

City of Golden PV Evaluation Final Design Report

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Final Design Report

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May 4th, 2021

Acknowledgments

Over the course of the last two semesters our team has had the pleasure to work with the City of Golden and members from the Sustainability Board. We would like to thank Theresa Worsham and Marissa Major for allowing us to lead this project and providing us with the assistance we needed along the way. We would also like to thank the Sustainability Board members for providing feedback and asking thoughtful questions throughout the duration of this project. Special thanks to Micha Allen for assisting with cost estimates and other information related to solar energy. During this last semester we have been in contact with Jill Engel-Cox from the National Renewable Energy Laboratory (NREL) in Golden. We would like to thank her for the help she has provided with her background in renewable energy. Next we would like to acknowledge Tim Ohno from the Physics Department at Colorado School of Mines. He acted as our technical advisor and consultant on this project. Another important person we would like to thank is Leslie Light, our project advisor and professor. She has aided us in every step of this project and encouraged us to provide the best possible information to the client. Lastly, we would like to give thanks and appreciation to the Colorado School of Mines and specifically the Capstone Program for providing us with the opportunity to work on this project and learn alongside all of the previously mentioned people.

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Executive Summary

The City of Golden Photovoltaic Evaluation is a project undertaken by the Golden Solar Solutions team. The project's goal is to perform a feasibility analysis to help the City of Golden achieve their goal of 100% renewable energy by 2030. Our team consists of Zachary Simpson, an electrical engineer and Scrum master; William Simpson, an electrical engineer; Jessica Ellis, a civil engineer and communications leader; Robert Scavo, a mechanical engineer; and Daniel Morrison, a mechanical engineer. The scope of the project has expanded from its original 2 MW goal to include the entire plot of land designated for solar off of Pine Ridge Rd. and W. 56th Ave. This allows for a much higher generation, but also presents new challenges for the project. These challenges include interconnection, sloped areas, possible floodplains, and increased project time. The team has addressed the new scope along with the new challenges it brings through analysis of methods for risk mitigation, detailed design critique, engineering modeling, and financial analysis. To support these aspects of the project, validation has been provided through engineering calculation, ground testing, and design drawings.

The final design includes a risk matrix and risk register to address the possible risks of this project and provide mitigation and potential solutions. Along with risk analysis, many methods of mitigating these risks were investigated. These risk mitigations include lightning mitigation, array security, and meeting city construction standards. Sustainability was also a large focus of the project. The team investigated panel longevity, panel recycling, and land management strategies such as agrovoltatics and pollinator plants around the arrays.

In this final design report we include our recommendations for the racking design and electrical components. We present a phased approach for array implementation in order to maximize the land area while being able to implement in more manageable sections. After making our recommendations we discuss the engineering design analysis and cost analysis of the final design. Included in the final deliverables are a combined phase analysis, land sustainability options, recycling plans, and further risk mitigation according to the risk analysis. The initial work breakdown structure is updated to reflect the changes of the project, along with a more detailed cost analysis. The end of this report details the lessons we learned as a team and the challenges we overcame along the way. We also have suggestions in moving forward for the work we were not able to complete.

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1. Introduction

1.1. Overarching Project Goals

Upon first arriving at the land plot, the team noticed a solar array was already installed. However, no company could be reached about its usage. This meant the team had to begin their work by first working around the already installed solar garden. At first, it was not considered in any design. However, it does provide some initial insight into the feasibility of solar on the land. Also, by looking at the existing array initial estimates for required components and interconnection could be made.

Another challenging aspect of the array was a large, heart-shaped divot which sat towards the middle of the plot. The divot had steep slopes and a curved design, making it difficult to properly simulate any solar panel implementations. On top of this, the ground at the base of the divot appeared unsuitable for building on and was strewn with trees which would cause significant shading on any panels installed in the divot unless they were to be cut down. This location on the plot proved to be the most challenging to address [2].

The other major challenge involved the size of the land. At roughly 80 acres, designing and installing a solar array that could utilize the entire plot would be a large financial undertaking to be done at once. To solve this, the team devised a phased approach. This approach would break up the major arrays into more manageable sections, allowing the City of Golden to complete them when the necessary resources are available. Suggesting the phased approach allowed the team to focus on optimizing individual array capabilities such as power outputs and subscriptions while maintaining a detailed and overarching plan for the entirety of the project.

1.2. Other Considerations

In designing this array, the team spared no details when considering its security, public and land usefulness, and reliability. With the array's massive size and visibility, it is liable to become the target of vandalism and robbery. Solar panels are expensive and contain many valuable materials, so solar garden owners are advised to maintain some form of security. Oftentimes, this is as simple as installing solar panels on the roof, where they are away from passersby. However, with this array, since it is located in the middle of a large field, other security measures had to be analyzed. For this, the team decided to look into advanced array protection concepts, including special types of screws which are only extractable with a specific tool. Another source of security is the potential for security cameras to be installed or for security personnel to be stationed by the array during its initial operating months.

Another security and hazard risk will be weather, particularly lightning. The implementation of lightning rods throughout the array will help to mitigate this hazard. These will help ensure that should the array be hit by lightning, the high heat and current will not damage the array or the surrounding power systems.

A second important concept the team pursued was the implementation of a public education center in the array. The team planned to use the small heart-shaped divot near the middle of the land plot to design and install a mini solar array, featuring measurement equipment and energy readings taken from the array itself. This would allow groups of students or interested individuals to explore the solar array and learn about the work going on. Unfortunately, complications with construction on the heart shaped divot forced the team to relocate the educational array. The team decided the education center would be best located near the front of the array. Finally, the team has drafted a conclusive plan for the implementation and grid interconnection that needs to occur.

1.3. Sustainability

Perhaps the most important part of this project was determining the effect this array would have on the environment in Golden. Throughout multiple tests and models, the array efficiency was determined to be over 80%, classifying this design as a highly-efficient array. On top of this, the power output by the array is quite massive. The array will generate 19.5 GWh of power throughout the year, which is enough to offset nearly 9% of Golden's energy bill. The implemented array will produce a massive boost in Golden's push for 100% renewable energy usage in 2030. Besides the obvious sustainability effects that this array will produce for Golden, the team also looked into positive land sustainability options. These concepts included multiple types of plants and wild animals, which would allow the land plot to continue to serve its purpose to Golden's wildlife. The best options for this purpose included pollinator plants and bees, along with wildlife-aware fencing, so that the array would not interfere with any animal migration or grazing patterns. At the end of this array's lifetime, or when the current panel technology surpasses those used in the array, the team has also begun preparing a recycling plan so that the panels used in the array maintain a net-positive relationship with the environment.

2. Application of Design Methodology

2.1. Civil Design

The civil design portion of this project was done using AutoCAD Civil 3D which is an infrastructure design and documentation software. For the scope of this project we used Civil 3D to evaluate the land constraints based on existing conditions. Contours from the Denver Regional Council of Governments (DRCOG) database were imported into Civil 3D and a surface was created. Each contour had an associated elevation, and the program interpreted the elevations to create a 2D and 3D surface for evaluation. Slope analysis allowed us to determine which parts of the land were feasible to build on based on city and state requirements [1]. Further analysis can be done in Civil 3D in order to grade the land, design utilities, and create construction plans.

2.2. Helioscope

The main software used for the solar simulation was Helioscope which is an advanced solar design software. This software functions by letting the user design and simulate an array in an exact geographic location. The yearly weather trends for the year are taken into account so the amount of sunlight on the array per year can be approximated. Also the software has an extensive component library where you can simulate different components such as panels and inverters to see what will be most efficient for the design. Helioscope allows the user to simulate

the overall energy outputs along with a breakdown of system losses which helps the designer understand how to improve the system. There are many functions inside the software to increase array efficiency such as shading heatmap models.

2.3 Phased Implementation Approach

The team recommends going forward with a phased approach to the array. This allowed the team to look into the feasibility of the entire plot of land while still providing sections that will be financially possible by the client. The overall array was split into three separate arrays as seen below in Figure 1. The land was already naturally split up due to the access road currently on the land and wanting to keep this road for maintenance and installation access. Also it was important to leave ample space from the current array on the land owned by Clean Energy Collective. Space was also left between each array to allow for wildlife to move through.



Figure 1: Phased Approach Layout

2.3.1 Phase One

This section was chosen as phase one due to it being least affected by shading due to the hogback on the West side. Meaning it is the most efficient array on the plot. This array is also easily accessible from the access road. It is also close to the point of interconnection with the grid so not much extra work would be required to connect. Along with all of this, it is among the smaller arrays so it would be the perfect pilot array for the plot as it will show the potential for solar energy on the plot.

2.3.2 Phase Two

This was determined to be phase two due to its close proximity to the road allowing for easy installation and connection. This array will also include a separate educational array that can be seen in the North most section of phase two. This educational array would be separate from the rest of phase two and allow for Golden and the surrounding areas to come and learn about solar energy. Separate metering would be included to look at how much energy would be produced along with displays on the panels and racking system.

2.3.3 Phase Three

Phase three includes the largest standalone array and would need an extension to the access road to help with installation. This array is farther from the point of interconnection. Also the array is affected by shade on the west side but shading has been minimized by our array design. While this array was presented as one phase, it may be beneficial to split it into two phases or at least two arrays. The team recommends if splitting the phase three array in half it should be done with the split moving North and South. Despite being split, the arrays should still stay in close proximity and be surrounded by one fence in order to maintain the production and accessibility of the array.

2.4 Financial

For the financial calculations the team looked into three important aspects. First was looking into the initial capital sunk costs. These costs would consist of the pricing for implementing the initial solar plot (solar panels, raking, electrical BOS, etc). Next was obtaining the cost of energy and relaying how this data would relate back to the system payback. Finally we added in the other sunk costs and incentives. The main sunk cost coming from the maintenance needed for the system which would change depending on the year. While the incentives mainly consisted of Federal ITC . Using all of these data points we can find important financial measurements such as payback period, system costs, return on investment, and the internal rate of return.

2.5 Physical System

2.5.1 Electrical Component Selection

The team decided to use a Jinko JKM-580 panel for multiple reasons. First, Jinko has been on the forefront of efficient and cost effective panel design. While the company is based overseas in China they have opened a manufacturing facility in the United States. The Jinko JKM-580 panel is 580 watts per panel which helps to increase the overall efficiency of the system. The solar industry continues to move in the direction of larger panels and the team wants to provide a solution that will withstand the test of time and be efficient for the longest amount of time. This panel is also a split cell panel meaning the bottom half of the panel has the ability to be shaded on the lower half without cutting off the production of the entire panel like a single cell panel would. By being able to bypass the shaded portion of the panel, the mismatch losses of the panel and therefore string are decreased leading to higher efficiency. While there are cheaper alternatives to this panel they will not last as long and will not be as efficient as the suggested panel.

The team decided to work with a commercial utility scale solar inverter: the Delta M125HV. An efficient inverter is a key component in a solar array as it converts the direct

current of the solar array into alternating current which is used on the grid. This inverter has the ability to reach efficiencies of up to 99.2%. For this project no battery system was required as the team is using the grid as a battery. This means that the solar array will be producing energy and putting it on the grid directly and then Xcel energy will be able to determine the amount of energy from the community solar garden to take off the subscriber's energy bill. The Delta M125HV is a 1500 volt inverter which is an increase from the previous standard of 1000 volts. When generating and moving electricity at higher voltages the current in the line is lower. When the current is lower the electricity losses due to resistance are also decreased, leading to a higher overall efficiency of the system. The Delta M125HV is a string type inverter meaning it is in line with the panels covering a smaller amount of panels than the traditional central inverter. The string inverter has now become popular in industry as they are more cost effective along with providing flexibility to expand the array and being highly efficient. This brand of inverter is a standard in industry and was recommended by McKinstry, a local engineering firm based out of Golden. McKinstry has years of experience designing, developing and installing large scale arrays.

2.5.2 Racking

Following the preliminary design report, two racking solutions were chosen to be the leading options for the project. These options include the Advanced Modular racking system and the Titan racking system. The Advance Modular system is a four panel high, landscape orientation rack, while the Titan system is a two panel high portrait orientation rack. Of these two systems, the Titan racking system was chosen to move forward. The Titan system was chosen because portrait orientations are optimised for dual cell panels due to the way shading is mitigated on dual cell panels by turning off the lower half of the panel. When in landscape orientation, the dual cell panels cannot utilize this ability.

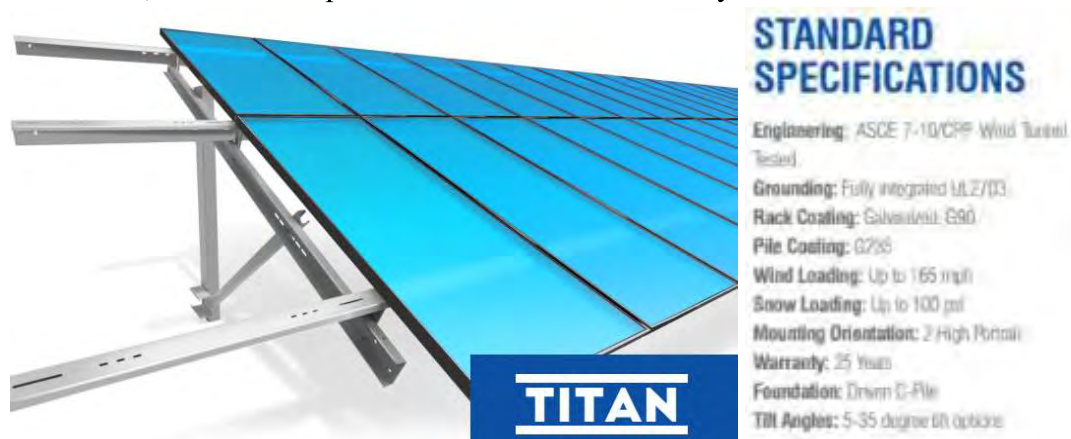


Figure 2: The Titan Racking System

The Titan racking system is two panels tall in portrait orientation and uses ground screws for the majority of the foundation. In rockier areas, driven c-piles will be needed for foundation, but this should only be a small portion of the land. The Titan racking system is within Golden's requirements for structural integrity, having a wind speed rating of 165 mph and a snow load rating of 100 psf. The optimal tilt angle for the Titan racking systems was found to be 23 degrees through Helioscope testing. The system has a 25 year warranty and will likely work past this time; however, 25 to 30 years would be a good conservative value to expect maintenance.

APA Racking provides all needed services for installation. We have received a full quote on how much the system will cost along with how much services such as ground testing, shipping, installation, and documentation will cost. The team recommends using all of APA's services for racking installation as the services will be needed regardless and APA has competitive pricing due to being able to consolidate to one company for all racking work.

HARDWARE		Price	Price / Mod	Price / Watt	
Foundation Hardware		\$144,020.48	\$22.57	\$0.0389	Required
Racking Hardware		\$300,865.27	\$47.16	\$0.0813	Required
Subtotal		\$444,885.75	\$69.73	\$0.1202	
SERVICES					
Shipping from APA (Ohio)		\$36,014.40	\$5.64	\$0.0097	Optional
Onsite Anchor Testing		\$9,630.50	\$1.51	\$0.0026	Optional
Engineering Documents (CO) PE Stamp		\$3,750.00	\$0.59	\$0.0010	Optional
Subtotal		\$49,394.90	\$7.74	\$0.0133	
INSTALLATION					
Foundation Installation (APA Managed)		\$83,183.85	\$13.04	\$0.0225	Optional
Post Installation (APA Managed)		\$14,801.91	\$2.32	\$0.0040	Optional
Racking Installation (APA Managed)		\$71,504.23	\$11.21	\$0.0193	Optional
Module Installation (APA Managed)		\$52,300.02	\$8.20	\$0.0141	Optional
Subtotal		\$221,790.03	\$34.76	\$0.0599	
Total		\$716,070.67	\$112.24	\$0.1935	

Figure 3: APA System and Installation Estimate

2.5.3 Security and Fencing

Due to concerns of animal movement throughout the land; a large, all encompassing fence has been ruled out. Instead of one large central fence, the team recommends frontside security fencing. This would entail having a large, highly secure fence near the road. This would discourage people from trying to get onto the property. This would also make it harder for passersby to throw rocks at the array from the road. Away from the road, smaller fences would be surrounding each phase of the array. This would not allow animals to roam within the array; however, it would allow animals to easily move between and around the arrays.

Due to lighter fencing, alternate security methods were considered to protect from panel theft. The array is most at risk for panel theft in the first few years following implementation. Using some or all of the team's recommended security solutions will help to mitigate panel theft for the first few years and throughout the life of the array.

Security fasteners are the first solution. The panels will need fasteners regardless, so switching to security fasteners would be a simple way to improve security. Security fasteners are bolts with a specially designed head that requires non-conventional tools to remove. Some examples can be seen in Figure 4 below. There are also companies that provide per customer



Figure 4: Security Fasteners

custom fasteners. This would entail custom tools and custom fasteners made for this project only.

It would be extremely difficult to find a tool that works on these fasteners unless they were stolen from the owners of the array. One such company that provides this service is Bryce Security Fasteners. While a fastener made specifically for this project would enhance security, it would be significantly more expensive than more available security fasteners. A standard security fastener should be sufficient and can be found from providers such as McMaster Carr.

Panel locks are another security option. Panel locks are devices that attach panels together. When implemented on a row of panels, it makes it impossible to remove one panel without removing the entire row at the same time. This makes quick, single panel thefts impossible, and paired with security fasteners, large scale panel theft would take a long time. The longer thieves need to work on a job, the more likely they are to get caught and the less likely they are to attempt theft in the first place.

The final recommendation is conventional security. This includes motion activated lights for movement within and close to the array fencing. A thief will likely be trying to steal panels at night. Being spotted by a floodlight has a high chance of scaring them into leaving. Beyond lights, a few security cameras could be implemented inside of the fence. Being inside of the fence would make the cameras hard to tamper with unless the thief was already in the fence and by that point would have already been spotted. A final security option would be to enlist an on duty guard to watch the panel over the first few years of high theft rate.

Risks other than security were also taken into account. An in depth risk mitigation analysis was done on the project. This risk mitigation rated each of the projected risks and rated them based on likelihood and danger. A mitigation strategy was devised for each. This risk mitigation will be talked about more later in the report.

2.5.4 Lightning Mitigation

An important consideration for an array this size are the environmental conditions that may be present during its lifetime. With such an expansive array, it is crucial to prepare for any and all weather conditions. This includes lightning and thunderstorms, which occur relatively often during spring and summer in Golden. A lightning strike to the array has not only the potential to destroy panels with intense heat and power, but also the ability to fry any electrical systems that have been installed.

Thankfully, there are multiple options for electrical storm security. The quickest solution would be installing charge-dissipation terminals, which work to remove charged particles from the air and ground, thus preventing lightning from even striking the area. Unfortunately, these systems are not designed to withstand heavy wind loads, and would be unsuitable for open fields in Golden. As a result, the team has reached out to multiple lightning rod array manufacturers for quotes and product information. Designing a suitable lightning rod array for the solar array will help alleviate some concerns about the array's longevity and durability. The design for the lightning rod array will be similar to Figure 5, which shows a mock, ground-based solar array fitted with lightning protection. The rods themselves will rise out of the top of the tilted solar panels, perpendicular to the ground. These rods will be designed to ensure they are above the top of any solar panel, thus ensuring their protection. Along with rods installed along the top of the solar panels, surge protectors will be used to ensure the lightning does not damage the grid and the array's connection to the grid.



Figure 5: Example Lightning Array

2.5.5 Grid Interconnection

For the interconnection with the grid the team was working under assumptions as during our time table and as this is a research project we were not able to get information from our local utility Xcel energy. The assumptions that were made for this project first is that the transmission lines currently located at the connection point can handle the load of adding the array. The second assumption is the transmission voltage at the connection point which the team decided to assume as 13.8 kV which is a typical low voltage transmission value. As this was a feasibility study the team wanted to look into the necessary aspects of interconnection which is over current protection (circuit breakers) and the transformer to step up the voltage to be able to connect to transmission lines. The team sized the interconnection for the first phases as it could be scaled or replicated for the following phases. It is not possible to size one transformer for the whole array as it would be inefficient until all phases are built.

First looking into the circuit breakers which function to protect our equipment in case of a fault on either the utility side, array side or in the transformer. Circuit breakers are rated based on the current that will be flowing through the lines and if the current is higher than expected the breaker will trip and disconnect from the line. Due to the lack of information on the utility side of our array a circuit breaker can not be sized. On the array side the current was based off the max current output from the inverters. For the Delta Electronics M125HV the overcurrent protection should be rated at 150 amps based on the max current output of the inverter which is 135 amps and the max output fault current of 160 amps. With there being 25 combiner circuits from the inverters in phase one that adds to the combiner panel having a max current of 3750 amps. For NEC compliance multiply the max panel current by 1.20% for a total current of roughly 4500 amps.

Next the team looked at our transformer sizing which will increase the voltage generated to be able to connect to the transmission network. The inverter selected outputs the voltage at

600 volts AC and typically low voltage transmission is 13.8 kV. Once the array is connected to the Xcel network it will go through the utilities substations and the voltage will further be stepped up for distribution. The team decided to use a pad mounted transformer meaning it is mounted to ground on usually a cement pad. Continuing with the overall sustainable design the team selected an Eaton Envirotran Transformer which uses environmentally friendly dielectric fluid and has a longer lifespan than typical mineral oil filled transformers. To size the transformer the output was based on the 3.13 MW in phase 1 and assuming the power factor is at unity which is when the system is most efficient. Therefore there is a value of 3.13 MVA and for NEC compliance must be increased by 20% for sizing. The transformer was sized to be 3.76 MVA which is well inside the limits of the Eaton Envirotran.

What is provided here is a simplification of what would be needed to interconnect to the grid. As this is a feasibility study the team wanted to show some of the major components needed to connect with the grid. For a full interconnection design a switch gear along with a control house would need to be included along with metering points on both array and utility side. This should not be done without additional information on the point of interconnection to the electrical grid.

3. Engineering Analysis

3.1 Helioscope Models

For our array design the team had to factor in the geographical constraint of the hill on the West side of the plot. This hill which has an elevation of 400 feet, referred to as a hogback, will cast a shadow later in the day during the months when the sun is lowest in the sky. Therefore the production of the overall array will be decreased significantly during November, December, and January. While in older array designs panels would not be placed wherever modules are shaded during the winter solstice now the popular method is to look into the shading on the panels throughout the year. This where the Helioscope software is an important tool as the software simulates the panels based on position of the sun through every hour of the entire year. This gives the team the ability to really understand how the array is with respect to the shading due to the mountain.

While in our previous designs the team was trying to understand the max amount of energy produced by the land we now shifted focus to look where it would be most viable and efficient. In the design stage of the project the team also looked into the possibility of a single axis tracker but this was discarded due to geographical constraints and cost. Therefore the team went forward with the South facing fixed tilt array with a slope of 23 degrees. The design included 15 foot setbacks from a fence line and 12 foot spacing between rows of panels. The final array design can be seen below in Figure 6.

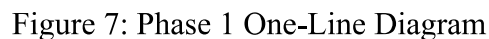


Figure 6: Final Array Design

The team wanted to provide a first off very efficient array which could have been done by just looking at the shadow cast on the winter solstice. Although this method would have led to a much smaller array and discount area that is still efficient for solar energy. Using the helioscope software the team decided to use a shading cut off of 10%. This means that any panel that has shading losses of over 10% will be removed from the array. While it is not perfect that part of the array will be shaded 10% of the time it still provides a large number of hours for production. It is important to remember that the purpose of the array is to generate a certain number of power throughout the year and by still including panels that are shaded during a small amount of time during the year should be overlooked. Also the most efficient hours for a solar array are during the summer months when the days are longer and there is no shade on the array at that time. The design still has a performance ratio over 80% meaning it is a highly efficient array.

3.1.1 Phase One

Phase one is a 3.77 MW DC array. With a DC to AC load ratio of 1.21 the AC nameplate of the array comes out to be 3.13 MW AC. The projected annual production of the array came out to be 5.82 GWh with the highest producing month being July and the lowest producing month being December for all phases of the array. The largest source of loss is shading which throughout the year will cause 6% loss. The physical components of the array include 6498 Jinko JKM580M split cell panels and 25 Delta Electronics M125HV string inverters. The array is made up of 12 strings with a string size of 21-24 . Overall the array had a performance ratio of 81.3% making it highly efficient.



3.1.2 Phase Two

3.1.3 Phase Three

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3.2 Civil Design

The initial civil design of this project was creating an existing conditions plan which can be seen in Figure 8. This involved working in AutoCAD Civil3D to draw the existing solar panel, roads and houses surrounding the area, and trees scattered through the plot. There are also contours that are contained in the property line of the plot. The contours from DRCOG were collected as a response to the 2013 Colorado flood, and served as a basis for starting land analysis. Elevations were put in for each contour and trimmed to remain inside of the property line. This gives us an idea of the best place to put solar panels.

From there, we were able to create a surface from the contours to provide a 3D view. After the helioscope models were imported into AutoCAD Civil 3D, the contours were laid over the reference and a two-point slope function was used to get the cross slopes of the panels. The slopes go across the panels as a “drop of water” that would act as the natural slope of the land. As can be seen in Figure 9 the slopes vary from 2.7% to 38.9%. The areas in which the slopes get that steep are in the heart shaped divot which we previously decided we cannot construct in the divot due to it being a floodplain. Aside from that section of the plot and the hogback, the remainder of the land is feasible to work with.



Figure 8: Existing Conditions

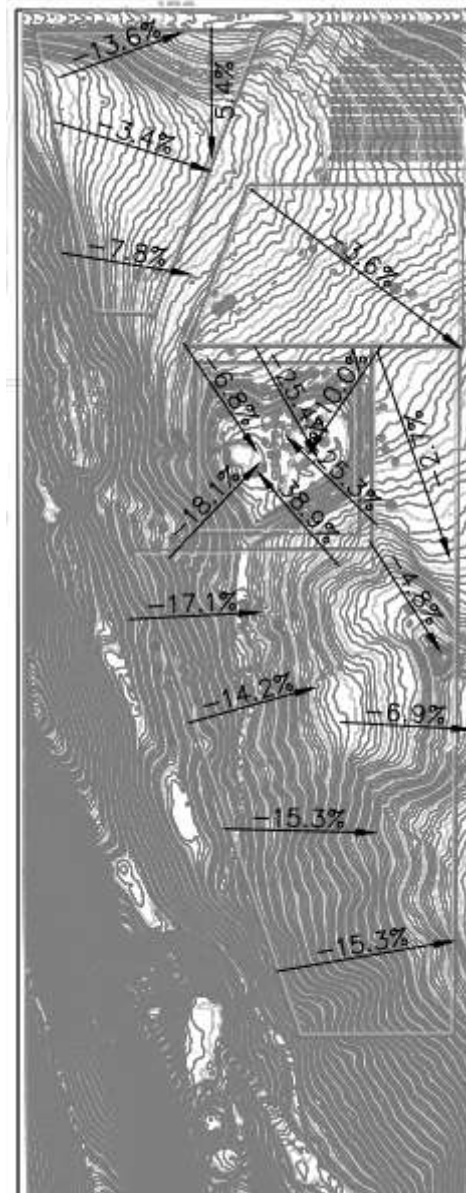


Figure 9: Slope Analysis

3.3 Ground Truthing

To verify our model, the team went out to the plot of land with a 100 watt solar panel owned by a member of the team. The team went on a sunny day and tried to replicate the tilt and direction the array faces. While doing so the team saw close to the max production the 100 watt panel can have which proves this plot of land is viable for solar energy. The team experimented with tilt angles and panel direction to see instantaneous effects on the output from the panel. This helped to prove our Helioscope design was correct as the tilt angle of 23 degrees saw the largest production. While it is hard to compare a megawatt scale array to a single panel this still helped the team to see firsthand solar energy being produced and not just blindly trusting our simulation. Pictures from these experiments can be seen below in figure 10 and 11. More information and data from the experiment can be found in the appendix.

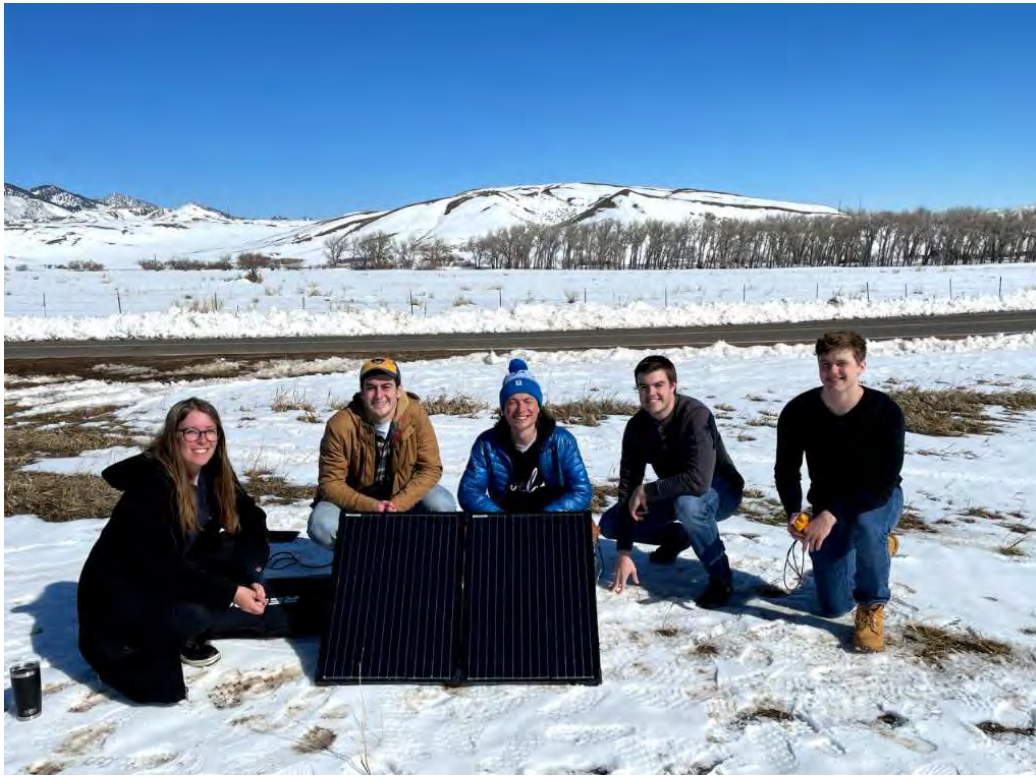


Figure 10: Team Experimenting With Solar Onsite



Figure 11: Jessica Measuring Slope Of Panel

3.4 Weather analysis (lightning, hail, snow)

Hail is a major cause of damage for solar arrays. The Jinko 580 modules used for this array have front glass made up of tempered glass. Jinko estimates that their panels will be able to resist 45 mm hailstones at a velocity of 29 m/s. For reference, this is a 1.27 N-s impulse impact. Class 4 hail resistant roofs are rated for up to 1.74 N-s impacts. For most hail storms, the panels will be able to withstand any significant damage [1]. That being said, in the case of a catastrophic hailstorm, extra panels have been factored into the cost of the system as a precaution.

Snow loading can be an issue for both the structural integrity of the racking and the shading of the panels. The racking system is rated for a snow load of 100 psf which is much larger than Golden's design requirements for a snow load of 30 psf [11]. As far as shading goes, the snow will typically slide off of the panels due to the smoothness, tilt and temperature of the panel surface. The panels will be at least three feet off the ground in all locations so that when the snow does slide off the panel, it will not pile up at the base of the panels and prevent further snow shed.

The wind rating of the racking system is 165 mph. Golden requires buildings to be able to withstand a wind load of 150 mph [11]. Our design exceeds this requirement with a factor of safety of 1.1.

To ensure full protection of the array, a lightning rod array was designed. Since Golden faces a relatively high number of lightning strikes a year, and the open area of the land plot would make the solar panels very vulnerable, the team went ahead and contacted multiple lightning protection companies in the Colorado area (NOAA) [10]. The team suggests following up with Mr. Lightning and pursuing the quote that they presented. This quote sets the installation and grid connection of the lightning rods to be \$520,925. This installation process will occur after the installment of the panels and racks themselves.

3.5 Cost analysis

For cost analysis of this project we looked into the sunk and prospective costs that would affect the system. For the sunk costs we looked into the initial capital costs, yearly maintenance, and array degradation. These capital costs include the overall materials needed for the solar system such as panels, racking, wiring, etc. For some of these costs we were able to get estimates from manufactures of the parts we were simulating, while other costs came from the NREL 2020 Q1 Solar PV system cost Benchmark report [4]. The parts we were able to get quotes for were the panels, racking, and install labor. Another included sunk cost was that of yearly maintenance. This was quoted at about \$17/ kWh produced annually [9]. Another important sunk cost was the array degradation. For this we assumed that the array degraded at a rate 0.5% annually. This is a sunk cost as the costing of the system depends on the power it produces and a degrade in power generated would lower the revenue. The prospective costs included the cost of energy produced in kWh at \$0.08/ kWh [6]. These prospective costs also included incentive costing which consisted of a federal ITC of 22% of the initial capital cost of the system. The cost breakdown Table 1 and the cash flow generated from our data can be seen in Figure 12.

Cost Breakdown					
	Cost(\$/W)	Phase 1	Phase 2	Phase 3	Total
Module	0.37	\$1,394,900.00	\$1,161,800.00	\$2,160,800.00	\$4,717,500.00
Inverter	0.05	\$188,500.00	\$157,000.00	\$292,000.00	\$637,500.00
Structural BOS	0.1	\$377,000.00	\$314,000.00	\$584,000.00	\$1,275,000.00
Electrical BOS	0.13	\$490,100.00	\$408,200.00	\$759,200.00	\$1,657,500.00
Install Labor and racking	0.12	\$452,400.00	\$376,800.00	\$700,800.00	\$1,530,000.00
EPC overhead	0.08	\$301,600.00	\$251,200.00	\$467,200.00	\$1,020,000.00
Sales tax	0.04	\$150,800.00	\$125,600.00	\$233,600.00	\$510,000.00
Developer Overhead	0.07	\$263,900.00	\$219,800.00	\$408,800.00	\$892,500.00
Contingency	0.03	\$113,100.00	\$94,200.00	\$175,200.00	\$382,500.00
Total	0.99	\$3,732,300.00	\$3,108,600.00	\$5,781,600.00	\$12,622,500.00

Table 1: Cost Breakdown [9]

Total cash flow vs. Year

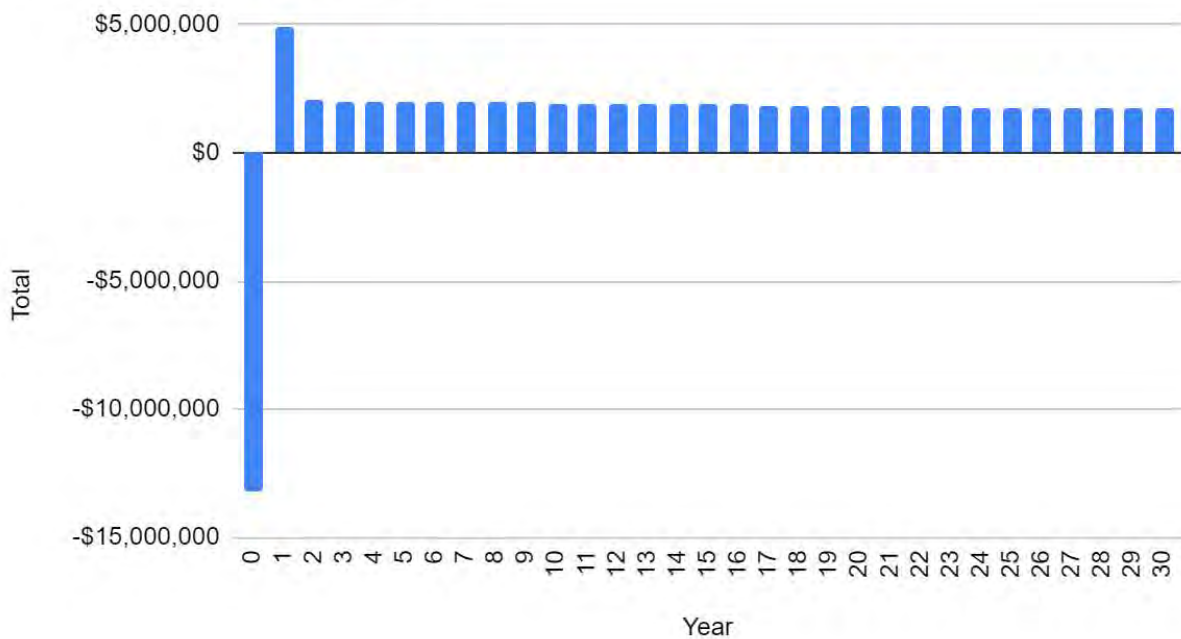


Figure 12: Cash Flow of the System [6]

From these costings, the payback period and the return on investment can be calculated

and are included below:

- ROI
 - 330% over the course of 30 years
- Payback Period:
 - 5 Years 3 Months

3.6 Subscription Analysis

To determine a subscription plan for the City of Golden, two approaches were taken. The first uses similar community solar gardens as a benchmark to estimate how many Golden households the array should support. This method was done for phase one and the solar garden as a whole. The second method is a stretch method that uses the total production of the solar garden to determine how much power each house in Golden would receive if all of Golden was connected to the grid.

The 1.1 MW Collective solar array was used as a benchmark for predicting subscription goals. Even though the 1.1 MW array is smaller than the phase one array, the array is in Colorado, so electricity prices and needs will be more similar to the needs of Golden rather than larger arrays in different states. As said before, the benchmark array has an installed capacity of 1.1 MW. The array has 500 customers which when split evenly would allow 2.2 kW to each subscriber. For phase one, at the same rate of 2.2 kW per subscriber, the array could supply around 1,680 customers. The Golden Solar Garden as a whole can produce 12.8 MW. This could supply close to 5,818 customers if subscriptions were used for the whole array.

Xcel energy reports 7,294 customers as of 2019. 1241 of these customers are businesses and 6053 of these customers are residential. The Golden Solar Garden would likely supply both business and residential customers. Split evenly, the solar garden is capable of supplying 2.9 kW to each customer if all customers with Xcel were able to subscribe. If half of Xcel's customers were to subscribe, each customer would receive 5.8 kW from the solar garden.

We expect to do a power purchase agreement through Xcel, so using Xcel customers to estimate the number of subscribers is an efficient way to estimate how much each subscriber should be allotted. The team recommends allocating 6.0 kW blocks per customer with moderate interest in subscribing, and if there is a city wide interest in subscribing, the team would recommend allocating 3.0 kW blocks per subscriber.

3.7 Risk Mitigation

Risk analysis is a vital part of any construction project, so we chose to build a risk assessment matrix and risk register for this project which can be seen in Figures 13 and 14 below. We have discussed many risks that can occur at different stages of this project including flooding in certain areas, panel reflection, tampering, electricity, weather, and toxins [1]. Each risk is assessed according to its cause and effect. The probability and impact score are estimates we came up with based on those factors, and a level of risk is determined from the probability and impact score. This gives the stakeholders an idea of what can be expected along with a risk response strategy in the event one of these things happening.

		Impact				
		1	2	3	4	5
Probability	80-100%	HIGH	HIGH	HIGH	HIGH	HIGH
	70-80%	MEDIUM	MEDIUM	HIGH	HIGH	HIGH
	40-70%	LOW	MEDIUM	MEDIUM	MEDIUM	HIGH
	5-40%	LOW	LOW	MEDIUM	MEDIUM	MEDIUM
	0-5%	LOW	LOW	LOW	LOW	LOW

Figure 13: Risk Matrix

Risk Number	Risk Title	Reason/Cause	Effect
(1)	(2)	(3)	(4)
1	Flooding	Water flooding from extreme rain storms in the heart shaped area	Could move the custom racking if the soil becomes too wet and destroy the area further
2	Reflection	Sunlight is reflected of of the panels and causes glare	Bothersome for neighbors and surrounding area
3	Tampering	People tampering with the parts - educational portion of it. Wildlife potentially moving through the area.	Replace expensive parts, functionality could diminish or disappear with enough damage
4	Electricity	Sparks or shorts in the electrical system	Cut off the power source, cause fires in the area if the ground is dry enough
5	Weather	Snow, rain, hail, lightning	Impact the performance of the panels. Snow specifically could cover a majority of the panel. Hail could destroy the face of the panel. Lightning could blow out panels entirely.
6	Toxins	Materials used for the solar panels	Put toxins into the ground and cause environmental issues

Probability	Impact Score	Level of Risk	Risk Response Strategy
(5)	(6)	(7)	(8)
0-5%	1	LOW	Do not construct in this area due to it being a flood zone and having steep slopes.
5-40%	2	LOW	Place panels so they are not going to reflect towards houses or major roads - proper siting, angling, and orientation. Use single-faced panels
5-40%	3	MEDIUM	Fence off most of the array and other equipment - protect what is most expensive. Adding security fasteners to keep panel parts in place. Potentially adding security guards for the first few months. Install frontside security fences.
5-40%	4	MEDIUM	Monitor the equipment, perform tests before installation.
40-70%	4	MEDIUM	Angle/tilt the panels enough so the snow can slide off. Put in less shaded areas so the snow can melt faster. Implement a lightning rod to absorb strikes. Have an overstock of panels so they can be easily replaced.
0-5%	4	LOW	Use materials that are less toxic for the environment. soil testing before construction

Figure 14: Risk Register

4. Final Deliverables

4.1 Combined Phase Analysis

Combined, the array is capable of producing 12.8 MW DC. Phase one produces 29% of the total power, phase two produces 25% of the total power, and phase three produces 46% of the total power. Phase 3 is nearly half of the total array. That being said, if phase 3 was to be split into two phases, each phase would have very similar production.

The entire array will generate 19.5 GWh throughout the year which is over 8.25% of the total energy consumed by the City of Golden based on the 2019 Xcel Energy consumption report. While Golden is already well on their way to 100% renewables by 2030 right now being 30% powered by renewable energy this project would be a huge increase in the goal. Currently Golden has 54 business subscribers and 12 residential subscribers to solar gardens for a total of 4.47 GWh which is less than 2% of Golden's total energy consumption [3]. With a larger increase in capacity and ease to our subscriber approach the team can increase these numbers significantly. Golden has shown a want for expanded solar capacity as 81% of Golden voted in favor of the Rooney Road expansion that never made it to construction.[9] With this project being built it will provide an easy way to residents to show their support for solar.

The largest loss for the array was shading. This was expected from the beginning of the project due to the close proximity to a hogback and north table. The losses actually turned out to be lower than initially expected. While it is a sizable loss, it is not detrimental to the design or feasibility of the array.

The physical design consists of a total of 22,000 solar modules and 82 string inverters. The panels are racked in portrait positions with 2 high rows. Each rack will have 15-20 columns depending on the needed size in each area. Depending on the chosen security solution, each rack will have security fasteners and/or there will be around 20,000 panel locks. The array will also be outfitted with 200 lightning rods.

4.2 Land Sustainability

The team wanted to include a full design for this project and this included how the array is going to affect the land we are building on. To combat the changes we are making to the land the team thought it would be best to provide options for land sustainability. Agro-voltaics was the original idea we had in mind for sustainability, and options for it included leaving adequate space for cattle and sheep grazing. Although this idea would sustain the current ecosystem, it would allow for the possibility of damage to solar panels if there is no barrier around the array. The next option the team considered was bee hives and flowers to allow for a new ecosystem. While this would help, it could be hard to control the population of bees and if the panels need to be replaced then it could potentially destroy the new habitat. While in previous iterations of the project the team looked into agro-voltaics this was not the direction the team decided to go as it would take away from the overall solar production of the plot and not provide many benefits. After discussing other options and getting input from our stakeholders, we decided to move forward with different pollinator plants. This is a similar idea to having beehives, but is less invasive in the event of replacing and maintaining the array. Pollinator plants can be planted year round for different conditions including the blooming season, elevation of the ground, expected weather, and sun and water needs. These types of plants provide options for the City of Golden

and serve as a sustainable option for the plot of the land in order to maintain an ecological balance [8]. The pollinator plants can be seen below in Figure 15.

Wildflowers listed are perennials unless otherwise noted. (*) May be aggressive spreaders with good soil and moisture.



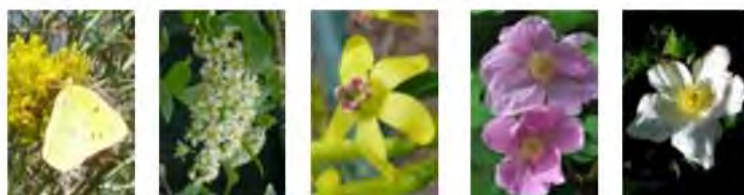
Early Season Wildflowers	Scientific Name	Notes
Nodding Onion	<i>Allium cernuum</i>	Nodding pale pink umbels; 6"-12" tall; open woodlands, sunny, dry locations, up to 11,000' late spring early summer
Sulphur Flower	<i>Eriogonum umbellatum</i>	6"-12", sunny, dry, well-drained, up to 10,500' Flower heads and leaves turn reddish later in the season
Wallflower	<i>Erysimum spp.</i>	6"-24" tall flower heads; biennial or short-lived perennial. Sunny dry locations up to 8,000'
Prairie Smoke	<i>Geum triflorum</i> (<i>Erythrocoma triflorum</i>)	Nodding rose-pink blossoms followed by long feathery seed pods, 6" – 12" tall; sun to part shade, moist to part-dry, up to 10,000'
Firecracker Penstemon	<i>Penstemon eatonii</i>	Bright red blossoms on spikes; 1-2.5' tall, sunny, dry, well-drained. Bees love this plant.
Blue Mist Penstemon	<i>Penstemon virens</i>	Small blue-violet spikes up to 1' tall in late spring. Dry, well-drained locations in sun to part-shade, up to 10,000'
Pasque Flower	<i>Pulsatilla patens</i> (<i>P. ludoviciana</i>)	6"-12" tall, part sun, moist to dry locations up to 9,000' Cup-shaped lavender blossoms followed by feathery seed heads
Golden Banner *	<i>Thermopsis divaricarpa</i>	1-2' tall, part sun, moist to dry; up to 9,500'. Can be aggressive.
Photos by Linda Smith, Volunteer for the Colorado Native Plant Society (www.conps.org) (Photos of <i>Penstemon eatonii</i> , <i>Penstemon virens</i> and <i>Rubus deliciosus</i> by Irene Shonle, Director, CSU Extension, Gilpin County) References: <i>Attracting Native Pollinators</i> , Xerces Society; <i>Bringing Nature Home</i> , Doug Tallamy; <i>Pollinator Biology and Habitat</i> - CO NRCS - http://efotg.sc.egov.usda.gov/references/public/CO/pollinators.pdf ; <i>Suggested Native Plants for Gardening and Landscape Use on the Front Range of Colorado</i> , Colorado Native Plant Society, Rev. April 2008, www.conps.org/Committees/horticulture.shtml ; Xerces Society www.xerces.org		



Mid-Season Wildflowers	Scientific Name	Notes
Pearly Everlasting	<i>Anaphalis margaritacea</i>	Silvery foliage, clusters of 'straw' white flowers, excellent dried flower; 1-2' tall, sunny, moist or dry sites; up to 10,000'
Showy Milkweed *	<i>Asclepias speciosa</i>	3-4' tall, back of border; sunny, moist to dry locations; up to 8,000'; will self-seed; great for the Monarchs!
Harebells	<i>Campanula rotundifolia</i>	Nodding bell-shaped flowers; 6-12" tall, moist to dry, sun to shade, up to 13,000'
Aspen Daisy	<i>Erigeron speciosus</i>	Daisy-type blossoms, lavender with yellow centers; 1-2' tall, sun to part shade, moist to dry; up to 9,500'
Blanketflower	<i>Gaillardia aristata</i>	1-2' tall, up to 9,000'; dry, well-drained, sunny locations. Most of the commercial varieties are non-native hybrids.
Beebalm	<i>Monarda fistulosa</i>	2-3' tall, sun to part-shade, moist or dry; up to 9,000'
Rocky Mtn. Penstemon *	<i>Penstemon strictus</i>	1-2' tall spikes; dry, well-drained, sun to part shade; up to 10,000'
Black-eyed Susan	<i>Rudbeckia hirta</i>	Golden yellow/brown centers; biennial or short-lived perennial, reseeds readily; dry mountain meadows up to 9,000'; moist to dry locations



Late-Season Wildflowers	Scientific Name	Notes
Rocky Mtn. Bee Plant	<i>Cleome serrulata</i>	1-3' tall annual; large pink to lavender flower heads; reseeds readily; sun to part shade, dry, well-drained; up to 7,500'; available by seed
Common Sunflower *	<i>Helianthus annuus</i>	2-5' annuals; sunny, dry, well-drained; give these plants lots of room in an informal, meadow-type setting
Prairie Sunflower *	<i>Helianthus petiolaris</i>	
Spotted Gayfeather	<i>Liatris punctata</i>	Spikes of fringed rose-purple flowers attract butterflies. Rigid linear leaves. 6"-12" tall; dry, sunny, well-drained locations; up to 7,500'
Tansy Aster	<i>Machaeranthera canescens</i>	Erect stems of small lavender daisy-like flowers; short-lived, but readily reseeds; 6"-30" tall; sun, dry, well-drained locations; up to 8,000'
Goldenrod *	<i>Solidago spp.</i>	1-4' tall depending on species; spreads by rhizomes; tiny yellow flowers in heads bloom mid-late summer; sun/part shade; moist to dry; elev. range varies w/species



Shrubs	Scientific Name	Notes
Rabbitbrush	<i>Chrysothamnus nauseosus</i>	Bright yellow flowers late summer; up to 6' tall which can be controlled by early spring-time pruning; dry, well-drained, sun; up to 8,000'
Chokecherry *	<i>Prunus virginiana</i> (<i>Padus virginiana</i>) ssp. <i>melanocarpa</i>	Racemes of white flowers in spring, followed by red/black fruit. Up to 6' high, wide-spreading, prefers dry, well drained location in sun or part-shade; up to 8,500'
Golden Currant	<i>Ribes aureum</i>	Yellow flowers in spring, black fruit for the birds; leaves red/orange in fall, 4-6' tall, arching branches; sun/part shade, well-drained; moist to dry, up to 10,000'
Woods Rose *	<i>Rosa woodsii</i>	Large pink flowers in summer; red/brown prickly stems; red-orange hips in fall; 2-6' tall, suckers from rhizomes; sun to part shade; moist to dry; to 10,500'
Boulder Raspberry	<i>Rubus deliciosus</i> (<i>Oreobatus deliciosus</i>)	Large white flowers in summer; fruit great for wildlife; 5' tall; sun to part shade, dry, well-drained, up to 9,000'

Figure 15: Pollinator Plants

4.3 Panel Recycling

Another sustainability topic that the team researched was panel recycling. The current lifespan of photovoltaic panels is twenty to thirty years, meaning they will eventually need to be replaced. When they are replaced the inoperable parts need to go somewhere and landfills do not provide a sustainable option. Most parts of solar panels should be fully recyclable, but due to the heavy metals in the panels, they are too expensive to take and are therefore not easily recycled [7]. Currently in the United States, there is only one company that is starting to recycle monocrystalline and polycrystalline solar panels. Recycle PV Solar is located in Nevada and will take panels from all over the country, but the shipping and transportation costs are paid by the customer. With the magnitude of this project, shipping thousands of panels to another state will incur high costs. There are other options for recycling in the United States, but they are scarce and one has to be a subscribing customer. In the next thirty years, we hope (and expect) to see improvements in panel recycling.

5. Project Management

For this project, our deliverables are summarized into a Work Breakdown Schedule in graphical form below in Figure 16. We changed some of our deliverables from the preliminary design report in order to better reflect the scope of work as it has changed from last semester. We were not able to get a simulation video flyover, but the rest of our deliverables have been met.

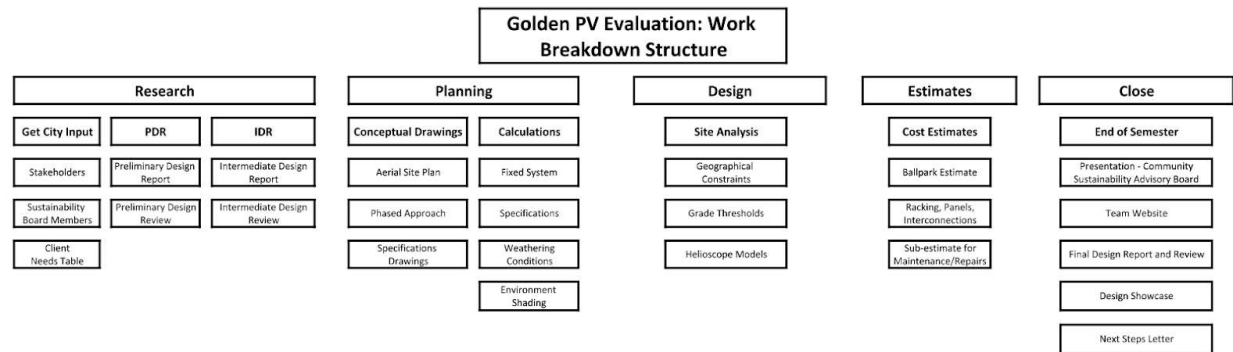


Figure 16: Updated Work Breakdown Structure

This was a purely analytical project. There is no budget associated with the work done by the students on this project. The cost analysis of the system can be referred to in Section 3.5.

6. Lessons Learned and Next Steps

For this team the design was based around providing a design that is efficient, sustainable and cost effective. These three components of design have changed a lot over the course of this project as in the beginning design we thought was based solely around the project, but now we believe it is also everything affected by the project as well. For example in our project, our design did not stop at a solar array but also encompassed how to combat affecting the land and soil the array is on and how to have little effect on the wildlife that passes through the land. Our project was also based in the Sustainable Design Studio and therefore the team wanted to make sure every aspect of the project was based around sustainability. Efficiency is closely tied to sustainability as being efficient means little to no losses when it comes to components. Cost effective solutions are also very important, as this will lead to the project actually being done.

The team learned a lot about working together throughout the semester and year. Some lessons were learned by bringing in personal experience and a lot by trial and error. One thing that worked really well for the team was assuring each member had a set role on the team and knew what topics they should be working on during each sprint cycle. By setting specific roles it helped clarify what needed to get done as it is very easy to get lost in a project of this size. Also having constant team meetings and client meetings was necessary and something that it took a little while for the team to implement. Having these constant meetings helped to keep every member accountable and the project moving forward.

Should the city of Golden look to move forward with this design, the team has some recommendations on what needs to be done next. First and foremost will be any civil work that needs to be done on the land. This would involve designing construction plans and continuing with land analysis for the entirety of the project (or for a specific phase). Following through with

more accurate and deliberate land analysis will ensure the area is fit for development and does not contain any concerns with regards to erosion or flooding. The team also advises the city to look thoroughly into the recommended land sustainability ideas and identify possible solutions before any major land development takes place. Once this is complete, the team suggests moving forward with mechanical work, including designing and maintaining fencing around the arrays and also ensuring the access path remains usable. This could involve creating multiple paths around the worksite to ensure quick and efficient installation or maintenance, but must not result in serious damage to the land. The next mechanical problem to tackle would be the impact running water will have on the array. While the overall plot itself does not face serious flooding threats, there are some areas on the land that may occasionally flood, including the heart-shaped divot near the center. It would be very important to establish a flood-mitigation plan before the array is complete. This will be implemented and used to ensure that any unexpected water has a runoff location that does not put any piece of the array in jeopardy of flooding. Should this plan be successful, and the flooding risk of the land plot deemed minimal, the central, heart-shaped divot can be used for an additional purpose (new array, grid interconnection, etc.). Another mechanical step for this array will be the lightning rod protection, which will be finished once the array has been installed. With these considerations in mind, the team recommends saving the electrical work for this project until the end. This portion will involve dealing directly with Xcel to finalize an interconnection plan. The team expects two options from Xcel: 1) the ability for the city of Golden to directly buy and develop the array, therefore owning it, or; 2) Xcel fronts the upfront cost for developing the array and Golden looks to buy back power. Finally, the team recommends continuing to develop a series of business plans that will help maximize the array's outreach. These plans may include working with Xcel energy to design accurate cash flow analysis and generate subscribers for the array. Overall, the team suggests a wide swath of ideas that can be used to push this project forward.

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