EVALUATING POTENTIAL FOR FLOATING SOLAR INSTALLATIONS ON ARIZONA WATER MANAGEMENT INFRASTRUCTURE

By

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Abstract

This capstone project evaluates the current state of floating solar photovoltaic technology and proposes use of the technology on water management infrastructure in Arizona. The study finds that floating solar photovoltaic has a higher energy density (100 W/m^2) than land-based, utility-scale solar and does not involve significant cost increases. The study proposes and models a small pilot installation on Lake Pleasant Reservoir, part of the Central Arizona Project, and finds that lifetime costs per unit energy are higher than what the Central Arizona Project currently pays for energy, assuming US median per-watt-installed costs for commercial solar. This cost however does not factor in savings from water conservation, existing infrastructure, reduced land costs, or other benefits. The study recommends water reservoirs by hydropower dams as ideal locations for floating photovoltaic installations. Justified with a significant background on Arizona's environmental, social, and economic sustainability, as well as regulations calling for increased renewable energy generation and reduced carbon emissions, this study recommends aggressive implementation of floating solar photovoltaic technology within a sustainable development paradigm.

Acknowledgements

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Introduction

The Colorado River – a primary water source for more than 40 million people -- is a severely vulnerable resource faced with projected increases in demand and decreases in supply. Already over-allocated, and with declining reserves, the Colorado River faces severe shortages in the near-term. The threat of shortage calls for a renewed look at the water delivery infrastructure of the Southwest United States.

At the same time, the looming danger of climate change – with concentrated impacts on the American Southwest – demands rapid and innovative responses for timely adaptation and mitigation measures. Determining a sustainable approach for continued habitation in the Southwest requires both reconciling water supply with projected water demand and meeting energy demand with renewable supplies. It is both possible and highly advantageous to address both of these objectives simultaneously, considering that water and energy are intimately intertwined.

A doctrine of sustainability implicitly calls for highly efficient, long-term solutions that utilize as much existing infrastructure as possible. One such approach exists that could potentially inject a large amount of renewable energy into our grid while also improving the efficiency of water delivery infrastructure. An emergent method of solar photovoltaic electricity generation known as “floating solar” dramatically improves the efficiency of photovoltaic generation while also insulating water bodies, thereby decreasing water loss due to evaporation and improving water quality. This is a systems-thinking approach that may be especially beneficial in transitioning to sustainable water and energy infrastructure for the American Southwest. This capstone will evaluate if water bodies in Arizona’s water management infrastructure may be a suitable place for floating solar installations, and if such a project would be a justified expenditure.

Background of the Problem

The state of Arizona has long been seen as a prime location for the development of solar energy. Ample year-round sun means that Arizona has one of the highest potentials for solar generation in the nation, and the 2,303MW of currently-installed capacity ranks the state second in the country in installed solar capacity (SEIA). But solar energy does not yet make up a significant portion of Arizona's energy supply, providing less than 3% of total power consumption in the state as of 2014 (US EIA).

Arizona faces an ultimatum of increasing its renewable energy portfolio. The Arizona renewable energy standard requires increasing renewable production for regulated electric utilities to 15% by 2025 (EIA). Annually, 30% of the required renewable energy target must come from non-utility distributed generation, split evenly between residential and non-residential installations. At the same time, the implementation of the EPA Clean Power Plan (CPP), finalized in August 2015, calls for drastic cuts in carbon dioxide emissions from existing fossil fuel fired power plants. Initially requiring a 52% reduction to be 90% achieved by 2020, the CPP now requires a 34% reduction in AZ emissions over a more gradual time frame (AZDEQa). Given an emergency stay granted by the Supreme Court in February, the enforceability of the Clean Power Plan has been called into question (AZDEQb). But should the CPP be enforced, there may be a strong call to replace existing fossil-fuel fired generation with renewables – with solar holding the most potential in Arizona.

The National Renewable Energy Laboratory (NREL) estimates Arizona to have 1,096 km^2 of urban land with technical potential for utility-scale photovoltaics – or about 53 GW capacity (NREL, 10). For rural land, NREL estimates 107,231 km^2 technical potential, or about 5,147 GW capacity (NREL, 11). This analysis assumes an energy density of 48MW/ km^2 based upon a single axis tracking technology, and excludes water, parks, contiguous areas smaller than .018km^2, and slopes greater than 3% (NREL, Table A-1). The NREL estimates, which evaluate technical potential rather than economic or market potential, do not consider "availability of transmission infrastructure, cost, reliability or time-of-dispatch, current or future electricity loads, or relevant policies" (NREL, 2). Further, they state, "estimates are based in part on technology system performance; as these technologies evolve, their technical potential may also change" (NREL, 2).

Variants in technology and market barriers are thus important to consider, with high costs arising from competing uses for land and for construction of electricity transmission infrastructure. Traditionally, solar developers look for utility-scale expanses of land for the development of solar fields. This land must be affordable enough that developers can make a return on their investment. However, land prices typically decrease as an inverse of urban proximity. And as solar fields are pushed further away from cities, additional costs may arise from distance, such as the construction of additional transmission lines to carry the power, or an increased loss of energy in transmission due to line resistance, which scales with distance (Harting).

What is overlooked in Arizona is the massive surface area of man-made lakes and reservoirs, used to bank increasingly precious water resources. Lake Pleasant, just north of Peoria, Arizona, and Lake Roosevelt, approximately 50 miles from the center of Phoenix, make up more than 33,500 combined surface acres of open-air water (SRP) (USBR). The development of technology to allow solar photovoltaic to be easily and efficiently deployed to float upon water surfaces opens up these vast reservoir areas to be considered as solar development sites. In fact, this solves one of the largest barriers to effective deployment of solar photovoltaic in Arizona – heat gain. As the temperature of solar photovoltaic cells increases, energy generation significantly decreases (Labouret & Villoz, 125). Thus, Arizona's consistently high temperatures reduce efficiency of solar when the sun is shining brightest. By floating solar photovoltaic panels on water bodies, the water acts as an effective thermal sink, keeping the panels cool and efficient.

Energy generation is traditionally seen at odds with environmental goals. But with the development of floating solar technology, this is no longer the case. Floating solar photovoltaic has emerged as a **drought adaptation technology** that allows water conservation through several parallel means. First, solar photovoltaic is incredibly beneficial in arid environments because no water is used in the energy generation process. This water conservation is in strong contrast to coal, natural gas, concentrated solar, and nuclear energy generation, which generate electricity through the production of steam. Secondly, by insulating the surface of water bodies, floating solar farms actually conserve water by reducing evaporative water loss. Preventing sunlight from entering the water has the added benefit of reducing algal growth, thereby improving water quality. In some cases, insulation mitigates sunlight-fueled chemical reactions that compromise water quality, such as the reaction of chlorine and bromine to form bromate, a known carcinogen (LADWR). The International Energy Agency states of photovoltaic production:

> "…solar photovoltaic (PV) may use very small amounts of water, such as for cleaning or panel washing. This makes them well-suited for a future that may be both more carbon- and water-constrained. In addition to lower water use at the site of electricity generation, these renewable technologies have little or no water use associated with the production of fuel inputs and minimal impact on water quality compared to alternatives that discharge large volumes of heated cooling water or contaminants into the environment" (Water for Energy 2012, p.10).

Where generally energy generation directly consumes water for generation, and regularly pollutes water as a byproduct, solar photovoltaic does neither. Floating solar's insulating capacity – and associated mitigation of evaporative water loss -- is an added benefit.

Floating solar photovoltaic is an economical commercial technology that has exploded in popularity in the past five years alone. For Arizona to remain abreast of technological advances and innovations, and to help to secure its water and energy future, serious looks need to be taken at large-scale deployment of floating solar on Arizona water infrastructure.

Statement of the Problem

Floating solar photovoltaic is a promising renewable energy source that is not yet well-known in the United States. Arizona, where we receive and abundance of sunlight, and where water resources are especially limited, stands to gain special benefit from this technology. The Central Arizona Project, along with other components of Arizona's water delivery infrastructure, has not been evaluated for potential siting of floating solar photovoltaic installations. It is important to explore any potential application of technology to improve water conservation or increase renewable energy generation given the background of climate change and water shortage in the Southwest. Floating photovoltaic technology is an approach that satisfies both calls.

Storage of water behind dams leads to consumptive water loss through evaporation on the water surface (UNESCO-IHE). Water loss in the Central Arizona Project due to evaporation is estimated at 4.4%, "or about 16,000 acre-feet from the canal and 50,000 acre-feet from Lake Pleasant." (Arizona Experience). While 4.4% seems small, 66,000 acre-feet per year corresponds to 21,506,323,323 gallons per year – or 58,921,434 gallons per day.

It is impractical at this time to assume the entire water surface of the CAP could be insulated. But 66,000 acre-feet per year is the amount of water that theoretically could be saved by ideal insulation. According to the AZ Department of Water Resources, an average person consumes 100 gallons per day – or 0.11 acre-feet per year (AZDWR). Thus, 66,000 acre-feet is equivalent to the consumption of 600,000 individuals or 120,000 households of five per year.

Deploying floating solar farms on the CAP system could potentially reduce evaporative water loss as a function of the percentage of insulated surface area. To a greater and more practical extent, floating solar appears an untapped source of renewable, cost-competitive, utility-scale power generation that has yet to be seriously evaluated in the Southwest.

Purpose of the Study

This study will develop an understanding of commercial floating photovoltaic methodologies related to the technology used, power generation potential, evaporation prevention, and cost differentials compared to traditional, land-based photovoltaic. Through a review of the literature, this study will evaluate the unique sustainability challenges of Arizona with an emphasis on water scarcity challenges, as well as the impetus for transition to renewable energy supplies. Through a thorough understanding of Arizona's sustainability challenges, and a developed understanding of the costs and benefits of floating photovoltaic technology, this study will compose arguments for the implementation of floating photovoltaic systems on Arizona water management infrastructure, culminating in the design and analysis of a pilot project. The considerations in the pilot design process will serve as a guide in evaluating the potential for regional use of floating photovoltaic as a drought adaptation technology.

Significance of the Study

Policy makers, planners, renewable energy professionals, and governmental bodies, as well as the academic community concerned with sustainability, will gain an introduction to floating photovoltaic technology, with an increased understanding of the capacity of floating photovoltaic to conserve water resources and generate low-carbon electricity in Arizona.

Theory

Floating photovoltaic is a drought adaptation technology that is worthwhile in pursuing as a means of simultaneous climate change adaptation and mitigation. This is one of many tools available for sustainable regional development, with goals of regional resource sustainability, autonomy, and livability. In combination with other design, technology, policy, and behavioral methodologies, within a paradigm of aggressive incrementalism, floating photovoltaic should be rapidly evaluated for its potential. If the benefits outweigh the costs of implementation, floating photovoltaic should be aggressively implemented. In pursuing climate change adaptation and mitigation, time is of the essence.

Definition of Key Terms

PV: abbreviation for photovoltaic

Watts (W): a measure of spontaneous energy potential

Kilowatts (KW): equivalent to one-thousand watts

Megawatts (MW): equivalent to one-thousand kilowatts

Watt-hours (Wh): a measure of generated energy, equivalent to 1 watt generation for a 1 hour duration

Peak Output: highest potential generation capacity at optimum solar insolation

Water-Energy Nexus: conceptual relationship between water used for energy generation and energy used for water processing and distribution.

NGS: Navajo Generating Station

CAP: Central Arizona Project

Delimitations

The exacting engineering and construction of a pilot floating photovoltaic installation, in order to meet certain requirements such as size, cost, capacity, and energy density, is definitely to be desired if preparing the project for actual implementation, for presentation to an investor or developer, or for demonstrating the sound understanding of engineering principles involved. Further beneficial would be an in-depth market analysis of the solar industry in Arizona, involving market forces such as investor response, tax and subsidy policy, company profiles, and financing trends, as well as component availability and pricing information. This would help to estimate costs and market potentials specifically and concretely. This capstone, while modeling energy density, location and siting, cost, and design, will not address in-depth technical or engineering elements involved in project design. Nor are the complex market forces in the Arizona economy explained in depth. This capstone will serve as a guide in considering floating photovoltaic, will discuss costs and benefits, and will model a potential installation based upon energy capacity, energy density, size, location and siting, cost, generation potential, conservation benefits, and sociopolitical concerns.

Methodology

This research venture constitutes a proposition of insulating water bodies in Arizona's water delivery infrastructure using, at least in part, floating Solar Photovoltaic technology.

To start, the raw technical potential for floating solar installations on Lake Pleasant Reservoir will be estimated. This figure will be determined by finding the total surface acreage of the open-air water reservoir and the mean energy density of existing floating photovoltaic installations. Technical potential is a measure of installed capacity (MW) that is the product of energy density (MW/Km^2) and usable area (Km^2) as measured by the National Renewable Energy Laboratory. Modeling methodology by the National Renewable Energy Laboratory, this capacity will be multiplied by the state capacity factor (a measure of solar insolation) and the number of hours in a year, producing an estimate for annual energy production.

With the total technical floating solar potential as a backdrop, this capstone will focus on the practical potential for an installation on Lake Pleasant Reservoir on the Central Arizona Project. This capstone will project design iterations of potential installations on to Lake Pleasant Reservoir to model scales of approach and the visual impact of such a system on the landscape. A considerable review of literature will be conducted to provide information on the quantity of CAP water lost to evaporation and the effectiveness of insulation strategies for mitigating this evaporation, as well as approaches to floating solar PV technology. To determine the costs and benefits effectively and appropriately, the physical geography of the chosen reservoir will be analyzed for where insulating infrastructure would be appropriate. Relevant energy flow data from the CAP will provide perspective on the power generation of potential installations. Some attention must be given in discussion to the ideal technology to be used, the effectiveness and cost-rate of different materials and technologies, the political-economic framework governing the project, and the feasibility of different approaches and scenarios.

A thorough analysis will then be presented regarding potential installations in order to determine the arguments for why floating solar photovoltaic installations would be beneficial on Arizona reservoirs. These arguments will be supported with background research on projected differences between water supply and demand in the coming decades, and the factors influencing both supply and demand. Moreover, the power generation potential of modeled projects will be important in justifying its installation. Most importantly from a cost standpoint, it is important to determine the ease of integrating generated solar electricity into existing infrastructure, and determine what additional infrastructure may be necessary.

By conducting these analyses, the end result will be an evaluation of potential pilot installations, which will inform if there is a worthwhile approach to insulating Arizona water reservoirs with Floating Solar technology. This is not an engineering paper, and will not be able to address certain specific technical elements, but rather will provide a well-supported argument for consideration of a floating solar projects on water infrastructure in Arizona.

Review of the Literature

A thorough review of literature concerning Arizona's unique sustainability challenges will provide an essential background to the consideration of floating photovoltaics on water management infrastructure. Without a developed understanding of the resource concerns of Arizona, the intricacies of Arizona's water supply, and the impact of climate change on the region, it will be impossible to accurately determine the impetus for implementation of floating PV technology. Developing this understanding, with a background in concepts of sustainability and global climate change, will be the first focus of the chapter.

It is also critical to understand the water-energy nexus in Arizona: how intimately water and energy consumption are interlinked. A study into the Navajo Generating Station, and its relation to the Central Arizona Project, will outline this linkage. The benefits of floating photovoltaic will be expressed in terms of both water conservation and energy generation – two measurements that are generally negatively correlated. A surface-level review of the physics of water evaporation, the function of solar technology, and the concept of floating photovoltaic will provide a basis for understanding and evaluating the case study data to follow.

Sustainability

Sustainability refers to the capability of a system to continue (or sustain) over time. Most often, "sustainability" refers to environmental sustainability, economic sustainability, or social sustainability. In the context of this paper, the ability of the projected water supply to meet the projected water demand over the future decades will be analyzed to determine approaches to a sustainable water supply. Further, renewable energy sources such as solar energy are considered "sustainable" because they do not generate carbon dioxide and do not consume nonrenewable resources.

"Sustainable Development" was defined by the UN Brundtland Commission in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Cassen, 41). This definition is commonly referenced when discussing climate change and other negative externalities of industry

Climate Change

The changing of our global climate, as accelerated by increased concentrations of greenhouse gasses and the conversion of natural ecosystems into developed areas, is a scientific reality. The International Panel on Climate Change, an international body of environmental scientists convened by the UN, succinctly summarizes the reality of a changing climate: "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen" (IPCC 2014, 2). Global Climate Models (GCMs) predict continued increase in average global temperature, continued sea level rise, and increased climate instability (IPCC).

Climate Change Adaptation

Climate change adaptation is defined by the United Nations Environment Programme as "Building resilience to climate change" (UNEP). This refers to the process of adjusting to the reality of climate change by recognizing and adapting to the impacts.

Climate Change Mitigation

Climate change mitigation is defined by the United Nations Environment Programme as "moving towards low carbon societies" (UNEP). Mitigation refers to decreasing emissions of greenhouse gases in order to prevent further warming of the atmosphere. While we are committed to continued warming even without further emissions, due to a lag in warming attributed to thermal inertia in the oceans, decreasing emissions will drastically reduce the severity of long-term climate change (IPCC 2007).

Shortage in the Colorado River System

The Colorado River is a primary water source for nearly 40 million people and 5.5 million acres of farmland (Snider). The river's flow is divided between seven US states and Mexico, with 2.8 million acre feet (MAF) apportioned to Arizona (USBRb). As of 2010, since the river was allocated, the population of the seven states that share the river has collectively risen 726%, creating a net increase in water demand (Gleick). At the same time, the flow of the river has been decreasing, with prolonged drought in the region. Scientific climate models predict continued dry spells with higher average temperatures and decreased precipitation for the foreseeable future (Zielinski). These factors lead to reduced snowmelt, and important source of the river's water, as well as increased evaporation, decreasing long-term water supply. This is summed up well by geoscientist Brad Udall:

> "Climate change will likely decrease the river's flow by 5 to 20 percent in the next 40 years, says geoscientist Brad Udall, director of the University of Colorado Western Water Assessment. Less precipitation in the Rocky Mountains will yield less water to begin with. Droughts will last longer. Higher overall air temperatures will mean more water lost to evaporation. 'You're going to see earlier runoff and lower flows later in the year, so water will be more scarce during the growing season', says Udall." (Zielinski)

Sixty MAF of storage capacity in the Colorado River's reservoirs have allowed consumers to use more than the annual water flow in certain years, but reservoir levels are universally low and predicted not to return to full capacity in the foreseeable future (USBRa) (Zielinski). Solutions to this problem must either increase the delivered supply of water or reduce the demand.

The Central Arizona Project

The Central Arizona Project (CAP) is a critical water delivery system designed to carry 1.5 Million Acre Feet of Arizona's annual Colorado River allotment to water users in Arizona. The CAP consists of 336 miles of canals, lifting water more than 2,900 vertical feet from its origin at Lake Havasu and termination south of Tucson (CAP Budget, 1-11).

The CAP system also includes the Lake Pleasant storage reservoir, located just north of Phoenix. Lake pleasant, at maximum capacity, spans 12,040 surface acres, with a maximum water surface elevation of 1,725 feet and a maximum reservoir capacity of 1,108,600 acre-feet. Lake Pleasant offers considerable recreational opportunities as well, with facilities provided by the US Bureau of Reclamation (USBR). Lake Pleasant's water level can fluctuate up to 125 feet within a year's operation (USBR-w). Almost the entire CAP system is open-air and subject to evaporative water loss. (USBR-w) "CAP's annual water loss due to evaporation is only about 4.4%, or about 16,000 acre-feet from the canal and 50,000 acre-feet from Lake Pleasant" (Arizonaexperience).

The CAP is both the largest single source of renewable water supplies in Arizona and the largest single end-user of power in the state (Modeer, 3). CAP requires approximately 2.8 million megawatt-hours of electricity annually to maintain pumping operations (Modeer, 3). More than 90% of this power is provided by the Navajo Generating Station (Modeer, 3). The CAP delivers Arizona's Colorado River entitlement to "municipal and industrial users, agricultural irrigation districts, and Indian communities comprising over 80 percent of the state's population and economic activity" (Modeer, 3). This ultimately includes "5.2 million people, roughly 80% of the state's population (CAP Budget, 1-13).

As part of the CAP system, additional electrical transmission infrastructure was installed to supply power to pumping plants and check structures of certain aqueducts (USBR-CAP). This electrical infrastructure is summed up in the following excerpt from the US Bureau of Reclamation CAP project page:

> "An electrical transmission system was also constructed as part of the project to supply power to pumping plants and check structures of the Hayden-Rhodes, Fannin-McFarland and Tucson aqueducts. Power for the Hayden-Rhodes Aqueduct facilities uses pre-existing federal transmission lines and about 318 miles of new transmission lines constructed specifically for the CAP. This new line consists of 251 miles of 230-kilovolt (kV) lines and 67 miles of radial 115-kV and 230-kV lines. Major facilities served by the Hayden-Rhodes Aqueduct radial transmission lines are the Mark Wilmer, Bouse Hills, Little Harquahala, and Hassayampa pumping plants, and New Waddell Dam. Construction of the Hayden-Rhodes CAP transmission system included building the Harcuvar substation in La Paz County, eight miles north of Wenden, Arizona, and a new tap station, the Hassayampa Tap, in Maricopa County, twelve miles north of Buckeye, Arizona.

> Power is supplied to the Fannin-McFarlan Aqueduct via pre-existing federal transmission lines and about 36 miles of new 115-kV and 69-kV transmission lines constructed specifically for the CAP. The major CAP facilities supplied by these transmission facilities are the Salt-Gila, Brady, Picacho, and Red Rock pumping plants.
>
> Power is also delivered to Tucson Aqueduct facilities on pre-existing federal transmission lines and about 32 miles of new 115-kV lines constructed for the CAP. The major features of the CAP served by these transmission facilities are the Twin Peaks, Sandario, Brawley, San Xavier, Snyder Hill, and Black Mountain pumping plants (USBR-CAP).

As noted, the Navajo Generating Station provides the majority of the energy for the CAP and is of profound importance to Arizona's water future.

Navajo Generating Station

A concern for the sustainability of the CAP is the intense energy demand required to pump water uphill from the Colorado River to the consumers as far away as Phoenix and Tucson. As stated earlier, The CAP is the single largest end-user of electricity in the state of Arizona, consuming 2,921,590 Mega-Watt Hours in the year 2014 (CAP Budget, 293). Around 90% of this energy is currently provided by the Navajo Generating Station, one of the largest coal fired power plants in the United States (Modeer, 3).

The Navajo Generating Station is a massive coal-fired power plant with three 750MW generators and a rated total output of 2,250MW (SRP). NGS consumes 22,000 tons of coal per day and emits 44,000 tons of CO2 per day (Propublic). According to environmental reporter Abrahm Lustgarten, the NGS is the third-largest producer of CO2 in the United States (Fresh Air). NGS has made significant expenditures into retrofit technology to reduce harmful emissions in recent years, including the use of electrostatic precipitators, limestone scrubbers, low-NOX burners and separated overfire air technology (NGS, facts). These technologies result in a 99% capture of fly ash, a 95% reduction in SO2 emissions, and a 40% reduction in NOX emissions (NGS, facts).

Taxes and royalties from NGS and the Kayenta Coal Mine, which supplies it, are paid to the Navajo Nation and the Hopi Tribe. Navajo Generating Station reports the employment of 500 full-time employees, 90% of whom are Navajo. NGS further reports that payments made by the plant to the Hopi Tribe compose 88% of the nonfederal tribal budget (NGS, economy). NGS estimates that NGS and the dedicated Kayenta Coal Mine that fuels it will contribute $13 billion to the Navajo Nation economy between 2020 and 2044 (NGS, economy)

In light of the imminent threat of Global Climate Change, and according international agreements to decarbonize energy grids, it would be environmentally, politically, and socially beneficial to replace this coal-fired energy with energy from renewable sources. Further, the EPA has mandated under the Clean Air Act that the Navajo Generating Station significantly reduce GHG and pollutant emissions (Modeer, 2). However, it is not simple to decommission NGS. Navajo Generating Station is a major source of employment for the Navajo nation, and operates a dedicated coal mine nearby. The NGS is further entrenched in payment schemes including the repayment of CAP construction costs and payments for Indian water rights settlements (Modeer, 5). Decommissioning the Navajo Generating Station means decommissioning an economic engine of the Navajo Nation.

Water Evaporation

Evaporation is a complex phenomenon with many factors at play, and a variety of methodologies for measurement. Factors influencing evaporation include wind, temperature, vapor pressure, and exposed surface area (Mekonnen & Hoekstra, 10). In the UNESCO-IHE Value of Water Research Report Series #51, hydropower is shown to be a water-consumptive form of electricity generation due to evaporative water loss caused by the damming and uncovered storage of water (Mekonnen & Hoekstra). Notably, the generation process itself does not directly consume electricity.

Water Reservoir Insulation

One approach to increasing the water supply is to mitigate water loss due to evaporation by insulating the water surface. Insulation has an added benefit of improving water quality by inhibiting the growth of algae and preventing chemical reactions caused by energy from the sun. Some municipalities have already worked to insulate open-air reservoirs, including Los Angeles, which applied millions of floating “shade balls” in Elysian, Ivanhoe, Upper Stone Canyon, and Lost Angeles Reservoirs in August of 2015 (LADWP). The Mayor, Eric Garcetti, estimates the insulating shade balls will conserve 300 million gallons of water per year from evaporation (LADWP). The cost of the project is $34.5 Million (LADWP). The balls are designed to have a lifetime of 10 years(LADWP).

Los Angeles plans to replace the shade balls at Elysian and Upper Stone Canyon Reservoirs with floating covers. They are temporary at Elysian Reservoir as well. The shade balls will be a permanent fixture at Los Angeles reservoir and will be replaced at the end of their lifetime every 10 years (LADWP).

Solar Photovoltaic Technology

Photovoltaic technology converts directly radiated light into electricity (Labouret & Villoz, 1). This differs from solar thermal technology and concentrated solar power, which are heat-based. Crystalline Silicon cells are most often used, though multiple other technologies exist (Labouret & Villoz, 54). These solar cells are arranged into modules commonly known as solar panels, which convert an average of 12-20% of incident solar radiation into DC electricity (Labouret & Villoz, 78). Solar photovoltaic is a renewable energy source that does not directly produce carbon dioxide or consume water in the production of electricity.

Solar in Arizona

Arizona's solar industry has experienced substantial growth in the 21st century and as of 2016 ranks second nationally for installed solar capacity with 2,303 MW (SEIA). In 2015, Arizona ranked 6th for growth in solar capacity with the addition of 234 MW in new projects and $582 million in solar investments (SEIA). Arizona generates enough solar energy to power 327,000 homes (SEIA). Arizona is also home to one of the largest solar plants in the United States – the Agua Caliente plant in Yuma County, with a capacity of 290MW (SEIA).

Floating Solar Technology

An emergent solar technology known as floating solar is now being deployed in projects across the world. This technology achieves a high degree of efficiency due to consistent thermal insulation of the solar cells by the water bodies that support them. This mitigates heat gain within the solar cells, which causes a significant decrease in efficiency -- "A normal crystalline panel loses around 0.4% of its power per [degree] C, which at 55 [degrees] C corresponds to 12% loss." (p.125, Solar Photovoltaic Energy). Further, land conversion disputes, a barrier to solar photovoltaic site selection, are rendered arbitrary. Floating solar systems are generally comprised of a racking assembly mounted on top of floating pontoons, and are often modular in nature. Most systems are proprietary. Notable companies in the field include Ciel et Terre, Infratech Industries, and Thompson Technology Industries. However, many different models and systems of varying scales have been created (Trapani, Fig 1).

Summary

Arizona's sustainability challenges in light of water scarcity, a changing local climate, and a reliance on carbon-intensive energy provide a foundation for understanding the benefits of floating solar photovoltaic. Having explained the basics of solar PV, floating solar concepts, and the effectiveness of reservoir insulation, it is appropriate to examine case studies of planned and existing commercial floating solar installations.

Data

Floating Solar Case Studies

Sunflower Solar Plant, South Korea

Surface Area	8,000 sq m
Total Modules	1,550 PV modules
Module Type	72-cell multicrystalline
Peak Power Output	465KWp
Additional Notes:	o Run by SolarPark Korea o Utilizes rotation and tracking system; est. 22% higher efficiency than land-based o Energy Density: 58.125 w/m^2

Figure 1Sunflower Floating Solar Plant, SolarPark Korea. Image: http://cleantechnica.com/files/2014/12/sunflower_image_2_2.jpg

Queen Elizabeth II Reservoir, Walton-on-Thames, Surrey, United Kingdo

Surface Area	57,500 Sq m
Total Modules	23,046 PV Modules
Module Type	275 W monocrystalline
Peak Power Output	6.33 Megawatts Peak
Projected Annual Output	5,800 MWh
Additional Notes:	Largest floating solar farm in Europe Completed March 2016 Recyclable, air-filled plastic float system Operator: Lightsource Energy Density: 110 w/m^2

Figure 2QEII Reservoir, LightSource UK. Image courtesy of Sky News

Yamakura Dam, Chiba Prefecture, Japan

Total Surface Area	180,000 Sq m **total reservoir area
Total Modules	50,904 PV modules
Module Type	270W Kyocera
Peak Power Output	13.74 Megawatts Peak
Projected Annual Output	16,170 MWh
Additional Notes:	Operator: Kyocera Largest planned floating solar farm on Earth. Currently under construction w/m^2 : >76.33*

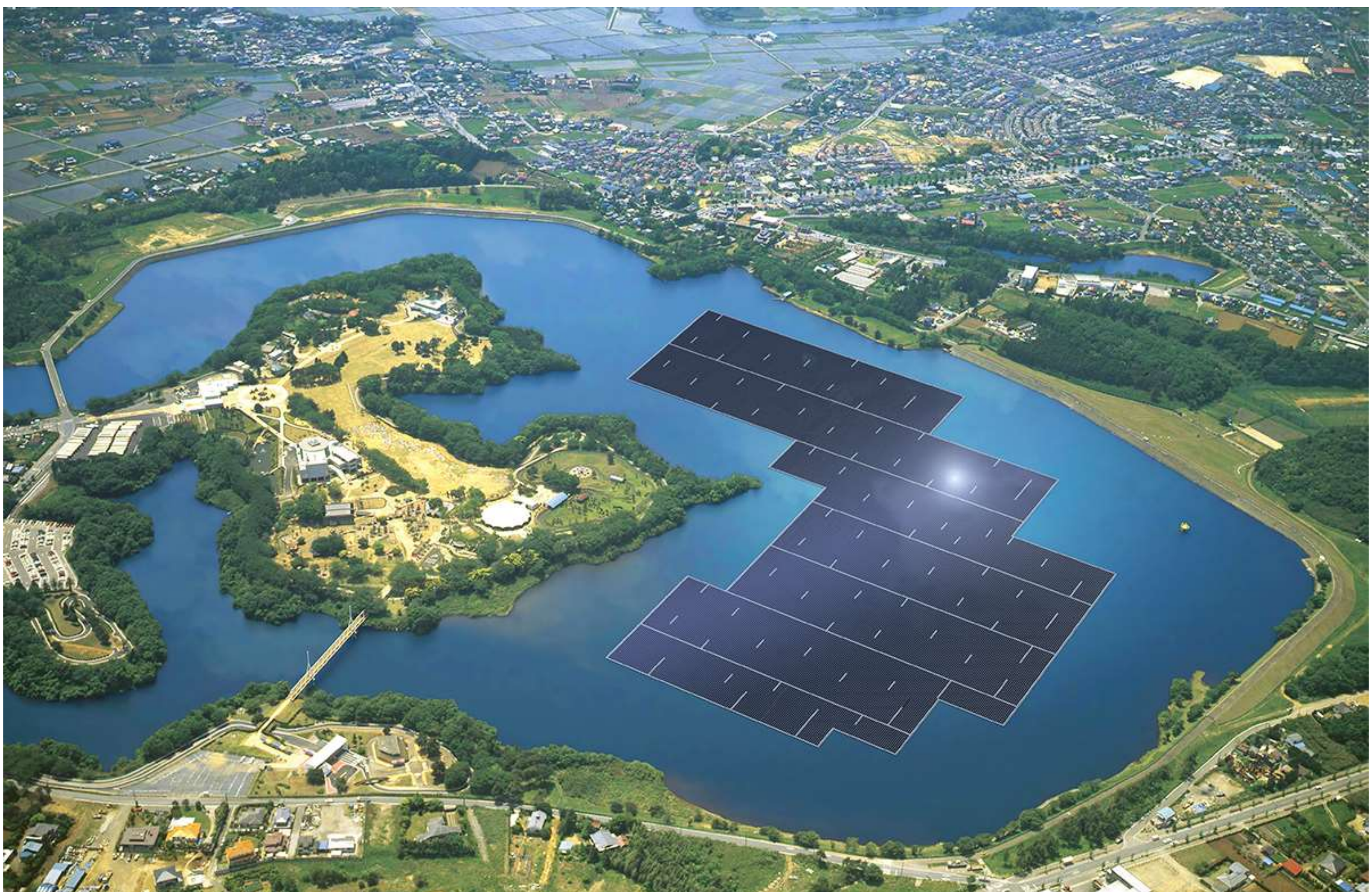


Figure 3 Yamakura Dam, Chiba Prefecture, Japan. Rendering by Kyocera LLC

Floating Solar Methodologies

The Ciel & Terre Hydrelio System

Ciel & Terre, a French company, has patented their Hydrelio© system for floating solar installations. This system uses a modular, interconnecting system of HDPE floats. The floats are shaped to hold a panel-mounting system at an angle of inclination of 12 degrees. A row of secondary, non-slip-surface floats connect between each row of main floats to provide maintenance access and additional buoyancy. Anchors are used to keep the solar array stationary.

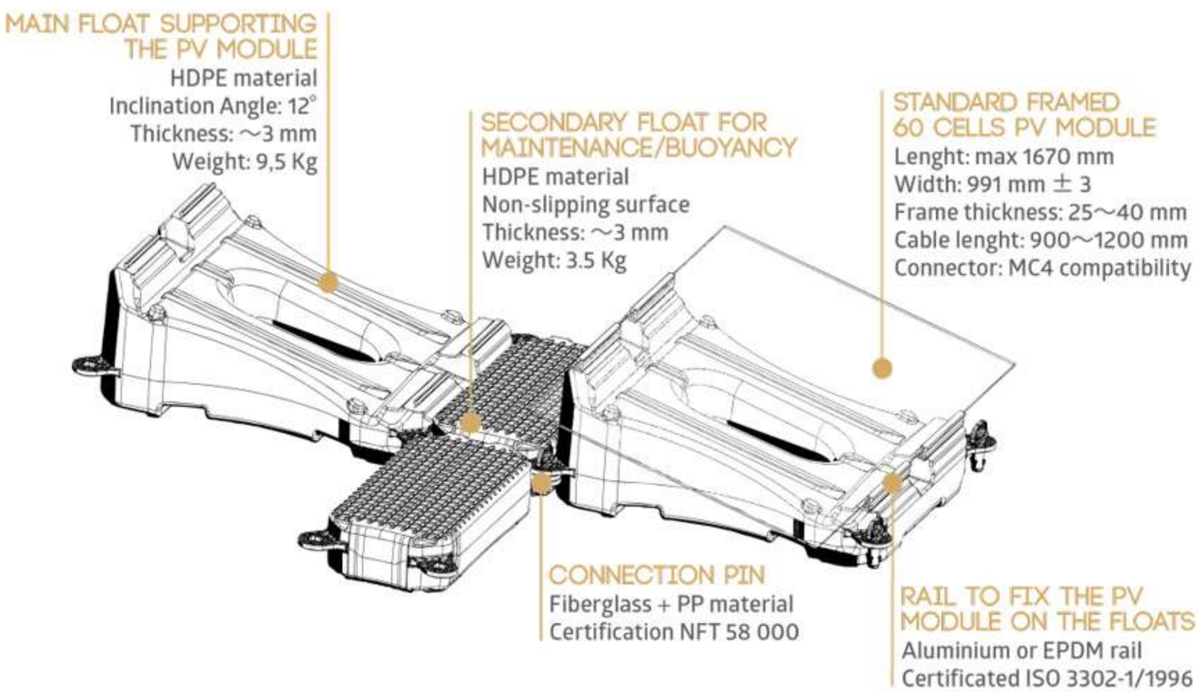
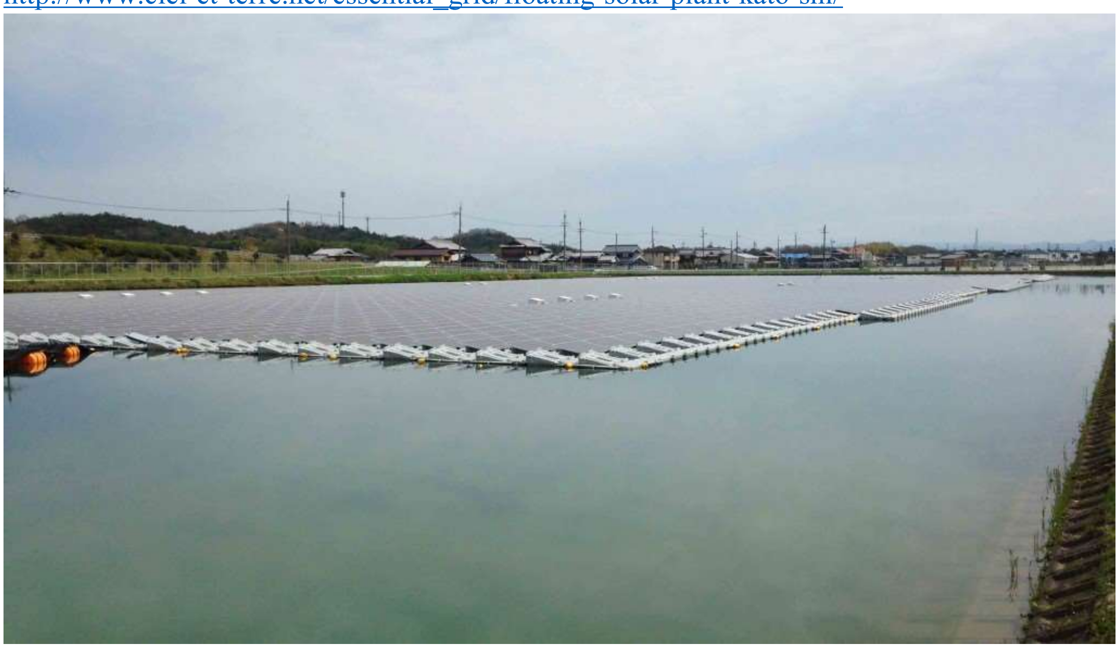


Figure 4 Intellectual property of Ciel & Terre -- Patented Hydrelio System

Ciel & Terre has been involved in a number of international floating solar installations. Several case studies of the Hydrelio system are shown below. Lightsource's floating solar array on the Queen Elizabeth II Reservoir (case studies, above) appears to use this technology, but does not state affiliation, and may use their own equivalent of the technology.

1) Umenoki, Japan.
   7,750.4 KWp (7.75 MWp)
   27,456 Panels (275Wp YINGLI)
   74,300 Sq. Meters
   104.32 Watts/ M^2
   http://www.ciel-et-terre.net/essential_grid/floating-solar-system-umenoki/

2) Kato-Shi, Japan
   2,870.28 KWp (2.87 MWp)
   11,256 Panels (255Wp KYOCERA)
   31,300 Sq. Meters
   91.70 W/ M^2
   http://www.ciel-et-terre.net/essential_grid/floating-solar-plant-kato-shi/



3) Kawagoe, Japan
   696.15 KWp (0.7 MWp)
   2,730 Panels (255Wp YINGLI)
   8,000 Sq. Meters
   87 W/M^2
   http://www.ciel-et-terre.net/essential_grid/floating-solar-system-kawagoe/

Infratech Industries

Infratech Industries, an Australian company, made headlines recently for its installation of a floating solar system on a wastewater treatment plant in Jamestown, Australia. They have recently contracted with the city of Holtville in Southern California to bring their technology to the US (source).

Infratech has not published any technical information on their installations and did not respond to a request for comment on their system. However, the CEO said the following in an interview with Huffington Post:

> "The efficiency is more, it's about 57 percent more on average, because it's got tracking -- the panels can follow the sun, it's got cooling so is more efficient, and it's also got concentrating systems (mirrors) to redirect light back on the panels -- it's a mixture of those three that help you achieve higher efficiency." (Beattie)

From this quote, it's evident that the Infratech system uses mirror-concentrating technology and single-axis tracking, mounted on a floating raft system. Images show a circular architecture, as opposed to the rectangular architectures seen in the Hydrelio© system.

Floatovoltaic

Thompson Technology Industries "Floatovoltaic" design was used in the 2008 design of the Far Niente wineries floating solar system in California. Individual pontoons hold modular crystalline PV panels mounted at an optimal tilt. The pontoons connect to a mounting structure including walkways between rows of panels and along the sides. (Trapani, 2.1)

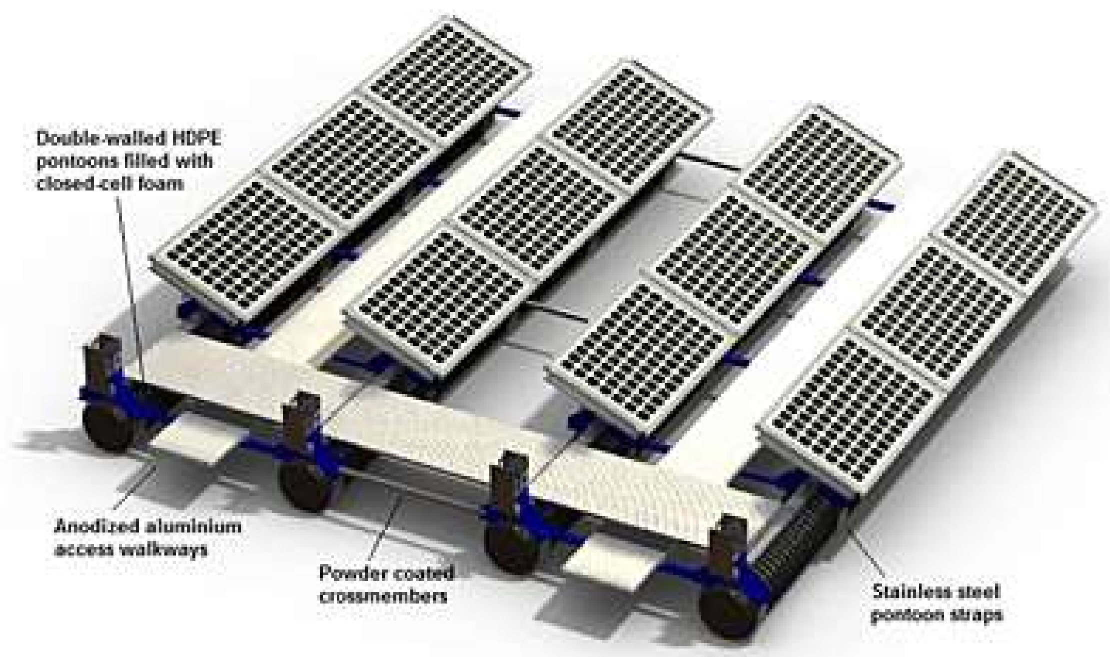


Figure 5 Floatovoltaics system. Source:Trapani 2014

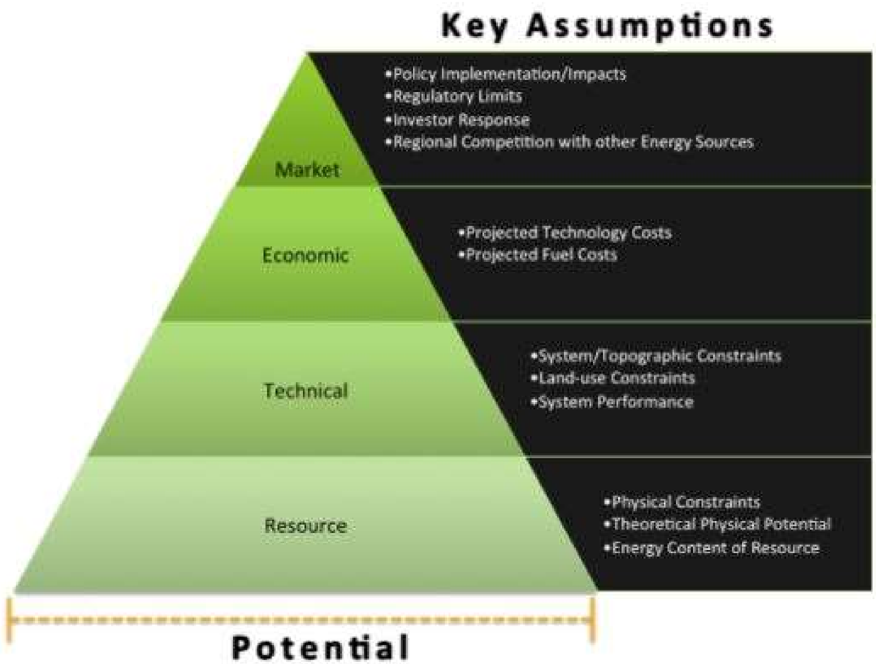
Other Technologies

A review of the literature shows the development of several kinds of floating solar technologies, including dual-axis tracking, concentrated solar, and submerged solar (and sometimes combinations of these technologies), but no commercial implementations were found at the time of this study.

Technical Potential for Floating Solar on the Lake Pleasant Reservoir

In the National Renewable Energy Laboratory (NREL) report "U.S. Renewable Energy Technical Potentials: A GIS Based Analysis", Published July 2012, NREL defines technical potential in the following way:

*"Renewable energy technical potential, as defined in this study, represents the achievable energy generation of a particular technology given system performance, topographic limitations, environmental, and land-use constraints. The primary benefit of assessing technical potential is that it establishes an upper-boundary estimate of development potential (DOE EERE 2006). It is important to understand that there are multiple types of potential—resource, technical, economic, and market—each seen in Figure 1 with its key assumptions" (*Lopez et al, 1).



The accompanying Figure 1 further clarifies different measures of potential.

Figure 6 Source: National Renewable Energy Laboratory 2012

These definitions of technical potential, economic potential, and market potential will be used to evaluate the floating solar potential of Lake Pleasant Reservoir. In this report, the NREL also published the formula used to determine technical potential. The formula used was:

$$State\ MWh = State\sum[urban\ openspace\ (km^2)\ \cdot power\ density\ \left(48\frac{MW}{km^2}\right) \cdot state\ capacity\ factor\ (\%) \cdot 8760\ (hours\ per\ year)]$$

Source: NREL 2012

where "urban openspace" is calculated using a conditional GIS analysis and "state capacity factor" is obtained from the National Solar Radiation Database Typical Meteorological Year 3 data set (table 1). (NREL 2012)

This formula can be adapted to determine the technical potential of Lake Pleasant Reservoir. "Reservoir openspace" will replace "urban openspace". This will refer to open areas of the reservoir with no surface or immediately subsurface impediments. In order to create a buffer for shallow shoreline areas and overly narrow canyons, 20% of the surface area of the reservoir will be considered unusable. Technical potential will not take into consideration the recreational use of the reservoir, but will consider fixtures such as boat docks and marinas as unusable.

The US Bureau of Reclamation claims that Wadell Dam's Lake Pleasant Reservoir spans 12,040 surface acres at maximum water surface, with 9,970 surface acres at maximum conservation storage (which is considered 100% full). (http://www.usbr.gov/lc/phoenix/projects/waddelldamproj.html). However, real levels deviate far below this figure. Historical data provided by the CAP on Lake Pleasant (from 2008 to 2014) shows a surface area as low as 5,793 acres, at a surface elevation of 1,633.28 feet, in September 2011. The greatest surface acreage in this same period was 9,661 acres, at a surface elevation of 1698.44 feet, in March 2010. Since floating solar will be a semi-permanent, moored installation, calculations must be made using the lower range of surface acreage. Giving a small buffer to the lowest surface area in the available data period results in a base capacity of 5,500 surface acres for floating solar. Assuming that 20% of this surface area provides a **technical obstacle** to development (such as too close to shore, too shallow, too narrow, or too shaded) results in a base figure of 4,400 surface acres.

By using the Google Earth Pro ruler tool, polygons can be drawn around built infrastructure on the water surface such as boat docks and marinas to determine the surface area that is unbuildable. Dock areas and their buffers make up a total of roughly 170.1 acres of unbuildable area, leaving **4,229.9 acres** (**17.118 Km^2**) available to determine technical potential.

Figure 7 Exclusionary polygons show unbuildable dock area buffers (Google Earth Pro)

The next part of the equation that must be adapted is the energy density. NREL in their study estimated an energy density of 48MW/ km^2 based upon a utility-scale, one axis tracking technology standard. However, based upon the floating solar case studies examined earlier, floating solar installations generally have a much higher energy density.

Plant Name	**Size**	**Energy Capacity**	**Energy Density**
Sunflower Solar Plant	8,000 sq m	465 KWP	58.125 W/ m^2
Yamakura Dam*	<180,000 sq m*	13.74 MWP*	>76.33 W/ m^2*
Kawagoe	8,000 sq m	696.15 KWP	87 W/ m^2
Kato-Shi	31,300 sq m	2.87 MWP	91.7 W/ m^2
Umenoki	74,300 sq m	7.75 MWP	104.32 W/ m^2
QE II Reservoir	57,500 sq m	6.33 MWP	110 W/ m^2
Combined*:	**179,100 sq m**	**18.11 MWP**	**101.11 W/m^2 = 101.11MW/Km^2**

*Only reservoir surface area data for Yamakura available. Figures used are for reservoir area. Not included in combined totals

As seen in the table above, combining the total surface area of the case study systems with the total energy capacity gives an averaged energy density of 101.11 W/m^2 (not including the Yamakura Dam project, for which no project surface area is provided). Further, energy density seems to be positively correlated with total size. Given that the technology has demonstrated the ability to perform at over 100 W/m^2, an energy density standard of **100 MW/km^2** will be used to calculate energy potential of the Lake Pleasant Reservoir.

Equations

Reservoir openspace (km^2) * Energy density (MW/Km^2) will be used to calculate technical potential for energy capacity.

Reservoir openspace (km^2) * Energy density (MW/Km^2) * State capacity factor (%) * 8760 (hours per year) will be used to calculate technical potential for energy production. NREL gives a state capacity factor for Arizona of 0.263.

Reservoir Openspace	Energy Density	State Capacity Factor (SAM)
17.118 Km^2	100 MW/ Km^2	0.263*

*NREL, Appendix A

Technical Capacity Potential:

17.118 Km^2 * 100 MW/ Km^2 = **1,711.8 MW**

Technical Generation Potential:

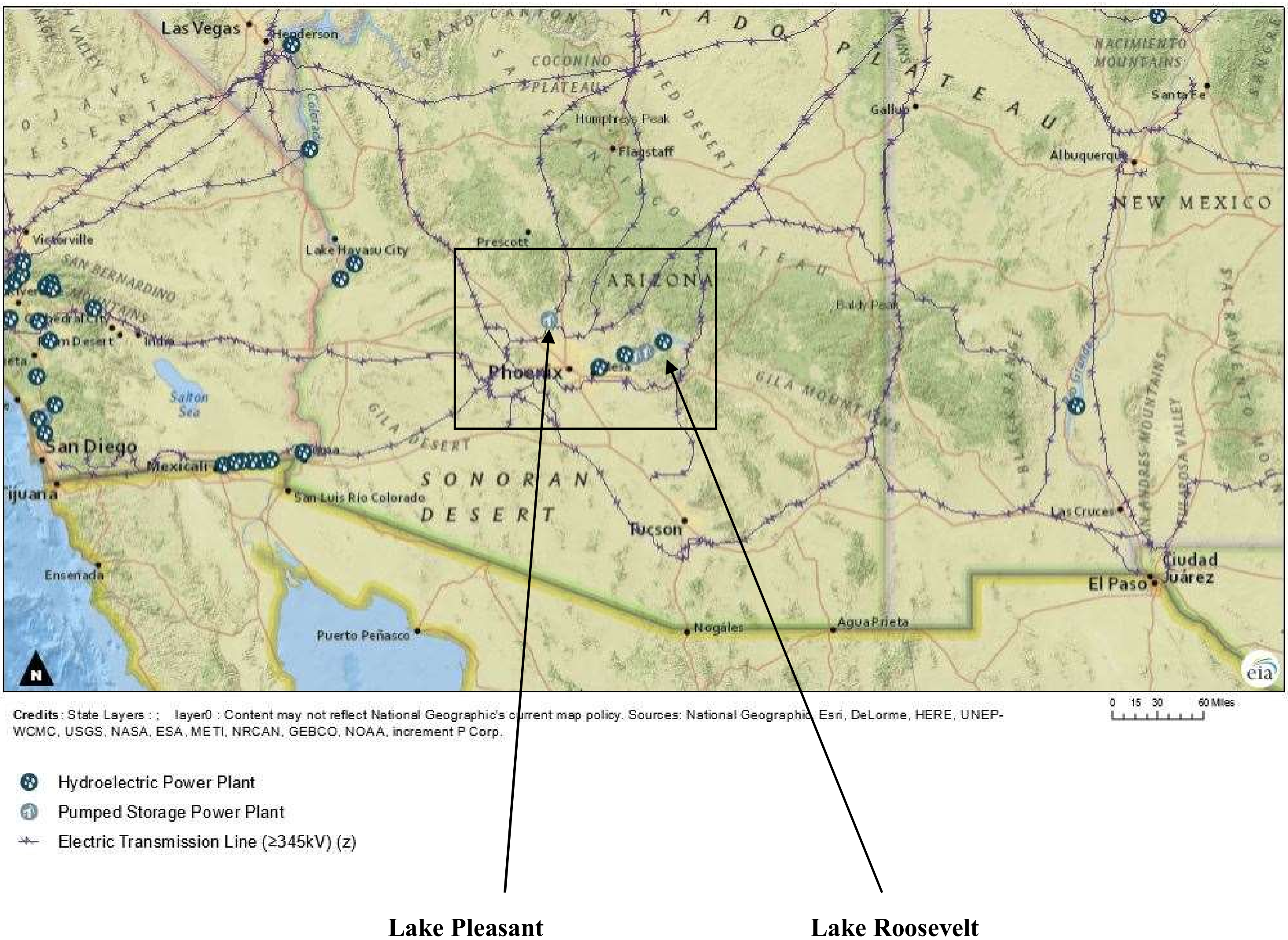
17.118 Km^2 * 100 MW/ Km^2 * (26.3%) * 8,760 = **3,943,781.78 MWh/ Year**

While achieving these figures is not feasible, the technical potential provides an upper boundary of the reservoir's potential. If there were no competing uses for the lake, and covering the entire reservoir with floating solar were economically, socio-politically, and environmentally feasible, this scale of generation would be possible.

Economic and Market Factors Affecting Solar Potential of the Lake Pleasant Reservoir

Location

This satellite image shows measurements of major water reservoirs (Lake Pleasant and Lake Roosevelt) from the city center of Phoenix, Arizona. As measured by the ruler tool in Google Earth Pro, Lake Pleasant is approximately 29 miles from the center of Phoenix and Lake Roosevelt is approximately 55 miles from the center of Phoenix. While measurement from the city center is arbitrary, the minimal distance of both major reservoirs from Phoenix infrastructure suggests that little energy would be lost in transmission.



The map above, provided through the US Energy Information Administration U.S. Energy Mapping System, shows existing high-voltage electric transmission lines (over 345kV) in Arizona. Also highlighted on the map are the hydropower and pumped storage power facilities at Lake Pleasant and Lake Roosevelt. It can be seen that these high-voltage lines run directly adjacent to Lake Pleasant, and within a short distance of Lake Roosevelt. As multiple pumped storage and hydropower generation plants are highlighted in the cascading reservoirs that descend from Lake Roosevelt, it can be assumed that substantial transmission infrastructure is already in place that connects these power sources to the transmission and distribution grids. This proximity to high-voltage transmission lines is of crucial economic importance for project success due to the incredibly high cost of construction for new transmission lines (Black & Veatch, Sec 2-3).

In fact, there is an existing 1.6MWP solar power plant directly adjacent to Lake Pleasant which powers the Lake Pleasant Water Treatment Plant (EIA). There is also an electrical station visible by satellite around 2 miles from the Lake. Existing transmission lines and power stations mapped by EIA give a high degree of confidence that additional electricity generated by a floating solar plant on Lake Pleasant Reservoir would be easily and affordably integrated into the existing grid.

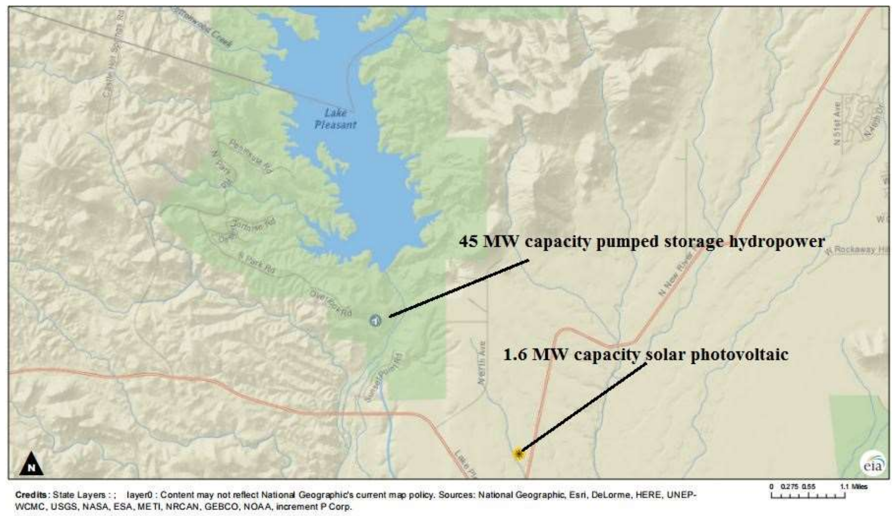


Figure 8 Relative location of Lake Pleasant hydropower generation and adjacent solar field. Source: EIA

The location of the pump/generator units at Lake Pleasant and the adjacent solar PV field can be seen in the image on the right. The New Waddell Dam includes four 11.25 MW reversible pump/generators and functions as a pumped storage hydropower facility (USBR). The aspect of pumped storage hydropower is actually a huge boon for the success of a piloted solar installation. In the case of excess solar PV generation, this energy could be used pump water into the aquifer for electricity generation when it is needed. However, it does implicate CAP in operations of the floating solar plant, meaning if CAP does not own or operate the plant directly, it will need to be an active stakeholder.

The combination of existing electrical infrastructure, an energy storage solution, and a large open area of water for siting make Lake Pleasant an excellent site for solar photovoltaic generation. However, other aspects of Lake Pleasant would provide obstacles to the successful development of especially large-scale floating solar.

Cost

Floating solar technology is not much more expensive than land-based photovoltaics. As shown in the floating solar methodologies above, the system consists simply of a floating platform upon which traditional photovoltaic panels can be mounted. The Queen Elizabeth II Reservoir plant, as well as the Ciel & Terre Hydrelio system, use interconnected air-filled HDPE floats, a low-cost material. Infratech Industries reports using plastic ballast with a metal structure, but information on their design is hard to find (Infratech Industries). Ciel & Terre claims that their system is cost-competitive in the industry. While floating solar soft costs may be marginally more expensive, these systems are also demonstrated to be more efficient, which may balance out the increased cost.

Land costs – or lack thereof – may also be an advantage of floating solar systems. Given that there are very few competing uses for development of water bodies, and that the installation of floating solar systems provides benefits including improved water quality and decreased evaporation, it is reasonable that leasing costs for the field would be small or non-existent.

The cost of solar photovoltaic has continued to rapidly decline and is projected to decline further, as explained in depth in Berkeley's Tracking the Sun VIII publication (Barbose & Darghouth, 15). The median installed cost per watt of non-residential solar photovoltaic (less than 500KW) in Arizona is $3.6 (Barbose & Darghouth, 29). Nationally, the median installed cost per watt for non-residential solar pv greater than 500KW is $2.8 (Barbose & Darghouth, 20). Prices are expected to continue to decrease, as they have been consistently over the past decade. Large (>500KW), non-residential solar installations, such as this paper suggests, experienced the greatest decline in median prices in 2014, declining by 21% (Barbose & Darghouth, 1). Further, median installed prices for systems >1000KW in size benefit from economies of scale, with 36% lower median installed prices than non-residential systems 10KW or smaller (Barbose & Darghouth, 3). Some decline in prices has been offset by a decline in incentives. Notably, in Arizona, rebates of more than $4 per watt installed used to be available. These have declined in the time since to $0 in state or utility level rebates (Barbose & Darghouth, fig 11). There are no data available for non-residential solar photovoltaic of greater than 500KW in Arizona.

The Queen Elizabeth II Reservoir solar plant cost approximately 6 million pounds – which is equivalent to $8,628,600 as of April 2016 (Harvey). At 6.33 MW capacity, that comes out to $1.36 per watt, installed. It was noted that government solar subsidies helped to make this project possible. Further, installed prices in the United States are higher than in most national PV markets (Barbose & Darghouth, 2).

Based upon the information available for this study, cost per watt installed does not deviate significantly from land-based photovoltaic. The addition of tracking equipment substantially increases costs, as does the use of high-efficiency modules (Barbose & Darghouth, 4).

What has not been incorporated into the calculation of cost for floating solar PV is the water savings provided by the system. As pointed out by Luis Pagán-Quiñones in "Shade Balls or Floating Solar Panels?" Los Angeles was willing to pay up to $179,800 per acre in their shade ball program to protect water quality and prevent water evaporation (Pagán-Quiñones). According to his calculations, based upon "Tracking the Sun VIII" figures, this is roughly one-third the cost of floating solar per acre. However, his calculations do not take into account the increased efficiency of floating solar, which provides a much greater installed energy capacity per unit area than land-based photovoltaic. His review highlights an important point: it is erroneous to evaluate the cost and benefit of a floating solar installation by energy capacity alone.

Water Savings

The mechanics of the evaporation of water are fairly complex, and there are a variety of methodologies for estimating evaporative water loss from bodies of water which are outside the scope and capability of this study. Factors influencing evaporation include temperature, humidity, wind, and exposed surface area (Makonnen).

The evaporation rate of the CAP is reported to be about 4% -- or about 50,000 acre-feet from Lake Pleasant, annually (Arizonaexperience). This study will make several fundamental assumptions in estimating water savings from floating solar installations. 1) The evaporation rate is uniform across the entire surface of lake and 2) the evaporation is directly proportional to exposed surface area of the lake.

Felicia Whiting, a representative of Infratech Industries, stated in interview "We're at about 90 per cent water evaporation prevention for the surface area that we cover" (Infratech Industries). Assuming this to be correct, and applicable to other floating solar designs, this figure will be used to roughly determine water savings.

The evaporation will be calculated using the average surface acreage of Lake Pleasant from the available data set (01/01/2008 – 12/31/2014). The average of elevations from this range, as calculated using Microsoft Excel, is 7,995 surface acres. Based upon the aforementioned fundamental assumptions, water savings attributed to a floating solar installation will be roughly equivalent to the following:

Annual Water Savings = Annual Evaporation (acre-feet) * % of Reservoir Insulated (acres covered / average total acres) * .90

Competing Uses for Lake Pleasant Reservoir

The greatest obstacle to the development of sizeable floating solar installations on Lake Pleasant is the recreational use of the reservoir as Lake Pleasant Regional Park. Lake Pleasant has recreational uses including hiking, biking, boating, watersports, kayaking, fishing & sportfishing, camping, picnicking, and more (Visit Arizona). Recreational use has been emphasized since the lake was enlarged by the construction of the New Wadell Dam in the 1990s. Two marinas have been constructed on the reservoir, in Southwest and Southeast corners of the lake, respectively.

In order to achieve public support of the project, very deliberate consideration would have to go into siting and design of the floating solar system. Lake Pleasant Reservoir was not always a recreational area, but the public has grown accustomed to the recreational facilities at the area. Recreational use and economic limitations are what make achieving the technical potential for floating solar generation impractical. Aesthetic and environmental concerns are what make achieving the technical potential undesirable. However, as water concerns in Arizona become more serious, and pressure continues to grow to transition from fossil-fuel energy, the public may be in greater support of sacrificing recreation for the sake of sustainability.

Siting

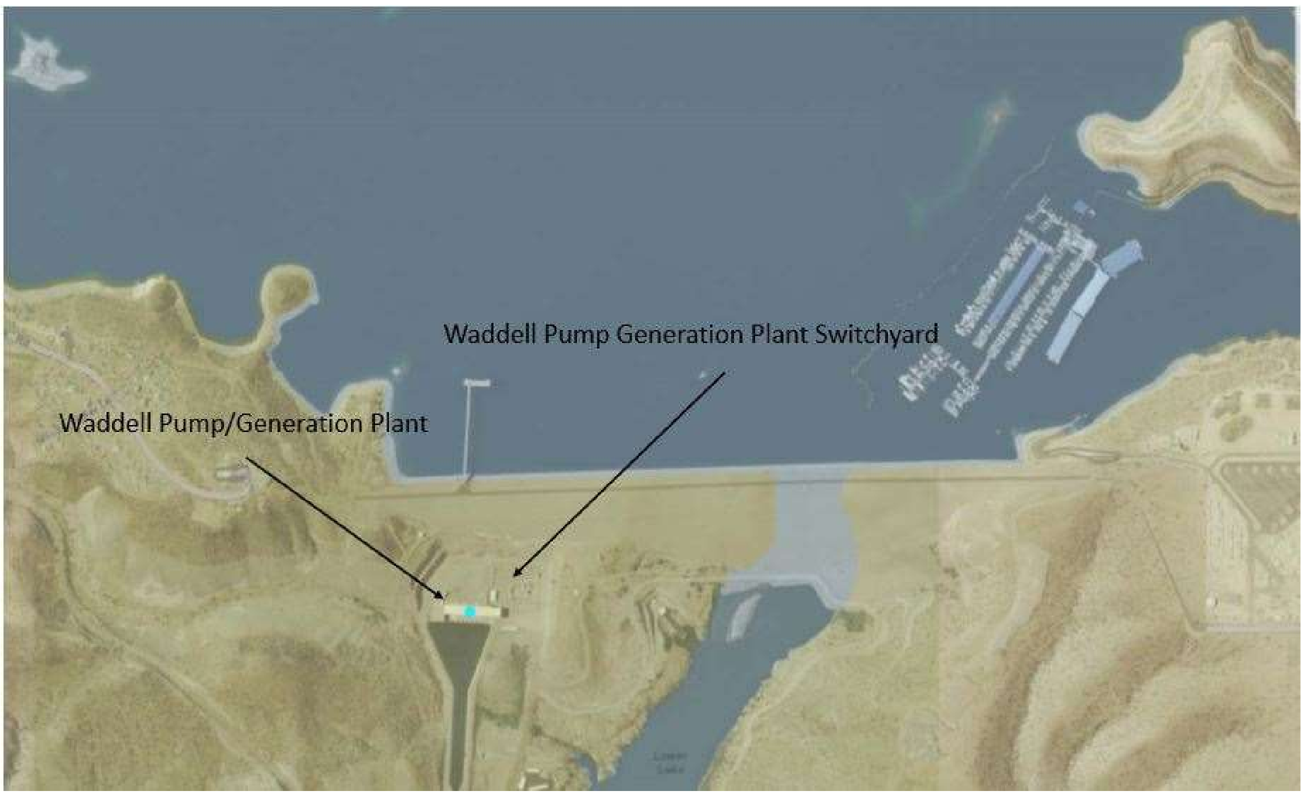


Figure 9 Image provided by the Central Arizona Project Water Control Department

In this image provided by CAP, the Waddell Pump/ Generation Plant and accompanying switchyard are highlighted. In order to 1) reduce infrastructure costs and 2) utilize the pumped storage function of the reservoir with solar photovoltaic power, it is ideal to locate the floating solar installation as close to this infrastructure as possible.

The cost and competing uses concerns in the previous sections will also factor heavily into the siting of an actual pilot project. Construction cannot occur in the developed areas of the boat docks, and avenues for boats to travel to the rest of the lake must remain open. The greatest depth of the lake is suggested to be directly adjacent to the dam as well – an important consideration given regular fluctuation of lake levels by 125 feet in an operating year. Given that the dam is a high point in the landscape, a pilot project in this area should receive near the maximum exposure to sunlight as possible.

Results

The considerations presented in the data section provide guiding information towards designing a pilot floating solar installation on Lake Pleasant Reservoir. Taking into account these factors, the results of this study, in addition to providing guidance in designing floating solar installations, is the design of a pilot installation.

The in-depth planning and design of a solar installation is a multi-year process involving many stakeholders and design decisions. The pilot herein addresses design considerations but not technical or engineering considerations necessary for the true implementation of such a project.

An ideal peak capacity of 12MW will be sought for this project, so that the solar farm could be used to power one 11.25 MW water pump at New Waddell Damn, in order to make pumped storage of solar generation a possibility.

This design assumes use of the Hydrelio© or similar floating HDPE pontoon system with anchored mooring. The design will assume that 100 W/ m^2 is a realistic and achievable energy density using this non-tracking, fixed-tilt system, as shown in the review of floating solar case studies. Economies of scale for larger installations result in decreased costs and improved efficiencies.

Given an energy density of 100 W/ m^2, the system will need to be 10,000 m^2 per MW capacity

(100 W/ m^2)(1MW/ 1,000,000 W) = 1 MW / 10,000 m^2

For a peak capacity of 12 MW, the system will need to be **120,000 m^2**

(1MW / 10,000 m^2) (12) = 12MW / 120,000 m^2

At 120,000 m^2 (approximately 29.65 acres) this system should preserve an estimated **166.89 acre-feet** annually from evaporation – about **54,381,261 gallons per year**.

(50,000 acre-feet annual evaporation)(29.65 acres covered/ 7,995 average surface acres) (.90 insulation efficiency) = 166.89 acre-feet

Pilot Floating Solar Visualizations

1) **Basic**

Most basic visualization of 120,000 m^2 . Composed my measuring 100m by 100m tile in Google Earth Pro and importing into Adobe Illustrator. Array composed of 12 10,000 m^2 tiles arranged in a 3x4 rectangle.

Fundamental Assumptions:

- Aesthetics unimportant
- 120,000 m^2 area of lake chosen has no subsurface obstacles that would break surface at low water level
- Open area provides passage for boats to pass.

2) **Graduated**

Graduated design with more clearance from the dam. Encircles pier structure more, and is closer to western shoreline. *Green square is reference for 10,000 m^2

Assumptions:

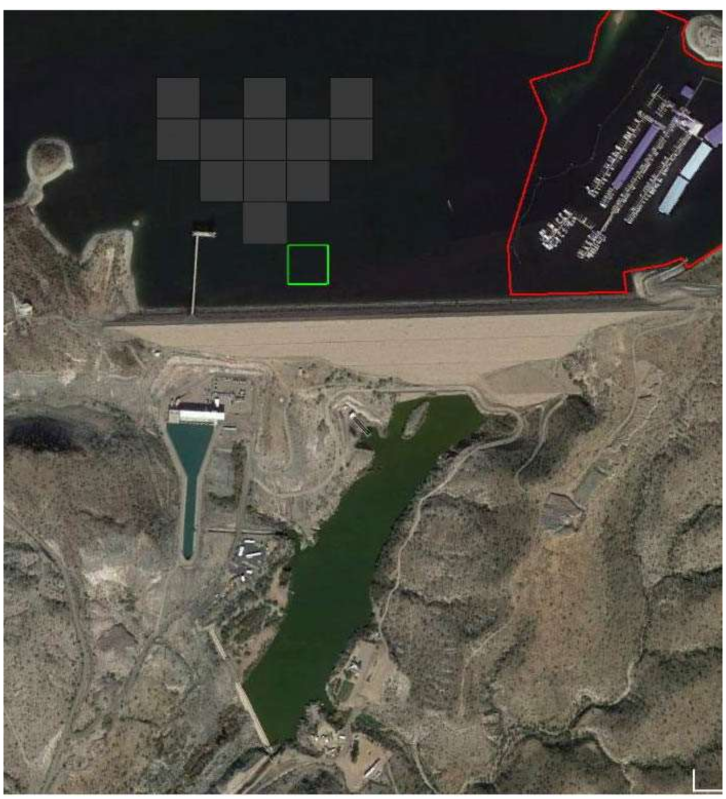
- Additional clearance from dam advantageous
- Area has no subsurface obstacles that would break surface at low water level
- Encircling pier is not disadvantageous
- Closer proximity to Western shoreline areas pictured is not disadvantageous

3) **Split-Lake**

120,000 $m^2$with 80,000 m^2 on Greater Lake Pleasant and 40,000 m^2 on the Lower Lake. The design covers close to 50% of the Lower Lake. More infrastructure would be necessary to attach both solar PV silos.

Assumptions:

- Assumes Lower Lake does not have predominant use that would make development problematic
- Assumes Lower Lake of sufficient depth
- Area has no subsurface obstacles that would break surface at low water level

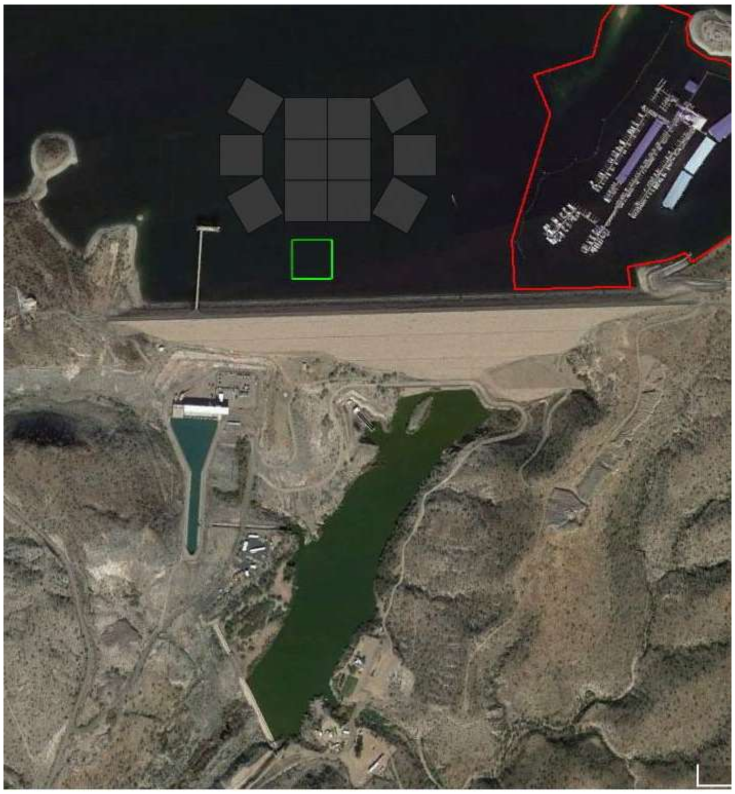


4) **The Saguaro**

- 120,000 m^2 in a branched saguaro design on Greater Lake Pleasant. Design may be more appealing to locals. *Green square is reference for 10,000 m^2

Assumptions:

- Closer proximity to the western shoreline is not disadvantageous
- Sacrificing density of generation for aesthetic is appropriate
- Area has no subsurface obstacles that would break surface at low water level



5) **The Solar Flare**

120,000 m^2 aesthetic-based design to improve public perception and enjoyment. Design emphasizes solar aspect. *Green square is reference for 10,000 m^2

Assumptions:

- Sacrificing density for aesthetic enjoyment is appropriate
- Area has no subsurface obstacles that would break surface at low water level

6) Pushing the Limit

227,500 m^2 22.75 MW design based upon use of the lower lake and aqueduct head. Uses 20 10,000m^2 tiles and 11 2,500m^2 tiles. Design intended to maximize power production without encroaching much further on Greater Lake Pleasant. The 160,000m^2 segment alone would be the largest floating solar farm in the world. At peak capacity, this could power two 11.25 MW water pumps (assuming minimal inversion loss).

Assumptions:

- Such a large installation is practical and economical
- Lower Lake is has no predominant use that would make development problematic

- There are no subsurface obstacles that would break the surface at low water level
- Additional infrastructure not cost-prohibitive

Discussion

The six iterations above are but a few of many possible design iterations to achieve 12 MW peak output (with the exception of #6). An installation of this scale is not unprecedented, as there is currently a 13.74 MW peak floating solar project under construction in Japan, planned to house 50,904 PV modules. To achieve 12 MW will take approximately **43,637 275W modules or 48,000 250W modules**

To estimate an upper boundary of the cost of a 12MW floating solar installation, the national median price for non-residential solar installations greater or equal to 500KW capacity will be used as provided in Berkeley's Tracking the Sun VIII ($2.8 per watt installed) (Barbose & Darghouth, 20). This is due to the fact that no information is available for the Arizona median installed price >500KW capacity from the Tracking the Sun report.

Estimated Installed Cost:

(2.8 US Dollars / 1 Installed Watt)(12,000,000 Watts) = **$33,600,000 for a 12 MW field.**

Multiplying 12 MW times the State Capacity Factor (NREL) and the hours in a year (8,760) gives the estimated annual power production:

Estimated Annual Energy Production:

(12MW) (26.3%) (8,760 Hours) = **27,646.56 MWh per year**

Most solar panel manufacturers offer a warranty on modules guaranteeing at least 80% of rated power production at 25 years of age (Maehlum). Due to the moderating effect of water bodies on panel temperature, along with lower concentrations of airborne particulate and dust, floating solar photovoltaic panels can be expected to last even longer, with minimal wear & tear. This study will assume a 30 year lifetime.

Cost Schedule (Assumes no loss in efficiency + 30 year lifetime)

Years From Installation	Total Megawatt Hours	Cost per Megawatt Hour
1	27,646.56	$1,216
5	138,232.8	$243
10	276,465.6	$121.5
15	414,698.4	$81.02
20	552,931.2	$60.77
25	691,164	$48.61
30	829,396.8	$40.51

Of CAP's annual energy use of 2,921,590 MWh in 2014, they paid an average of $32.33 per MWh (CAP Bi-Annual Approved Budget, 293). At the cost realizations demonstrated above, even assuming no decrease in output and a thirty-year lifetime, there would be no economic impetus to move forward on the project ceteris paribus, even given projections of increasing rates.

However, as stated earlier, it would be erroneous to determine the cost and benefit based upon energy cost alone. Several factors may lead to significant cost decreases, improved practicability, or improved return on investment:

1) If the project is sponsored or owned by CAP, no land purchase or leasing costs will be incurred.
2) Economies of scale should bring down the per-watt-installed price significantly more than the median cost used in calculations.
3) The elimination of tracking technology, concentrating technology, or high-efficiency modules will result in lower cost per watt-installed.
4) The estimated conservation of approximately 167 acre-feet of water per year has a dollar value.
5) The installation as designed will require very little additional transmission infrastructure.
6) Solar photovoltaic costs are projected to continue to decline

7) The Department of Energy has expressed a historic willingness to support large solar projects with guaranteed loans and retains, as of April 2016, "more than $24 billion in remaining loan authority to help finance innovative clean energy projects" (http://energy.gov/lpo/title-xvii-open-solicitations).

Conversely, other factors may lead to increased costs, such as the engineering challenges unique to creating floating electrical infrastructure that can accommodate up to 125 feet of fluctuation in water level annually. This will require an adjustable mooring system, which may add a slight cost over existing floating PV projects. But given that PV projects continue to develop nationally, floating solar is one of the most efficient forms of the technology, and Arizona features one of the highest solar capacities in the nation, there should be appropriate impetus for floating solar projects in Arizona to move forward. Given the threatened water supply for the Southwestern United States, there is a real need to implement water conservation technology, which further supports the installation of floating solar on water management infrastructure. There may be market forces aside from CAP that may seek to develop floating PV projects on the reservoir – providing lease revenue to the CAP while mitigating evaporation and algal growth.

The proposed pilot is truly very small considering the surface area of Lake Pleasant, at only 0.4% of the 2008-2014 average surface area of 7,995 acres. Lake Pleasant itself is smaller than Lake Roosevelt, which is not much further away from Phoenix. Lake Powell, adjacent to the Navajo Generating Station, and Lake Mead, just on the other side of the Nevada/Arizona border, are the second-largest and largest reservoirs in the United States, respectively (USBR, Upper Colorado). There are ample additional man-made lakes, reservoirs, water treatment facilities, storage pools and other water bodies in Arizona that would be suitable sites for floating solar infrastructure. The ability to mitigate evaporative water loss while providing low-carbon electricity makes floating solar an ideal technology for sustaining Arizona's future.

Reservoirs and dams prove to be compelling locations for siting floating PV based upon surface area of stored water and existing infrastructure. Lake Pleasant provides the extra benefit of pumped storage infrastructure, which can be used as a means of storing excess solar photovoltaic generation for later use. Pumped storage provides a solution for the intermittency of solar PV generation --a historic drawback of the technology. Floating photovoltaic technology may further provide an intermediary approach to combating dead pools at hydropower facilities – where water levels drop below what is necessary to run installed turbines and generate hydropower. Floating PV can prolong the health of the reservoir by mitigating evaporation. And should the decline of reservoirs to dead pool levels be unavoidable, floating PV on dead pools could generate electricity on-site to use the existing transmission infrastructure associated with hydropower generation.

Moreover, floating solar PV installations may be most valuable in the Lake Powell area directly adjacent to Navajo Generating Station. NGS is a massive emitter of carbon dioxide, and its continued operation is threatened by EPA regulation. Based upon the EPA final regional haze rule regarding the Navajo Generating Station (NGS), it is likely NGS will reduce coal generation on one of its three 750 MW generators or otherwise reduce capacity by 2020 (CAP Budget, 1-20,21). Further, it is likely Selective Catalytic Reduction technology will be installed on the remaining unites in the 2028-2030 time frame (CAP Budget, 1-21). This represents a reduction of 750 MW capacity of reliable, stable energy production that has traditionally powered the CAP. It is imperative that the state of Arizona must seek low-carbon alternatives to replace this lost generation capacity. As stated in the Background to the Problem, the EPA Clean Power Plan calls for a 34% reduction in AZ CO_2 emissions (AZDEQa), but the regulatory authority of the Clean Power Plan is currently stayed. There is local, regional, federal, and global impetus for the aggressive development of low-carbon renewable energy capacity. Installing floating PV on the ample water surface in the immediate area is a possible method of reintroducing lost coal capacity in the direct area of generation.

The ease of colocation of floating PV with existing electrical infrastructure is one of the greatest advantages of the technology. The traditional marriage of water and energy consumption in the water-energy nexus – where water is consumed to produce energy and vice versa – is reversed by floating PV.

Electrical generation with this technology conserves water – both through mitigation of evaporative water loss and by replacing alternative forms of electrical generation which consume water (coal, natural gas, nuclear, concentrated solar, and others).

It is of course not practical or desirable to cover all water reservoirs in the Colorado River system with floating PV. And the technology does not make sense on all open water bodies. Speaking on floating PV technology, Singapore's Environment and Water Resources Minister sums this up quite eloquently: "The appearance of water is still far more beautiful than that of a photovoltaic cell … But where we can, and where it makes economics and operational sense, we will do so" (SUNSEAP).

After the compilation of data on existing floating solar installations, it was discovered that plans are in place by Sonoma Clean Power to develop a 12.5MW floating solar installation in Sonoma County, California – the largest underway in the US (Pyper). This installation would certainly have been included in the case studies and data compilation if this information had been available at the time. This installation is similar in scope to the proposed pilot floating PV system for Lake Pleasant Reservoir. This project adds confidence to estimations of the regional practicability of floating solar installations in the Southwestern United States.

Conclusion

Arizona and the entire Southwestern United States face very real water shortages in the near term as the Colorado River continues to decline. Over-allocation, the driving force behind dropping reservoir levels, now pairs with the demonstrated impacts of climate change to threaten the sustainability of the Colorado River. In the absence of timely solutions to decrease demand and increase supply – policy-based, technological, or other-wise – Arizona will face very real and legally mandated water rationing (CAP Budget, 1-17,18)

The Central Arizona Project is far from the only area that is suitable for the technology in Arizona. As noted in the Discussion, Lake Roosevelt, Lake Powell, and Lake Mead are man-made reservoirs with a massive surface area of open water that may be suitable for floating solar development. But there are many smaller water bodies that are excellent sites as well. In reviewing case studies, wastewater treatment facilities, irrigation districts, and agricultural sites are among some of the most popular sites for smaller-scale installations. This opens up substantial aggregate areas within urban and rural areas for renewable energy generation.

Floating solar photovoltaic is a drought adaptation technology that promises both water conservation and low-carbon energy generation, providing a method of simultaneously adapting to and mitigating climate change. The evaluation of this technology's potential opens up hundreds of thousands of acres of water surface in Arizona alone as potential sites for solar electricity generation – adding gigawatts of potential technical capacity to the state. In exploring capacity for the addition of renewable energy to Arizona's energy grid, it is important to consider floating solar as part of Arizona's renewable energy portfolio.

It was unfortunately outside of the scope of this capstone to determine with any certainty the savings provided by economies of scale with larger installation sizes. It can be assumed quite confidently that installations at the size of 12MW will experience a cost-savings per watt installed over a 501KW installation. However, in the cost dataset available, 500KW or larger was the largest installation size category available. It was also unfortunately not within the means of this study to precisely approximate cost savings due to colocation of floating solar with existing transmission infrastructure, nor to technically model the installation with a component inventory. Many assumptions were made regarding the percentage of Lake Pleasant technically suitable for development, the effectiveness of floating solar at mitigating evaporation, and the amount of water conserved as a direct result of reservoir insulation. All final figures should be taken as rough estimates. All costs are estimated based upon aggregated industry data. Further, lifetime cost per unit energy was calculated assuming a 30 year lifetime and no decline in solar cell performance over that lifetime (though 0.5% decline in output per year is standard).

What the study did find is an upper-boundary cost estimate for a large floating solar installation, which does not factor in the savings provided by colocation with existing infrastructure, improved efficiency and energy density, economies of scale, materials savings, or any of the water savings associated with the installation. The lifetime cost per unit energy from the piloted 12MW installation was estimated at approximately $40.51 per Megawatt-hour. This is less expensive than the rate CAP pays for energy from the Hoover Dam -- $43.68 per Megawatt-hour in 2014 (CAP Budget, 293). It is more expensive than energy purchased by CAP from the Navajo Generating Station by a margin of less than $10 per Megawatt-hour. However, CAP has budgeted for Navajo power rates to increase to almost $39 per Megawatt-hour in 2015 (CAP Budget, 293). If it were possible to build this system in Arizona with the same low costs as the Lightsource QEII Reservoir Project in England (at less than half the median cost of US installations per watt installed), the power would provide a substantial lifetime savings over the current energy market purchases by CAP.

As the impacts of climate change become more severe and better understood by the public, and as water resources become scarcer, a paradigm shift concerning our water and energy resources is inevitable. Technology such as floating photovoltaic – with real potential to save water and generate clean energy – will become increasingly valued. And recreational use of water reservoirs may become less realistic.

Now that we know floating PV can be cost-competitive globally, it is imperative to determine how to bring down costs in the United States. Further, solar companies should look into specific cost estimates and look to floating PV as a potential revenue source. The technology is simple, straightforward, and replicable, using existing mass-produced PV modules. And the benefits of the technology are substantial.

Factoring in all of the benefits of floating PV, the value as a drought adaptation technology becomes fairly clear. Floating photovoltaic has installation costs similar to that of land-based installations, but improved efficiency, energy density, and location availability, with lower site costs, and with an added public benefit of water conservation. It is a more efficient and long-lasting implementation of photovoltaic technology. Floating PV should be considered by solar developers, policy makers, government bodies, planners, and academia as a viable and efficacious response to climate change. In evaluating technical potential for renewable energy generation, as is carried out by the National Renewable Energy Laboratory, reservoirs, wastewater ponds, retention basins, and other water management infrastructures should be considered as appropriate space for photovoltaic energy generation. Further, a higher energy density should be used in these calculations than the average of 48 MW/Km^2 used for estimating technical potential of utility-scale, land-based PV generation. In promoting a sustainable development paradigm of aggressive incrementalism, floating PV is one of many responses to resource scarcity and climate change that deserves consideration for rapid implementation.

Appendix

US State Capacity Factors

Table A-2. Capacity Factors for Utility-Scale Photovoltaics[a]

State	Capacity Factor	State	Capacity Factor	State	Capacity Factor
Alabama	0.200	Maine	0.191	Oklahoma	0.223
Alaska	0.105	Maryland	0.179	Oregon	0.227
Arizona	0.263	Massachusetts	0.182	Pennsylvania	0.177
Arkansas	0.207	Michigan	0.173	Rhode Island	0.176
California	0.252	Minnesota	0.189	South Carolina	0.202
Colorado	0.259	Mississippi	0.197	South Dakota	0.214
Connecticut	0.182	Missouri	0.193	Tennessee	0.201
Delaware	0.186	Montana	0.212	Texas	0.218
Florida	0.209	Nebraska	0.217	Utah	0.248
Georgia	0.203	Nevada	0.263	Vermont	0.176
Hawaii	0.210	New Hampshire	0.184	Virginia	0.200
Idaho	0.220	New Jersey	0.200	Washington	0.199
Illinois	0.186	New Mexico	0.263	West Virginia	0.172
Indiana	0.184	New York	0.184	Wisconsin	0.180
Iowa	0.199	North Carolina	0.206	Wyoming	0.229
Kansas	0.238	North Dakota	0.203		
Kentucky	0.186	Ohio	0.173		
Louisiana	0.196				

[a] (SAM)

Figure 10 NREL "US Renewable Energy Technical Potentials", Page 25.

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