- SOLAR RIVER -

A STUDY LOOKING INTO POWERING THE CAP CANAL WITH RENEWABLE ENERGY THROUGH PARAMETRICALLY ADAPTIVE STRUCTURAL SYSTEMS

75%
17.3 MILES
73,074 5X5' MODULES
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Proposal 3 p13-14 Colin Kenyon Architecture Ba
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Central Arizona Project - Critique on student projects
Bureau of Reclamation - Critique on student projects

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Introduction

The Solar River project is an applied research proposal that looks into covering and powering the entire CAP canal in Arizona with solar panels. The research progress is at stage three currently, having gone through an initial hypothesis in 2015, to a student-led design phase in 2017, and now onto analysis of those designs. This research can be applied to any powered canal with adequate sunshine, the CAP canal system is simply a real-world test scenario. The man-made river is pumped uphill from Lake Havasu 336 miles and 3000 feet in elevation through some of the most rough and arid landscapes on the continent. Currently its powered by the largest and most polluting coal power plant in the USA, the Navajo Generation Station (1). In light of climate change caused by Co2, severe drought due to changing rainfall patterns, and the ever-lowering price of solar energy we predict this type of utility-scale overhaul project a necessity in our future. The canal draws approximately 700 MW of coal generated electricity through its 13 pumps situated all along its length. The proposal leverages Arizona state land, BLM, and other CAP leased lands thus allowing for improvements without purchasing land through eminent domain or other politically difficult means. This plan would save tens of thousands of acres of virgin desert landscape from being bulldozed as compared to a typical solar utility of similar size and location.
Goal and Objective
Our preliminary calculations show that we would be able to generate a sufficient amount of electricity by mounting solar panels directly over the surface of the canal. The first objective of phase three is to precisely calculate the potential generational power using the canal area (rim to rim X 336 miles) as a baseline data point. This calculation will use basic photovoltaic panels typically used in a utility. Comparing this output value to pump demand we will then know whether to use only a percentage of the canal area or to use additional CAP leased land on either side of the canal. The second objective is to select two or three of the most promising student designs done in 2017 to take forward for further analysis. This will be a side-by-side analysis of these design options looking into energy output, amount of structure used, evaporation rates in the canal, ease of access to canal, maintenance of panels, ease of fabrication, parametric adaptability of the design itself. The goal is to make an easy to understand comparison that synthesizes the differences between the design options and layers them over the real-world difficulties facing the management of the canal.

Rationale
The driving idea behind the project is to leverage the land holdings and energy demand of any utility-scale powered canal in such a way that it's demand is met within its pre-established land area without relying on surrounding areas to supply renewable energy. When planning the CAP canal numerous environmental reports were made to guide the design of the project to have a limited environmental impact on wild lands through which it would pass. In the 40 years since the canal has been built much of the impacted areas have begun to recover and re-grow. Canal maintenance access roads, ten-foot-high security fences, drainage, wildlife crossings, public rite-of-ways have all been build and are currently maintained out of the CAP annual budget. By building the panels directly atop the canal all of these expensive to maintain infrastructures would be in double-use and would contribute to a shared budget. Placing equally large arrays outside existing improved areas, even if directly next to the canal would destroy sensitive desert wilderness areas, cost much more in land improvements, security, and maintenance, and would not generate any more electricity than being atop the canal.

Intellectual Merit
This study wishes to look at the issue through an architectural problem-solving lens, a structural engineering approach, and finally a comparative energy and evaporation analyses. Numerous design options have already been explored with many changing variables. Factors in those designs included canal accessibility, structural materials and types, previously improved land usage, topographical analysis, construction feasibility, and solar array optimization. We see this as a problem that can be solved with a design and analysis feedback procedure. Much of the design feedback was worked directly into a parametric script which automatically adapts the 3d model for each design. This is known as a stochastic process which one or more variables are plugged into the algorithm to change or test the output. Geometries of the structure itself, panel size, orientation, truss members all can change in real-time. Some of the modeling software with this capability we plan on using and have used is Rhinoceros with the Grasshopper...
plugin, Ladybug plugin, and Galapagos stochastic optimizer. For more precise photovoltaic analysis we plan on using the NREL SAM calculator. For water evaporation rates, we worked with a hydrology student to help calculate and compare the evaporation rates of the student's designs. One systems engineering student helped calculate the energy production for each student design proposal. If grant or seed funding can be found, new and more precise calculations need to be made on two or three of the most promising design options to further focus the structural design research.

Broader Impacts
Reducing the intellectual roadblocks to a real proposal for which, pending political will, can be implemented by CAP, BoR, and the Army Corps of Engineers. This is a concept that has been studied by the Government of India, UCLA, Texas A&M, CAP, and the Bureau of Reclamation with various conclusions generally relating to the design problems of the structure itself, but not the concept, energy generation, or other broad issues. Working through an architect's creative problem-solving design methodology we hope to resolve the design problems that have come to light in all of the similar studies. This system could be applied to any large canal system worldwide not just Arizona's CAP. A project like this, if built would make an enormous impact in the reduction of Co2 emissions, the western US energy grid, and help the cities of Tucson and surrounding municipalities meet the Paris Climate Accord to which they have signed onto.

Expected Outcomes
The upcoming third phase of the research will rely on seed funding or a small grant to be carried out. The previous independent and student-led design proposals were only possible through a tuition-based platform. The accurate calculations, analysis, and strategic re-focusing of design solutions should be done by one person or a small team of specialists, not un-trained students. The objective of the third phase is to mix, hybridize, and distill the previous ideas into two or three different design proposals. The fourth phase would also rely on a larger grant to fully develop those designs to get a concrete breakdown of energy production, evaporation rates, material usage, construction budget, and Operation and Maintenance feasibility. Both the third and fourth phase could lead to entries in peer-reviewed publications. The fourth phase could possibly lead to a fifth phase of a small test or sample area actually being built and tested by an entity such as the UofA, BoR, or other utility operator.
The team hiking above the study site, Picacho, Az 2017

The team at the study site, Picacho, Az 2017

Phase two, student designs, site visits
The team at the TEP testing yard, Tucson, Az 2017

Colin and Andy Presenting their design to Physics Professor Dr. Richard Powell, UofA

The team at the CAP headquarters, Phoenix, Az 2017

Phase two, student designs, site visits
SIDE -BY- SIDE ANALYSIS

Seven proposals from the study are compared on two factors, energy production and evaporation effects. Staying within the fence-line of the canal, overall system efficiency is measured by how many linear miles of canal it takes to generate the energy needed to power the Picacho pump at its maximum daily demand of 260 mwh/ day. Evaporation rates are a function of how much a proposal shades the canal.

Proposal 1
17.3 miles canal length
260 mwh avg /day
75% evaporation reduction

Proposal 2
24 miles canal length
260 mwh avg /day
38% evaporation reduction

Proposal 3
5.8 miles canal length
260 mwh avg /day
56% evaporation reduction
<table>
<thead>
<tr>
<th>Proposal</th>
<th>Canal Length</th>
<th>Avg. Daily Energy</th>
<th>Evaporation Reduction</th>
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<tr>
<td>Proposal 4</td>
<td>25.5 miles</td>
<td>260 mwh</td>
<td>25%</td>
</tr>
<tr>
<td>Proposal 5</td>
<td>11.9 miles</td>
<td>260 mwh</td>
<td>23%</td>
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<tr>
<td>Proposal 6</td>
<td>17.5 miles</td>
<td>196 mwh</td>
<td>0%</td>
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<tr>
<td>Proposal 7</td>
<td>26 miles</td>
<td>208 blimps</td>
<td>0%</td>
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</tbody>
</table>
SOLAR RIVER - HCPV MICRO-CELL ARRAY

CORRIE WILCOX

ARC 451

MODULE EFFICIENCY
CELL EFFICIENCY
NREL DATA

DC/AC POWER PRODUCTION
POWER OUTPUT

Structural precedent - quonset hut

Array precedent - kenspris micro-cell array (Tucson)

(Freshnel lens section)

Fresnel lens section

OVERALL SYSTEM BENEFITS

Cell type - HCPV dual junction micro-cells

Cell size - 0.346M2

Cell efficiency - 35.2814%

Module efficiency - 29.3613%

Cell irradiance under 1000 suns - 850W/M2

Cells per module - 700

Overall module area - 2.3225M2

Tracker tilt - 15-95 degrees E/W

POWER REQUIRED DAILY - 177MWH - 260MWH (PEAK)

SINGLE MODULE POWER GENERATED ANNUALLY - 952.05 MWH

SINGLE MODULE POWER GENERATED DAILY - 2,600.0 KWH (2.6 MWH)

MODULES REQUIRED - 417 80' MODULES

REQUIRED SPACE - 17.3 MILES

AVAILABLE SPACE - 17.3 MILES

POTENTIAL SYSTEM MODULE COUNT - 73,074 MODULES

MILES REQUIRED TO MEET MAX. POWER NEEDS - 23.5 MILES


SITE PLAN

(System 2017)
The canal is monitored with an interior sensor. If tripped, the corresponding module can be lifted out of place to allow access to the liner.

Each 24’ module could be welded or faceted to the last, only leaving space for nature crossings as needed. In case of a breech, each section of the structure can be detached, lifted with small forklifts and stacked onto the concrete slabs that weigh each module down.

The planned areas around each side of the canal should act as a staging area when the system is installed and maintained. The system’s mechanics would be maintained along the canals while the array modules are shaded from direct sunlight. System boxes are screwed into place on the wall of the steel structure.

(Phil Pauley, 2015) Publication
TENSILE SOLAR

STRUCTURE SPREAD ALONG THE CANAL = 24 MILES

PRECEDENT: Thin Film Solar project is inspired by Frei Otto’s tension work and the idea of minimizing material use. In Munich Olympic Stadium Frei used steel cables to cover vast amount of space with acrylic glass surfaces.

Those ideas were utilized to create structure for the solar panel structure that would supply Piccacho Pump in Casa Grande, AZ.

PANEL: In order accomplish the goal, amorphous thin film was chosen for its light weight and low cost. During design different configurations of simple tension structure with attached acrylic solar panels were tested. The most efficient is presented to you in the form of the tension fabric.

Thin film solar panels are resistant to the temperature changes and those do not affect the production of kwh. Panel fabric is adaptive to the change of angle of the sun via rotating masts.

THE SITE: Specific Topography of the site creates shadows and requires designing for afternoon light of the South West direction.

THE STRUCTURE: The structure is formed through the tension cables that rest on the steel mast and are attached to the ground via steel posts.

TECHNOLOGY: Grasshopper plug in for Rhino was used to generate tensile structure and for the placement of panels on the regularly spaced distance.

ADAPTATION TO CANAL DIRECTION CHANGES

South East And South West direction are most beneficial for solar energy production. The structure goes across and on the side of canal depending on the canal typology to capture the direct sunlight.

SUMMER. 12 PM

WINTER. 12 PM

THIN FILM AMORPHOUS SILICON ACRYLIC GLASS PANELS

Transparent acrylic glass outside layer
transparent conducting coating
antireflection coating
op n-type “window” layer
first semiconductor materia junction
bottom p-type “absorber” layer
ohmic contact substrate
(D. E. Carlson, 1976)

SITE PLAN

MUNICH OLYMPIC STADIUM

(engineeringtoolbox.com, 2017) (www.directindustry.com)
1. A single 3’x3’ size panel produces 3871.88 Kwh annually in average (NREL data)
2. There are 190 to 200 panels per unit
3. Piccacho Pump requires up to 260000 kwh daily
4. 1290 * (60 width of the structure + 40 feet gap in between) = 129022.08 foot or 24 miles.

MAINTENANCE
Panels, cables, masts and other materials are brought to the site for the assembly

Excavator of a small size is able to create a footing within the given distance between the structure and the fence

Small size crane or an "apple picker" truck are helping to elevate the masts.

Two workers at minimum are required to activate the tension forces. Structure masts can serve for security cameras. Water level sensors also can be placed on the masts or panel system

CONCEPT
- Centers of panels are 3’ apart in x direction on cable
- Structure reduces evaporation by about 38.3%
OVERALL SYSTEM DESIGN

POWER DATA

Pisgah Pump Power
7,900,000 kWh per month for Pisgah Pump

Average Power per Month for Panels
120 panels per panel = 144,000 kWh per unit
199.3 units = 11,706.3 kWh per month per unit

Units Needed
11,706.3 kWh / 14,000,000 kWh = 661.6 units

System Length
660.6 units x 300' per unit = 198,180 Linear Feet

Water Saved from Evaporation
58.33% of the 1,000 miles covered

Total System Length
198,180 Linear Feet

TOTAL Linear Feet Needed
1 Mile = 5,280 Feet

One Unit Cost
$8,454.56 per Unit

Total Cost of One Unit of Steel
$84,465

Total System Cost of Steel
$84,465 per Unit

SYSTEM COST

Truss Cost
20' x 20' x 20' x 4' x 4'/unit = 1,644 Linear Feet
6.75' x 3.25' x 144'/unit = 576 Linear Feet
7.75' x 3.25' x 204'/unit = 1,004 Linear Feet

Average Cost of Steel per Unit
$25 per Linear Foot

Member Cost
20' x 20' x 20' x 4'/unit = 1,644 Linear Feet
6.75' x 3.25' x 144'/unit = 576 Linear Feet
7.75' x 3.25' x 204'/unit = 1,004 Linear Feet

Average Cost of Steel per Unit
$25 per Linear Foot

PRECEDENT

P-R Farms
Location: Buffalo, NY
Power Production: 1,132 kWh / 81,430 kWh/ month
Cost: $0.187 per kWh

Colin Kenyon, Andrew Kraut
**Panel Data**

**Price per Sqft**
Price of a typical 65"x39" at $225.25/unit

**Life Expectancy**
Average 25-30 years

**Size**
Typical size 65"x39"
Thickness approximately 160-190 micrometers

**Power Output per Unit**
A single unit can produce 265 watts
Average efficiency 18-25%, maximum 36%

**Functioning Temperature**
Works best at 150 degrees Celsius

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**Structural System**

- **Locking Panels to Cable Pull**
- **How Panels are Winched In and Out**
- **How Panels Lay When Fully Extended**

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**Plan**

**Short Elevation**

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**Section Elevation**

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**Panel Components**
- Front surface electrode
- Transparent electrode
- Monocrystalline silicon wafer
- Surface grid electrode

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**Development of an electrode with a high aspect ratio**
- Improvement to silicon passivated (P) cell and (PP)
- Reduction of recombination losses through further improvement to a-SiQT solar technology
- Improvement to front-side passivated (P) cell

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**Panel Benefits**
- Improved light absorption
- Increased efficiency

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*(Panasonic, 2012)*
Keeping material costs in mind, the approach was to maximize efficiency by using something that was as close to a pure reflection-compression system as possible. Using both parabolic and Galilean mirrors, the individual structural features were specifically designed for a continually varying distance. Fractal subdivision and optimisation of the effectiveness of minimal amounts of materials were achieved. The tension members are woven in place. This method of construction allows for a good deal of flexibility in the positioning and spacing of the individual mirrors for pin connections and hooks. The tension members of the structure were cohesively attached to the compression members.

With modern manufacturing techniques, the assembly can be produced and easily assembled for a high level of precision and the overall assembly process can be used to great cost savings.
WOVEN CARBON FIBER
The primary tension members of the structure are based on a woven carbon fiber precedent which does not require the use of off-site manufacturing.

CONCENTRATED SOLAR
The initial concept was a molten salt concentrated solar project which superheated water past the boiling point to drive a steam turbine.

1ST ITERATION
The first iteration of the project was a pure tension compression system which used the efficiency of tensegrity to optimally span the gap.

2ND ITERATION
The second iteration was one which largely carried over to the final. Using a physics engine, all members were brought into optimal balance.
High Concentration Multi Junction Photovoltaic Dish
Light Weight Tensile Steel Net Structure

Power Output
260 MWH @ 24 hours cycle
630 panels required to power Picacho Pump Station (260mwh peak) 12 miles if placed consecutively

dish area 5.5 sq/ft concentration ratio: 1200 suns
triple junction photovoltaic cell efficiency: 40-48 %
each panel has an average of 486 cells and fully tracks the sun
average area of each panel is 3,500 sq/ft (50’x70’)

Evaporation Decrease: 23% decrease (NREL Power Production Data 2017)

Utility Precedent
Valldoreix-greenpower CPVRS 072

Relationship to Canal
Adapts for placement along any portion of CAP canal regardless of orientation
90° 67.5° 45° 22.5°
Specifications:
- Stainless steel concentrating dish with mounting bracket on cables
- Parabolic dish reflects sunlight to secondary mirror which reflects it to the optical lens
- Electrical current transferred from cell runs along cable structure to inverter

Assembly and Maintenance: Transpoted in flatbed to site in a roll. Two people needed for installation. Can telescope up and out of the way for canal maintenance.

Structure: Two axis joints and telescoping members support full tracking of the sun.
MAKANI POWER

Makani Power focuses on constantly moving energy takes that collect energy at multiple altitudes attached to a "kite" or "pigeon." The kite creates energy and uses the movement to create its own wind energy. Makani Kites designed as a simple four-part system: Ground Station, Tether Box, and the system of Tethers mounted on the kite.

ALTAEROS

Designers of the Buoyant Airborne Turbine (BAT) Conceptually, it will remain stationary in the sky and benefit of the more consistent and unobstructed winds speeds at higher altitudes. Altair focuses on internal communications, energy generation, and overall autonomous flight control technologies.

SECURITY + MONITORING

(Solar, Makani, 2017)

(Solar, Makani, 2017)
**STRUCTURE DETAILS**

**ENERGY GENERATING BLIMP**

Blimps will maintain variable cruising altitudes that will allow maximum energy generation. Blimps have the ability to move vertically along a tether to optimize "wind-catching". Blimps will provide additional support systems such as constant security monitoring along canal and accurate wind readings for local areas.

**ADDED BENEFITS**
- 24/7 Security
- 24/7 Energy Generation
- No need for helicopter flyover
- Easy maintenance

**INTERMEDIATE ANEMOMETERS AND WIND VANES**

Combination of two basic instruments: Anemometer and Wind Vane

Allows for the streamlining and compression of instruments. Allows more correlated information to be sent at once to systems in order to allow for better reactivity.

Anemometers located incrementally along tether / between blimps moving vertically, will periodically shift to accommodate the movement of the blimps. Will relay information to Blimps as well as to ground station to maximize energy generation from blimps.

At least one "system" per blimp + one at the very bottom and one at the very top to ensure efficient blimp movement and positioning.

**GROUND STATION**

Ground station serves a multitude of functions. Provides a relay location for energy production, maintenance location, and anchor for blimps.

1. Through ground station, energy will be recorded and relayed to next destination. Station meant as a conduit for energy. Information about energy production as well as all maintenance issues will be sent to staff as necessary.
2. From ground station, maintenance staff will be able to access both interior and exterior of blimp via maintenance platform and tether platform. Stations will be well grounded to provide blimps an anchor as to keep them from floating above the land. Stations will have the ability to pull in or release tether in order to allow for blimp movement along the tether / pulling the blimps in for maintenance.
3. Stations will be well grounded to provide blimps an anchor as to keep them from floating away from their intended positions above the land. Stations will have the ability to pull in or release tether in order to allow for blimp movement along the tether / pulling the blimps in for maintenance.
4. Ground station requires initial energy to operate. Tesla battery will allow initial movement of tether vertically to allow blimps necessary leeway to maximize energy production.
5. After initial energy, cost, all energy will be regenerated and made up via blimps once there is little to no initial cost to actually move the blimps into the air. Blimps will be towed into position in the air.