The Advantages of "Floatovoltaics" Over Land-Based Solar Power

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I. Introduction

As the United States seeks to curb its CO_2 emissions using renewable sources of energy, solar power has emerged as a promising alternative to burning fossil fuels. Electricity generation by solar power does not emit any CO_2. However, the sun does not deliver concentrated packets of energy to focused points on the Earth. Thus, a large surface area of solar collectors is required for energy to be effectively collected and converted into electricity. However, there is only a finite amount of land, and opponents of solar power may argue that land could be better used for something other than solar energy collection. To avoid using land, systems of water-based solar panels, also known as "floatovoltaics," have been installed in various countries, including the United States. In this paper, I will show how floatovoltaics are superior to current conventional solar power systems.

II. Current State of Solar Energy

There are two forms of solar energy: thermal and photovoltaic. Thermal solar power can be used for heat as well as generating electricity. Thermal solar works by collecting energy from the sun through solar panels, and then transferring that energy to a heat-absorbing fluid. In a thermal solar heating system, this fluid is then circulated throughout the area that is to be heated (building, swimming pool, etc.). To generate electricity, this fluid is circulated through pipes to transfer its heat to water. The heat converts the water into a pressurized steam, which is fed through a steam turbine and generator to generate electricity.[1] Unlike thermal solar, photovoltaic solar is strictly used for electricity generation. By definition, a photovoltaic cell converts sunlight directly into electricity. When sunlight strikes the cell, the photons from the sunlight will either be absorbed, reflected, or pass right through the cell. The absorbed photons provide energy to dislodge electrons in the cell, which are absorbed by electrical conductors on the cell. The electrons in the cell will generate a direct current (DC). This DC electricity can then be stored in

[1] "Solar Explained: Solar Thermal Collectors." U.S. Energy Information Administration. 2015. http://www.eia.gov/Energyexplained/index.cfm?page=solar_thermal_collectors.

batteries or converted into alternating current (AC) electricity to be distributed through the power grid. This allows photovoltaics to be implemented on a variety of scales, ranging from powering a single appliance to supplying thousands of homes with electricity. As mentioned before, not all of the photons from sunlight are absorbed by photovoltaic cells. In addition, PV cells will not be as effective if they are not constantly facing the sun. This can be countered by solar tracking systems that keep the solar panel pointed directly at the sun throughout the day. However, this increases the price of the photovoltaic system, and is not feasible for consumer use. Thus, most commercially available photovoltaic systems are only 5-15% efficient.[2] While both thermal and

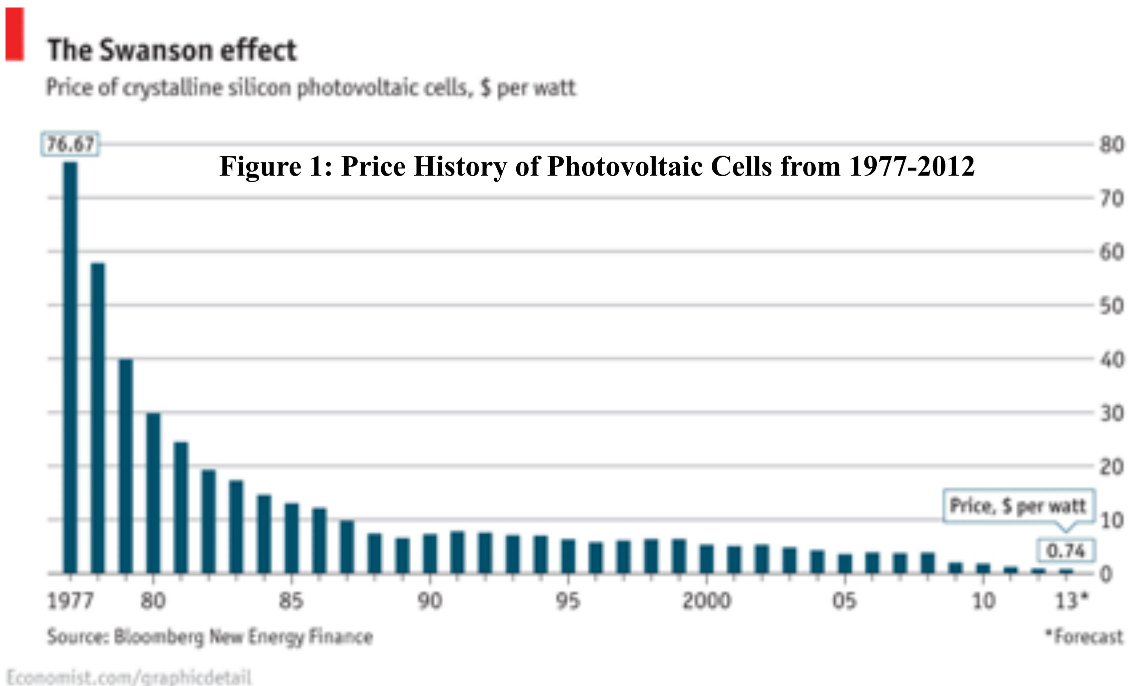

Figure 1: Price History of Photovoltaic Cells from 1977-2012

photovoltaic solar are capable of generating electricity on a large scale, photovoltaic solar makes up a very clear majority of the worldwide solar capacity, accounting for 98% of the electricity generated by solar power. One of the main reasons for photovoltaic solar's dominance is its low price. According to the United States Energy Information Administration (EIA), in 2013, the average levelized cost of a photovoltaic power plant entering service in 2020 was $0.125/kWh, while a thermal power plant cost nearly twice as much. In comparison, the average leveled cost

[2] "Solar Explained: Photovoltaics and Electricity." U.S. Energy Information Administration. 2015. http://www.eia.gov/Energyexplained/index.cfm?page=solar_photovoltaics.

of a conventional coal plant, the cheapest of all energy sources, was $0.095/kWh, that of an advanced combined natural gas plant was $0.072/kWh, and that of an onshore wind farm was $0.074/kWh.[3] The price history of photovoltaics is shown in Figure 1.[4] As seen in Figure 1, the price of photovoltaic cells seems to have dropped exponentially from 1977. The observation of this trend of declining prices was dubbed Swanson's Law. Swanson's Law states that the price of photovoltaic cells drops by 20% with each doubling of manufacturing capacity.[5] Using the EIA levelized cost information and assuming Swanson's Law holds true, quadrupling 2013 global solar power capacity would bring down the price of photovoltaics to $0.080/kWh, which would make photovoltaic solar a competitive alternative to fossil fuels. Note that the EIA does not factor in the externalities of fossil fuels in calculating costs. Since natural gas has only recently become the cheapest fossil fuel, there is little data on its externalities. However, there is data on the externalities of coal, which was the cheapest fossil fuel until 2014. A study by Harvard Medical School found that the total externalities of coal cost between $175 billion per year ($0.09/kWh) and 523 billion per year ($0.27/kWh), with the best estimate costing $345 billion per year ($0.18/kWh).[6] Thus, solar is already a viable alternative to coal in terms of costs, and is likely competitive with natural gas. Increasing 2013 global solar capacity eightfold would drop the price of photovoltaics to $0.064/kWh, making it the cheapest utility scale energy source. While increasing the global solar capacity is no small task, it is certainly possible given the advances photovoltaics have made thus far. Photovoltaic solar presents itself as a competitive renewable energy source for the future. Because photovoltaics are considerably less expensive and used significantly more than thermal solar power systems, I will only focus on photovoltaics for the remainder of this paper.

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[3] "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015." U.S. Energy Information Administration. 2015. https://www.eia.gov/forecasts/aeo/electricity_generation.cfm.

[4] The Economist. "Pricing Sunshine," December 2012. http://www.economist.com/blogs/graphicdetail/2012/12/daily-chart-19.

[5] The Economist. "Pricing Sunshine," December 2012. http://www.economist.com/blogs/graphicdetail/2012/12/daily-chart-19.

[6] Paul R. Epstein. "Full cost accounting for the life cycle of coal" Annals of the New York Academy of Science (2011). Accessed February 29, 2016. <http://www.chgeharvard.org/sites/default/files/epstein_full%20cost%20of%20coal.pdf>

III. Drawbacks of Conventional Solar Power

Although solar power is a relatively clean source of energy, it is still not completely harmless. The manufacturing of photovoltaic cells uses hazardous materials, such as hydrochloric acid and sulfuric acid, to clean and purify the semiconductor surface of the cell. Carbon dioxide is also emitted during the manufacturing, transporting, maintenance, and decommissioning of photovoltaic systems. It is estimated that these emissions equate to 0.07-0.18 lbs/kWh of CO_2 emitted over the life cycle of a photovoltaic system. This is still far less than the life cycle emissions of coal and natural gas, which are 1.4-3.6 lbs CO_2/kWh and 0.6-2 lbs CO_2/kWh, respectively. Both photovoltaic and thermal solar power also require land to

Figure 2

Technology	Direct Area		Total Area	
	Capacity-weighted average land use (acres/MWac)	Generation-weighted average land use (acres/GWh/yr)	Capacity-weighted average land use (acres/MWac)	Generation-weighted average land use (acres/GWh/yr)
Small PV (>1 MW, <20 MW)	5.9	3.1	8.3	4.1
Fixed	5.5	3.2	7.6	4.4
1-axis	6.3	2.9	8.7	3.8
2-axis flat panel	9.4	4.1	13	5.5
2-axis CPV	6.9	2.3	9.1	3.1
Large PV (>20 MW)	7.2	3.1	7.9	3.4
Fixed	5.8	2.8	7.5	3.7
1-axis	9.0	3.5	8.3	3.3
2-axis CPV	6.1	2.0	8.1	2.8
CSP	7.7	2.7	10	3.5
Parabolic trough	6.2	2.5	9.5	3.9
Tower	8.9	2.8	10	3.2
Dish Stirling	2.8	1.5	10	5.3
Linear Fresnel	2.0	1.7	4.7	4.0

house their respective power plants.

> “Unlike wind facilities, there is less opportunity for solar projects to share land with agricultural uses. However, land impacts from utility-scale solar systems can be minimized by siting them at lower-quality locations such as brownfields, abandoned

mining land, or existing transportation and transmission corridors."[7]

While land impacts from solar power systems can be minimized by the methods mentioned above, solar power nevertheless takes up land, and that land cannot be used for other purposes. Figure 2[8] shows the land-use requirements of photovoltaic and thermal solar in the United States. According to the United States Department of Agriculture, the average value of farm real estate was $3,020 per acre in 2015.[9] If we assume that a small photovoltaic plant is built on land of value equal to that of farmland, that land alone will cost between $17,818 and $356,360. This cost makes photovoltaic solar a less attractive utility-scale energy source.

IV. "Floatovoltaics" – Water-based Solar Farms

Floatovoltaics are photovoltaic solar panels that float on a stagnant body of water, and they may very well be the answer to the problems that land-based photovoltaics face. Floatovoltaics are placed on the surfaces of wastewater ponds, reservoirs, and sewage treatment pools, as these bodies of water are relatively stagnant and do not hold much aesthetic value. There is no exact price information for leasing bodies of water, but multiple articles on floatovoltaics have stated that the cost of leasing water for solar installations is lower than that of land.[10] Since floatovoltaics also require waterproofing as well as an apparatus on which the solar panels will float, I will assume that this cost combined with the cost of leasing the body of water is equal to that of leasing the same amount of land for a solar farm. At the bare minimum, floatovoltaics solve the problem of taking up land that could be used for non-solar power purposes. The first floatovolatic system at the Far Niente winery in Napa Valley, California, allowed the winery to save more than 3/4 of an acre of vines. This equates to $150,000/year in

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[7] "Environmental Impacts of Solar Power." Union of Concerned Scientists. 2013. http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-solar-power.html#bf-toc-0.

[8] Ong, Sean, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath. "Land-Use Requirements for Solar Power Plants in the United States." National Renewable Energy Laboratory. 2013. http://www.nrel.gov/docs/fy13osti/56290.pdf.

[9] "Land Values 2015 Summary." United States Department of Agriculture. 2015. http://www.usda.gov/nass/PUBS/TODAYRPT/land0815.pdf.

[10] "Ahmad, Maheen. "Floatovoltaics - A Solution for Water and Energy Conservation?" Sustainable Energy Coalition. 2016. http://sustainableenergy.org/floatovoltaics-a-solution-for-water-and-energy-conservation/.

bottled wines.[11] Floatovoltaics also assist water conservation and are highly compatible with water utilities. Since solar panels cover the surface of a body of water, they block most of the sunlight that would normally hit the water. This decreases evaporation, allowing more water to be conserved. At the Far Niente winery, the floatovoltaics reduce evaporation by 70%.[12] Blocking sunlight also limits algae growth by preventing algae from photosynthesizing. This can be either positive or negative. If the water contains a species that depends on the algae, this could be harmful, especially if the species is endangered.[13] This will likely not be too big of an issue so long as floatovoltaics are installed in man-made wastewater ponds, reservoirs, and sewage treatment pools. On the other hand, limiting algae growth decreases algae buildup in pipes in water treatment facilities, which in turn decreases the maintenance costs for these facilities. According to the U.S. Environmental Protection Agency,

> "3-4 percent of national electricity consumption, equivalent to approximately 56 billion kWh, or $4 billion, is used in providing drinking water and wastewater services each year."[14]

Having floatovolatics at water treatment reservoirs would allow the treatment plant to use some of the power generated by the floatovoltaic panels, which would help combat this high cost of water treatment. Floating solar panels on water will allow the panels to stay cooler than land-based solar panels. Heat absorbed by the panels will be transferred to the water below, allowing the panels to stay relatively cool. The electrons in a cool solar panel will be less excited than those in a warm solar panel. Therefore, there will be a larger potential difference between the sun's rays and the cooler solar panel than there will be between the sun's ray and the warmer

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[11] "Floatovoltaics." Solar Outreach Partnership. 2015. http://solaroutreach.org/2015/02/23/floatovoltaics/#.Vx2kvmNhiVg.

[12] Ahmad, Maheen. "Floatovoltaics - A Solution for Water and Energy Conservation?" Sustainable Energy Coalition. 2016. http://sustainableenergy.org/floatovoltaics-a-solution-for-water-and-energy-conservation/.

[13] "Solar Panels Floating on Water Will Power Japan's Homes." National Geographic. 2015. http://news.nationalgeographic.com/news/energy/2015/01/150116-floating-solar-power-japan-yamakura/.

[14] "The Energy-Water Nexus: State and Local Roles in Efficiency & Water and Wastewater Treatment Plants." U.S. Department of Energy. 2013. http://energy.gov/sites/prod/files/2014/05/f15/energy_water_nexus_roles_effic_water_wastewater_treat_plants.pdf.

solar panel. As a result, the cooler panel will generate more power.[15] This increased efficiency brings down the price per kWh of floatovoltaics. Floatovoltaics trump conventional land-based photovoltaics in land use and efficiency, and they have additional benefits in conserving water and keeping it clean.

V. Cost Comparison of Floatovoltaics and Land-Based Photovoltaics

I will be comparing a 12.5 MW floatovoltaic solar farm with a land-based solar farm of equivalent capacity. For my calculations of the costs of a floatovoltaic solar farm, I will use the reported costs of an installation that is scheduled to come online in 2016 in Sonoma County, California, pictured in Figure 3.[16].The reported cost of leasing the ponds is $30,000/year.[17] The land-based equivalent of the Sonoma County floatovoltaic installation will be a fixed, 12.5 MW

Figure 3

[15] "Does Temperature Affect the Amount of Energy a Solar Panel Receives?" UCSB ScienceLinen.d. http://scienceline.ucsb.edu/getkey.php?key=2668.

[16] Pyper, Julia. "Sonoma County Is Building the Largest Floating Solar Project in the US." Greentech Media. 2015. http://www.greentechmedia.com/articles/read/sonoma-county-to-build-the-largest-floating-solar-project-in-the-us.

[17] "Ahmad, Maheen. "Floatovoltaics - A Solution for Water and Energy Conservation?" Sustainable Energy Coalition. 2016. http://sustainableenergy.org/floatovoltaics-a-solution-for-water-and-energy-conservation/.

photovoltaic solar farm. Based on the data in Figure 2, a 12.5 MW solar farm will take up a total area of 95 acres of land. According to the average cost of leasing land in 2015 in California was \$329/acre.[18] Thus, the land-based photovoltaic farm will cost \$31,255/year. Most manufacturers of photovoltaics offer a 25-year standard solar panel warranty, meaning that the power output of a solar panel should not be less than 80% of rated power after 25 years.[19] I will assume that both the floatovoltaic and land-based plants will operate at peak capacity for 25 years. The cost of leasing space will then amount to \$0.274/kWh for floatovoltaics and \$0.285/kWh for land-based photovoltaics. Floatovoltaics are cheaper by 1 cent/kWh in terms of land costs alone. If we account for the increased efficiency of floatovoltaics over land-based solar, we find that the price gap increases. According to a 2013 study, floatovoltaics are 8-10% more efficient than land-based photovoltaics.[20] If we assume that the floatovoltaic installation operates at full capacity for 25 years while the land-based solar farm operates at 90% capacity, we find that the the cost of leasing space will be \$0.274/kWh for floatovoltaics and \$0.317/kWh for land-based photovoltaics. Floatovoltaics have a 4 ¢/kWh advantage over conventional land-based photovoltaic solar farms in terms of land costs alone. In some cases, the cost of land could even be free for floatovoltaics. If a pond is already owned and used by a utility, such as a water treatment plant, the ponds would not have to be leased out to the utility company to install floatovoltaics. This advantage in land costs, coupled with the potential for water conservation that floatovoltaics present, make water-based photovoltaics the better option for utility-scale solar power.

Word Count: 2639 words

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[18] "Quick Stat." United States Department of Agriculture. 2016. https://quickstats.nass.usda.gov/results/58B27A06-F574-315B-A854-9BF568F17652.

[19] Maehlum, Mathias A. "The Real Lifespan of Solar Panels." Energy Informative. 2014. http://energyinformative.org/lifespan-solar-panels/.

[20] McKay, Abe, "Floatovoltaics: Quantifying the Benefits of a Hydro-Solar Power Fusion" 2013. Pomona Senior Theses. Paper 74. http://scholarship.claremont.edu/pomona_theses/74