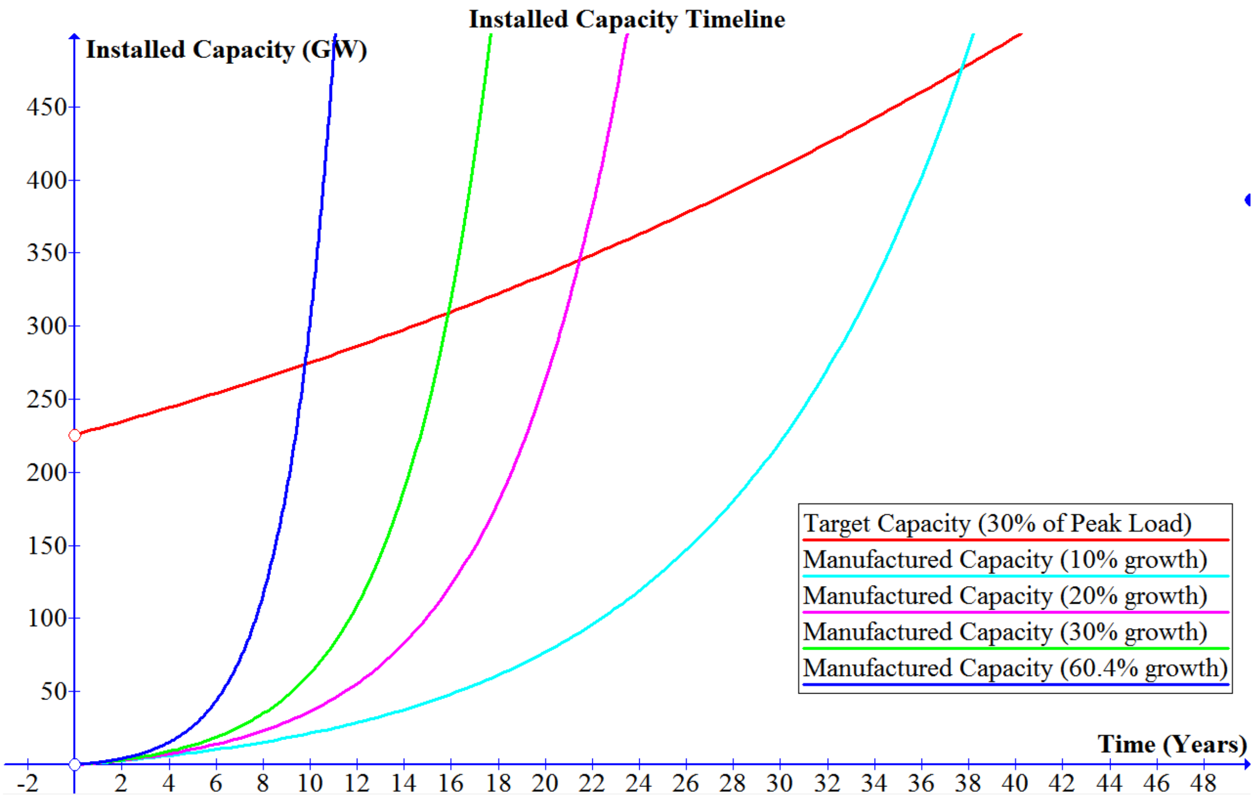

Figure I.7: A graph of the projected installed capacity compared to the 30% peak load target capacity. The current growth rate (60.4%) projects that we will meet our target capacity within 8 years, while an extremely conservative 10% growth rate will still reach the target capacity within 40 years.

We assumed a higher-than-average growth rate of 2% to make a conservative estimate of target achievement times. The plots above show that in a perfect exponential growth scenario, CdTe will be able to achieve the target capacity in ten years with 60.4% growth and sixteen years with a more conservative 30% growth rate. In reality, it should take longer to reach the target capacity for several reasons. First, amorphous silicon, our standard for local generation, makes up a much smaller market share than cadmium telluride and will take longer to grow and help reach our target. Next, cadmium tellurium may become more expensive in the future due to materials scarcity and improving efficiencies of other technologies. Finally, while there is a large solar photovoltaic industry in the United States, much of the panels produced are exported out of the country. This will slow the deployment of solar panels in the United States unless it becomes more profitable for manufacturers to cater to a domestic market. Factors that affect this profitability include consumer acceptance and demand for solar panels, as well as government subsidies and incentives to increase U.S. purchase of panels. Nonetheless, as fossil fuel costs increase due to scarcity and solar panel costs decrease due to learning curves, solar will become more attractive to U.S. consumers and will become an important part of U.S. energy generation.

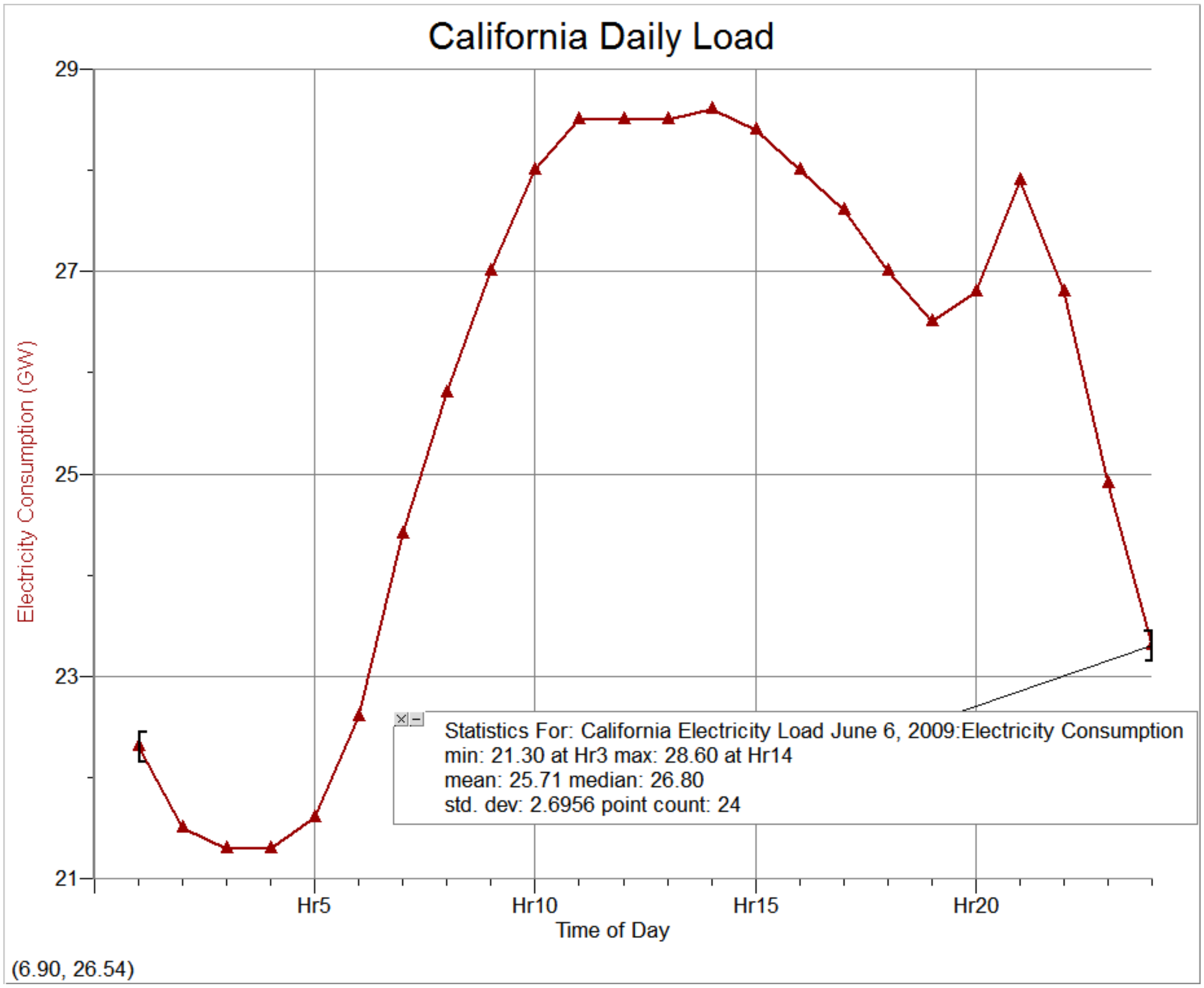

Figure I.8: Electricity consumption in California on 6/6/2009. (California ISO, 2010)

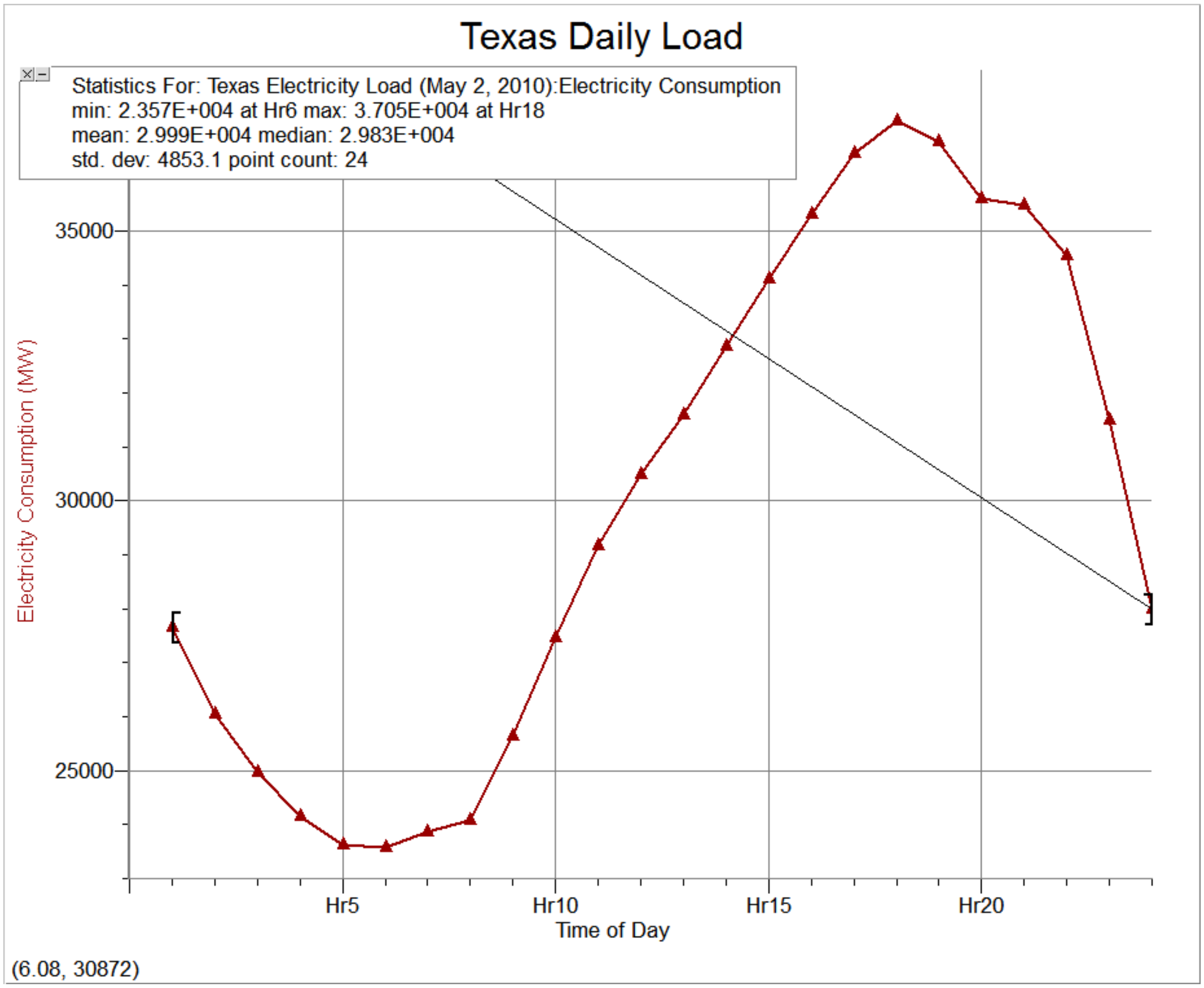

Figure I.9: Electricity consumption in Texas on 5/2/2010. (Historical Load by Area, 2010) Texas's load peaks at night, presumably because of high air conditioning usage as people return home from work. In this case, solar thermal concentrators might be a better solution for grid generation, because they can store and continue to produce electricity for a few hours after sundown.

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