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Final Report - Team 26
Solar to Steam: A Sustainable Reintroduction to Fireless Steam Locomotion

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Abstract

The diesel engine is very efficient for high-speed (40+ miles per hour) rail operations; however, a low-speed (5-7 miles per hour) switching locomotive spends 75% of its day at idle, dropping its diesel engine efficiency to 2%. Furthermore, these engines create excessive CO_2 and NOx emissions that are harmful to the local environment and operators. A fireless steam locomotive eliminates these harmful emissions and increases efficiency while not reintroducing the dangers of the traditional steam locomotive. This project explores the use of solar power to generate steam for a 1:8 scale fireless locomotive for hobbyists and museums to use for recreation and as an educational demonstration to invigorate change within the locomotive industry.

Executive Summary

Prior to the introduction of diesel and electric locomotives, the steam locomotive dominated all locomotion. This project offers a sustainable reintroduction to fireless steam locomotion by leveraging a renewable and highly-abundant energy carrier: solar. The main objectives of this project can be summarized into three final deliverables: a system conceptualization and model of how to use solar heat to create steam for the purpose of powering a steam-powered locomotive that operates at low speed operations (i.e. a switching locomotive), a baseline of current methods of low speed rail operations, and this final report which assesses the operational advantages of a solar to steam system versus current systems while considering alternative technological applications. First looking at the system conceptualization, this system can be separated into three subsystems: energy generation, steam generation and recharging, and the fireless locomotive. Together, these three subsystems create a system that requires solar energy as an input and outputs a functioning steam locomotive. With regards to the design context, the team has created a holistic list of stakeholders that include clients and consumers, society and environment, government, manufacturing and suppliers, and rail companies / yards. Given the diverse amount of people and groups impacted by this project, five criteria have been identified that impact each of these stakeholders: environmental impacts, upfront costs, operational costs, job creation/loss, and working conditions. Moving onto the user requirements and engineering specifications, these have been tailored to each of the three subsystems. Overall, it is essential to understand each of the three subsystems and how they interact with each other as well as the role they play in the entire system. In order to ultimately generate an “Alpha Design”, the team leveraged its knowledge of functional decomposition, morphological analysis, and design heuristics to identify more than twenty potential design concepts to pursue within the project scope. The team then narrowed the potential solutions down to iterations of energy generation, specifically the four common types of concentrated solar power and solar photovoltaic. From there, the team used its initial engineering analysis and model to select an “Alpha Design”: a 1:8 scale fireless locomotive that uses a linear fresnel concentrated solar power (CSP) system along with a heat exchanger, steam accumulator, and high-pressure hose for locomotive refueling. However, this differs from the team’s final design which still uses a 1:8 scale fireless locomotive, but with solar photovoltaic (PV), an electric steam generator, and a hose for refueling.

Extensive engineering analysis was conducted to evaluate the solar array size, PV power generation, the power use breakdown between household applications and the locomotive, the amount of steam generated using the remaining power, how long that steam can be stored, and the overall system cost. The team then created a CAD model of the final design to truly understand how all subsystems interact with one another. From there, the team created a verification plan to verify engineering specifications such as PV efficiency, steam generation, and safe handling conditions. Furthermore, hypothetical short-term and long-term validation plans were created to ensure the team met our project sponsor's desire to create an application for using solar energy to generate steam for the purpose of fireless steam locomotion. Continuing with anticipated challenges, the team had struggled with creating the system overview, especially considering the project scope fluidity that began with steam generation for a full-scale switching locomotive before moving to a 1:4 scale hobbyist locomotive and then a 1:8 scale hobbyist locomotive. Furthermore, the team has struggled to address some of the solar heat and steam generation specifications while also originally trying to understand how a switching yard functions in tandem with the freight cars traveling between rail yards. To conclude, current diesel engines used in switching applications are inefficient and a fireless steam locomotive presents an attractive alternative. In the final phase of this project, the team adapted its analysis to accommodate an end-to-end scenario-based analysis in which a user inputs variables such as the month of operation, type of 1:8 locomotive, and years of anticipated system use, among other factors, to determine relevant information such as how expensive such a system would cost as well as the necessary solar array size to power such a locomotive. The team also concluded the project by completing a baseline of current methods of low speed rail operations.

Project Terminology and Nomenclature

1. 1:4 Scale Locomotive: 10" standard gauge (distance between inside vertical surfaces of rail head, compared with 56.5" standard gauge used for most large-scale railroads)y7
2. 1:8 Scale Locomotive: 7 ¼" standard gauge.
3. A : Area
4. AC: Alternating Current
5. C : Clearness Index
6. CB : Cylinder Bore
7. CSP : Concentrated Solar Power
8. C_p : Specific Heat of Water
9. D : Driving Wheel Diameter
10. DC: Direct Current
11. DF : Derating Factor
12. DNI : Direct Normal Irradiation
13. DNI_N : Normalized Direct Normal Irradiance
14. DNI_U : User Specified Direct Normal Irradiance
15. DSG: Direct Steam Generation
16. EPA: Environmental Protection Agency
17. EPDM Rubber: Ethylene Propylene Diene Monomer Rubber
18. FF : Fill Factor
19. F_s : Flash Steam
20. H : Humidity
21. h_s, h_w, h_1, h_2, h_{fg}, h_g : Enthalpy
22. h_a, h_w: Heat Transfer Coefficient
23. HTF: Heat Transfer Fluid

24. I, I_a: Current
25. ITC : Current Temperature Coefficient
26. K : Efficiency
27. k : Boltzmann Constant
28. k_1, k_2: Thermal Conductivity
29. L_1, L_2 : Thickness
30. m_w: Mass of Water
31. m_{steam}: Mass of Steam
32. MPH: Miles per Hour
33. N : Number of Panels
34. NREL: National Renewable Energy Laboratory
35. P : Pressure
36. P_a : Power
37. PV: Photovoltaic
38. Q_h: Energy Required Per Hour
39. Q_s : Energy Required to generate steam
40. q_1, q_2: Energy Loss
41. Q, Q_o: Solar Irradiation
42. q= Electron Charge
43. R_1, R_2: Resistance
44. S = Piston Stroke
45. T_2, T_1, T_a, T_M, T_C : Temperature
46. TE : Tractive Effort
47. TES: Thermal Energy Storage
48. V, V_a : Voltage
49. VTC : Voltage Temperature Coefficient
50. W : Wind Speed

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Section 1: Introduction and Background

Project Introduction

Railway transportation moves one-third of the United States exports and accounts for approximately 40% of the freight volume transported within the United States [1]. Advances in technology have made the long haul operations of locomotives more environmentally friendly by greatly improving their fuel efficiency and greenhouse gas (GHG) emissions, while low speed operations such as switching applications are utilizing these same engines in their most inefficient manner. To further the positive impacts of an environmentally friendly railway system, Ted Delphia would like to explore how to bring switching locomotion up to the same efficiency standards as their long haul counterparts by reintroducing the fireless steam locomotive to the market. In conjunction with the Southern Michigan Railroad Society, he strives to educate the public on these remarkable engines and how they can create positive change for the environment, industry, and society. In this project we set out to explore harnessing solar energy to generate steam to power these fireless locomotives and how they will impact the environment, rail industry, and society. Exploration for this project begins with the current fireless steam locomotives being used for switching applications in Germany, Austria, Switzerland, and India. Each of these countries have harnessed the power of waste heat and waste steam to power their locomotives [2]. Swiss company Dampfspeicherfahrzeuge Ersatz von Elektro - und Dieselfahrzeugen, referred to as DLM-ag, is a steam locomotive engineering firm that is actively researching and developing more modern ways of using the traditional steam and fireless steam locomotive to replace the less switching-friendly diesel locomotives. Using waste steam from local power plants, DLM currently has eight fireless steam locomotives in operation.

While waste steam presents a viable option for powering fireless steam locomotives in Europe, the location of power plants within the United States does not allow for this easy alternative. For this reason this project will look into how to create a self sustaining energy solution for railyards to power fireless locomotives. We will explore photovoltaic and concentrated solar power technologies (Subsystem 1: Energy Generation) and how each system generates thermal energy to be used to generate steam (Subsystem 2: Steam Generation and Recharging Station). Subsystem 2 also explores methods for this steam to be stored and injected into the fireless locomotive. We will also create a baseline of energy requirements for different industry standard switching locomotives and functioning small scale models (Subsystem 3: Fireless Locomotive). Our overall system can be viewed below in figure 1.

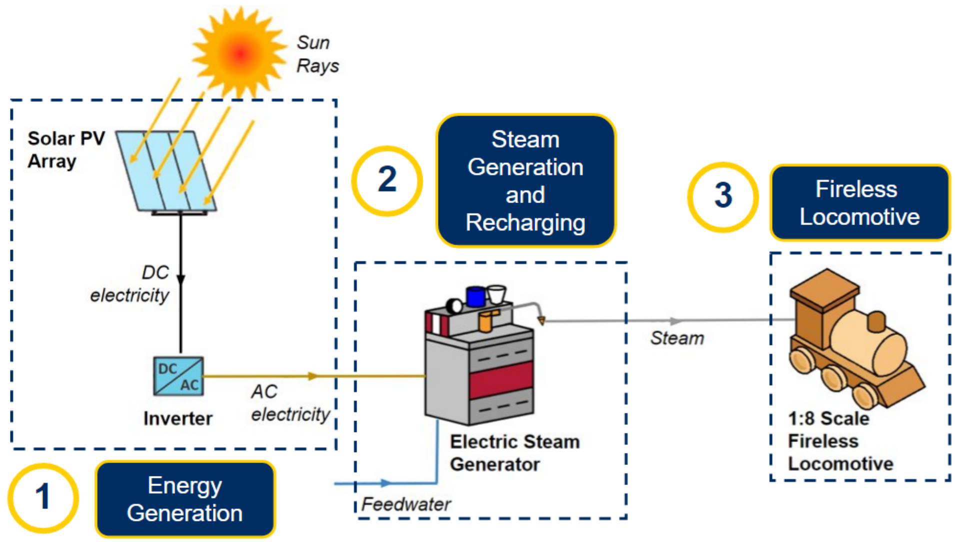


Figure 1: System Overview

By the conclusion of this project, we will have created a computer model that will take a user's scenario-based inputs and generate the energy requirements, estimated cost, and the solar field size they would need to power their switching locomotives. This deliverable will serve as an educational tool for Ted Delphia, our project sponsor, and the Southern Michigan Railroad Society to use within their museum in hopes of invigorating change within the rail industry. Using this computer model we will specifically be able to assess the energy requirements, estimated cost, and the size of the solar field needed to power a 1:8 scale fireless switching locomotive for the Southern Michigan Railroad Society Museum in Clinton, Michigan. Moving onto the second deliverable, the team will be creating a baseline of current methods of low speed rail operations, guided by the Swiss document "Dampfspeicherfahrzeuge Ersatz von Elektro - und Dieselfahrzeugen" and statistics on US switching locomotives such as numbers, types, and operational costs.These two deliverables culminated in the third and final deliverable: this final report that assesses the feasibility of this technology while considering alternative applications. Ultimately, this project could result in a hands-on backyard or room scale room scale system in a future semester.

Background

The invention of the steam engine in the 1700's changed the world, as it launched the industrial revolution. From the early 1800s to the early 1900s, steam engines were the primary engine for locomotives. Highly efficient machines for their time, steam engines made cross country transportation of goods and people possible [3]. Steam engines use combustive materials such as coal, oil, and sometimes wood to feed the fire that heats water in a large tank until it boils and water vapor is created [4]. This water vapor is transported throughout a system of pipes into piston cylinders as the steam expands. The amount of steam entering the piston cylinders is dependent on a controlling valve. The reciprocating motion of the pistons push and pull the rods connected to the driving wheels, providing the force needed to make the locomotive move. To increase the efficiency of these machines, condensers were added to recirculate some of the steam and supercharging was created by redirecting the steam pipes over the boiler heating source to raise the steam temperature higher than boiling water was able to achieve [4].

Though revolutionary for their time, the operation of these machines did not come without risk. Controlling the pressure within these boilers, for example, was a difficult task. If the pressure became too high, the boiler would explode and send metal flying through the air. Pressure relief valves were created to combat this, but it was not a fail safe system. In addition to safety concerns, the environmental impact of these machines cannot be ignored. The burning of coal releases carbon dioxide, sulfur oxide, nitrogen oxide, and particulate matter into the atmosphere, thus creating harmful greenhouse gasses and contributing to smog and acid rain. Not only are these emissions harmful to the environment, they are also harmful to the operators as the inhalation of these emissions can cause respiratory illness and chronic lung disease [5].

In the 1930s, technology shifted and the diesel locomotive replaced the steam engine as the industry standard. In a diesel locomotive, the diesel engine does not move the train. Instead, the energy created by the diesel engine powers an electric generator attached to the traction motors, which move the wheels of the locomotive [4]. The diesel engine provided significant power and fuel efficiency, while also being easier and safer to operate than the steam engine. These locomotives quickly took over the market and remain the primary engine for locomotives today. While safer than the steam engine, the diesel engine still poses a risk to the environment and nearby communities. The emissions from a diesel engine help contribute to ground level ozone which destroys crops, trees, and other plant life; furthermore, the sulfur oxide created also contributes to acid rain [6]. On a human level, the effects of these emissions are similar to those of the steam engine as the particulates and emissions can cause respiratory damage and chronic lung disease [5]. Presently, the United States Environmental Protection Agency (EPA) regulates the quantity of emissions from these engines in an effort to combat harmful effects. Modern diesel locomotives that transport goods and people over great distances at high speeds have great fuel efficiencies and emissions are much lower and less harmful than ever before. While the diesel locomotive is great for long haul operations, these same engines operate extremely poorly when used for high idle, short distance applications, such as switching.

A switching locomotive is a locomotive used to ferry train cars and goods around switching yards. Located at strategic points along railroads, switching yards are a component within a large freight yard complex. These yards are where train cars are brought to be sorted for various destinations and assembled into blocks. Depending on the country the yard is located in, it may be referred to as a classification, freight, marshaling, shunting, or switching yard, like it is here in the United States. Of the 20,000 large-scale locomotive engines currently in operation in the US, five thousand of these are estimated to be switchers. In addition, smaller railroads typically also operate smaller switcher locomotives. As mentioned previously, these locomotives are known for operating at very low speeds and are typically idling 75% of the day [7]. Currently, these locomotives are operating with the same diesel engine as the long haul locomotive, but since these switching locomotives are operating a diesel engine in the most inefficient way possible, a viable solution needs to be explored. Due to the special nature of switching yards, the modern electric train would not be a viable solution to this emissions problem as electric train cars require overhead lines to recharge; in switching yards, these locomotives must be able to move without the restrictions imposed by overhead power lines. Certain switching yards also utilize overhead cranes to move product on and off train cars, thus eliminating the possibility of overhead lines [8]. One example of a switching yard is the Union Pacific Railroad's Bailey Yard in North Platte, Nebraska which spans 2850 acres and 315 total miles of track [66]. The yard handles over 14,000 rail cars every 24 hours by using 985 switchiners. Employing more than 2600 people in the greater North Platte area, most of these people help with day-to-day switching operations.

The traditional steam locomotive and diesel engine have dominated locomotive engineering since their inception, but there is a lesser known steam locomotive engine that shows immense promise for the rail industry. The fireless locomotive is similar to the traditional steam locomotive in all areas except one, the steam for a fireless locomotive is not generated onboard the train, thus eliminating the firebox and providing the locomotive with its name. The steam for this engine is generally created in steam power plants using electric or fossil fuel boilers; more recently, waste steam from power plants is being harnessed. This engine type reduces the risk to the operators and passengers without having to sacrifice efficiency and power. Specifically, if reintroduced to mainstream applications, the fireless steam locomotive has the potential to help the industry achieve a safer, less energy intensive, and less carbon emitting future. Furthermore, generating this steam by harnessing waste steam or a clean, renewable energy source such as solar power would eliminate the harmful diesel emissions, thus paving the way for a cleaner future. In the next section, various methods of energy generation will be discussed in the context of powering a fireless steam locomotive.

Subsystem 1: Energy Generation
Historically, steam for fireless locomotives has been generated by burning fossil fuels such as coal, natural gas, and petroleum or biomasses like wood, pellets, bagasse, chinese reed, and peat [9]. More recently, in Germany, Switzerland, and India, waste steam and waste heat from factories and power plants has been harnessed to generate steam, providing an environmentally friendly way to power fireless locomotive fleets. For this project, we will concentrate on how to generate steam for the fireless locomotive using solar energy. There are two major types of solar power generation that can be considered: photovoltaic (PV) and concentrated solar power (CSP).

Photovoltaic
Photovoltaic (PV) solar modules absorb the energy from sunlight and convert it to electricity using semiconductor materials within the solar panel, an inverter changes this direct current (DC) electricity to alternating-current (AC) electricity that can then be used to power an electric boiler to generate steam. [10]. These panels are constructed with many smaller PV cells that generate 1 to 2 watts of power each. In an average commercial application, 72 PV cells are strung together to form a single solar module. Depending on power generation needs, solar modules can be strung together until the proper electricity output is reached, as illustrated in figure 2 [11]. While PV energy generation can easily be scaled up or down depending on energy requirements, the most significant shortcoming of this technology is efficiency. The efficiency of a PV panel is the percentage of solar energy that is converted to electricity and currently, most commercial solar panels have an efficiency between 15% and 20% [12].

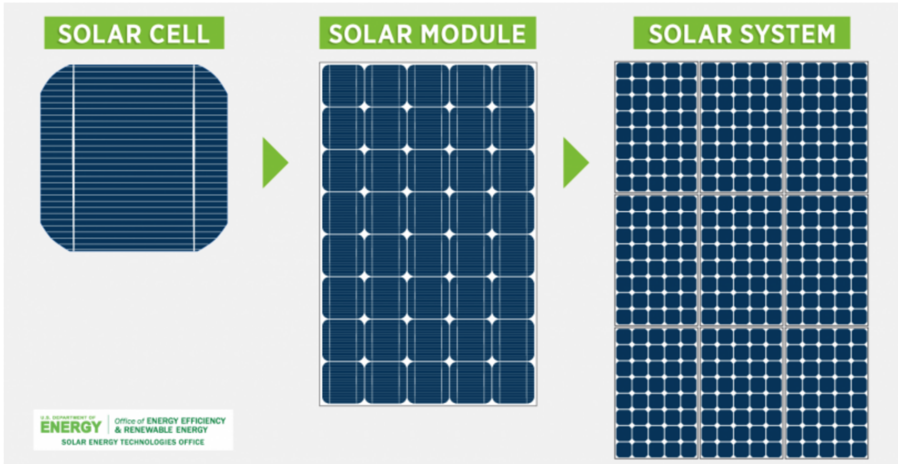


Figure 2: Illustration of photovoltaic cells strung together to form solar modules and solar power systems [10].

Concentrated Solar Power

In past applications, concentrated solar power (CSP) has been used for electrical power generation, but has faced complexities such as requiring the use of a heat transfer fluid as well as losses in thermal power potential and energy through conversion. Some applications will use water as the heat transfer fluid which when heated by the mirror fields, turns into steam that is fed into a steam generator. This is referred to as Direct Steam Generation (DSG). DSG reduces complexities within the system, eliminating potentially harmful heat transfer substances and the need for a heat exchanger. Eliminating these items also helps reduce the overall cost of the system, but these eliminations do not come without disadvantages. The thermal energy capacity of water is significantly lower than substances such as molten salts and synthetic oils. These higher thermal capacities allow for more heat to be transferred through the system and more steam to be generated. These heat transfer fluids also work as a thermal energy storage to power the system when solar energy is at a minimum. In this project, we will explore the four most common types of CSP plants: linear Fresnel, power tower, parabolic trough, and parabolic dish. A summary of the four possibilities for solar to steam generation depicted in figure 3 below.

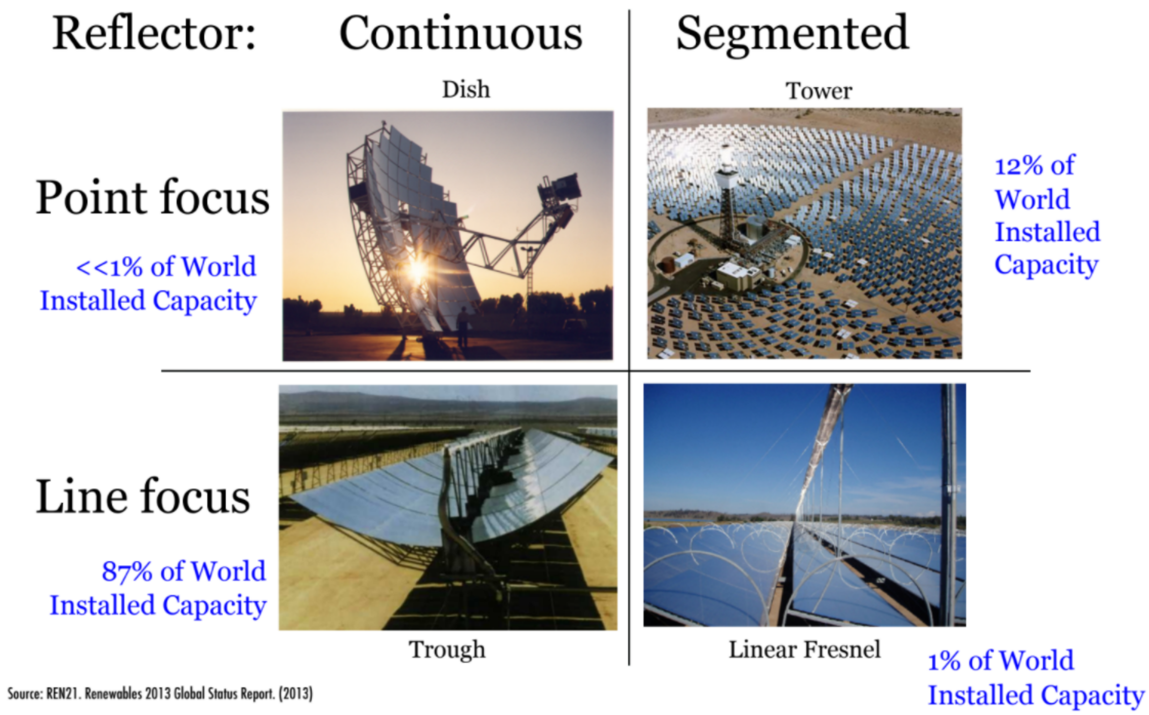


Figure 3: Comparison of four solar thermal electric generation technology types [11].

CSP Option 1 - Linear Fresnel

So named due to similarities with Fresnel lenses, a linear Fresnel solar collector utilizes long reflectors at the base of the system to focus sunlight into an absorber located at the focal line of the mirrors to concentrate energy. A thermal fluid flows through the absorber, receiving energy in the form of heat, for it to then go into a heat exchanger and generate steam [13]. This technology was first conceptualized in the 1960s, but had very little development until the 1990s, when the first linear Fresnel plants began physical construction [14]. The first linear Fresnel plants began operation in the early 2000s, and in 2009 the first US commercial plant utilizing this technology was built in Bakersfield, California, producing 5 megawatts (MW) [14]. Representing only around 1% of the world installed capacity of concentrated solar power, linear Fresnel plants are being held back due to the relatively high solar collector area needed for large applications and the need for further refining their efficiency, as it is still an emerging technology. With regards to our potential use for powering a steam locomotive, linear Fresnel becomes a better choice the smaller the application is..

CSP Option 2 - Power Tower

Previously thought to be an impractical application of concentrated solar power, the power tower has recently become a popular technology option in China and Spain due to its higher temperature operation than other CSP options; thus, it offers higher efficiency. This system features a receiver atop a central tower which absorbs reflected sunlight from dual-axis tracking reflectors, known as heliostats. This central tower receiver contains a heat-transfer fluid such as molten salt or oil which is used in a heat exchanger to produce steam. Power towers have been favored in new, larger plants (over 50 MW) since 2010, due to superior power output per land area compared to other CSP technologies. In the US, the technology is only considered in six states: California, Nevada, Utah, Colorado, Arizona, and New Mexico, but could expand to other states if the $/kWh continues to decrease; the National Renewable Energy Laboratory (NREL) estimated that electricity from concentrated solar in 2021 was $0.076/kWh, but will drop to $0.056/kWh in 2030 and $0.052/kWh in 2050. These cost reductions are expected to come from optimizing heliostat mounting systems by using smaller mirrors. Currently, most applications use between 1.5-3.2 million square meters of heliostats; therefore, it is not as prevalent in small-scale applications, such as powering a switching locomotive.

CSP Option 3 - Parabolic Trough

A parabolic trough solar power plant uses a set of concave mirrors that concentrate sunlight onto a central receiver tube. The receiver tube contains a heat transfer fluid that will absorb the thermal energy from the reflected rays and is pumped through a heat exchanger where water is turned into steam to power a steam turbine to generate electricity [16]. These troughs are typically oriented north to south to maximize the amount of sunlight that hits these mirrors and is reflected to the tube. Previously, the heat transfer fluids were only able to reach 400°C, decreasing the efficiency and speed of steam generation. The introduction of synthetic oils or molten salts as a heat transfer fluid has caused the maximum attainable temperature to increase to 600°C. In addition to the new heat transfer fluids, thermal energy storage tanks have been added to further increase efficiency [17]. The parabolic trough power plant has the advantage of being scalable to most applications; however, complexities with heat transfer fluids and additional systems (heat exchanger and steam turbine) make the technology difficult to implement in a personal small scale application such as powering a single home. In consideration of steam generation for the fireless locomotive, the steam turbine would be eliminated and replaced with the recharging station, simplifying the system and increasing efficiencies since losses from electricity generation would be eliminated.

CSP Option 4 - Parabolic Dish

Parabolic Dish CSP units feature a parabolic mirror or multiple mirrors arranged in a similarly shaped shell that reflect light onto a central receiver unit. This receiver can be a Stirling engine, PV panel, or in our case a module through which a heat transfer fluid is circulated. Parabolic dishes are most effective when pointing directly at the sun and can thus be mounted on single or dual axis trackers to ensure optimal alignment over the course of a day. Given that dish concentrators have a point focus, they can achieve working fluid temperatures upwards of 1500°C. Parabolic dishes can be scaled simply by making a larger dish, or more commonly by simply using more units. Since each dish has identical unit-level efficiency, system-level efficiency scales nearly linearly when the number of units is increased.

Direct Normal Irradiance

To measure the effectiveness of a region to collect solar energy, direct normal irradiance (DNI) is used to guide the analysis for sizing a locomotive's energy generation subsystem. DNI is defined as the amount of direct irradiance received on a plane normal to the sun, and is the industry standard as it pertains to concentrated solar technology [18]. Furthermore, figure 4 below shows where solar energy is most available in the United States. Per the figure, the Southwestern United States receives over 7.5 kWh/m^2 on average on a daily basis. This DNI value is nearly double the amount of solar energy Michigan receives on average on a daily basis.

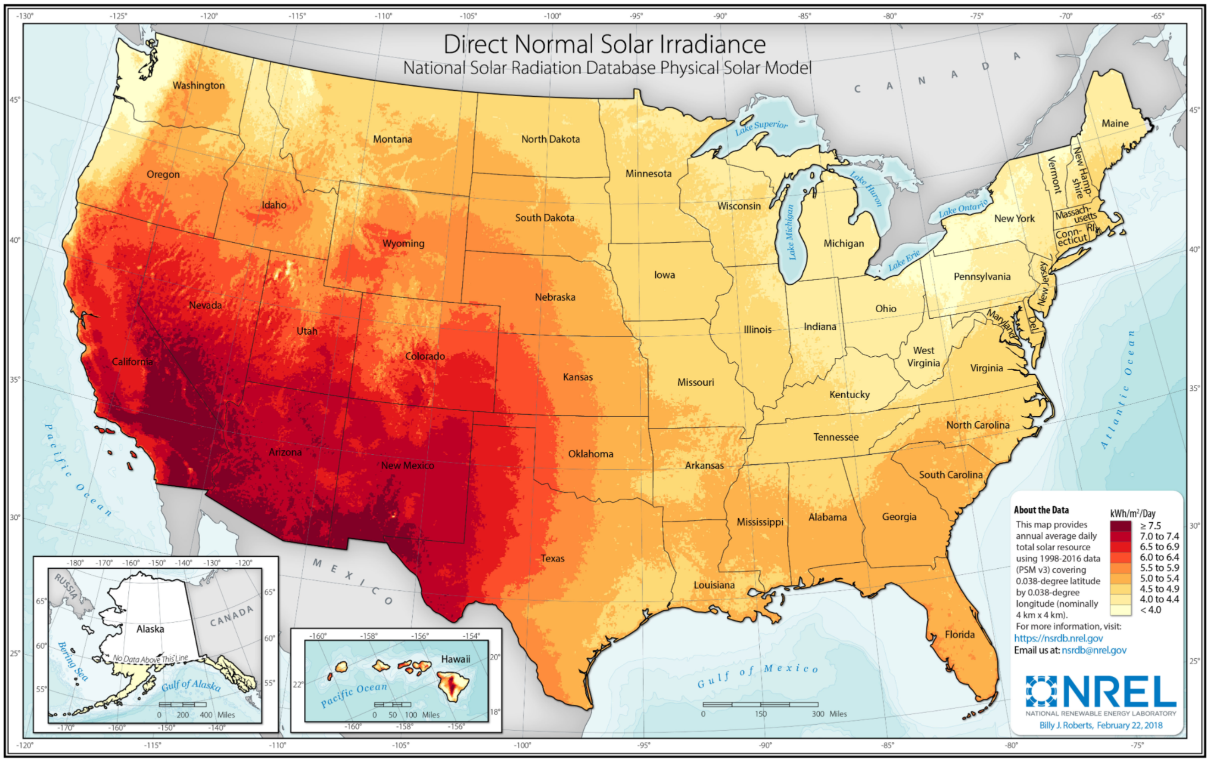


Figure 4: Average solar energy available in the United States based on DNI [19].

Subsystem 2: Steam Generation and Recharging Station

Steam Generation

To generate steam from a concentrated solar power plant, the heat transfer fluid contained within the receiver flows through a set of tubes located within a shell and tube heat exchanger, shown in figure 5. The heat dissipates from the higher temperature heat transfer fluid located within the tubes into the lower temperature water that is located within the tank of the heat exchanger. The temperature of the water rises until steam is created and sent out to a separate steam accumulation tank that is part of the recharging station, that will be introduced in subsystem 3. When sized properly, these shell and tube heat exchangers can operate at 85% to 91% efficiency [60]. To ensure the fireless locomotive can run without excess down time the heat exchanger needs to be large enough to recharge the locomotive multiple times in one day, as determined by the user.

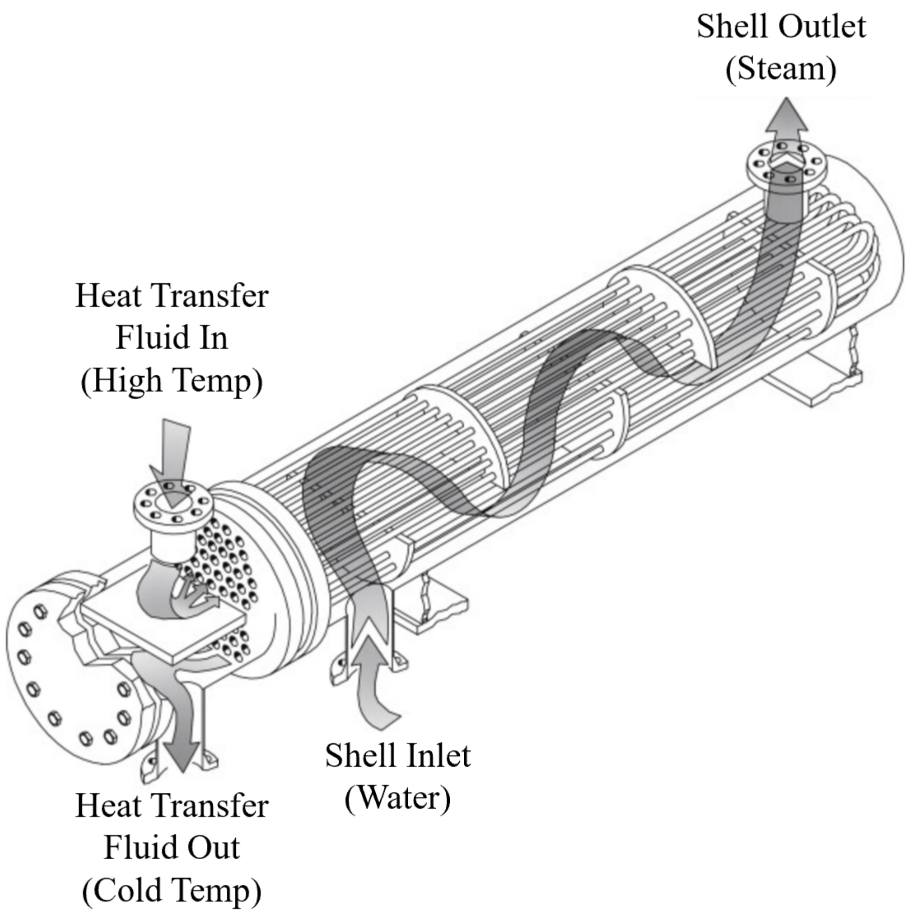


Figure 5: Shell and U-Tube Heat Exchanger [20]

The PV power plant uses solar irradiation to generate electricity that can then be used to power an electric boiler to turn water into steam. Electric boilers have a very similar look and operation to the tube and shell heat exchanger, outlined above. Rather than a heat transfer fluid moving through the tubes, the tubes are replaced with a heating element placed within the cylindrical shell, seen in figure 6. When sized properly these electric steam generators can perform with 98%-100% efficiency [22].

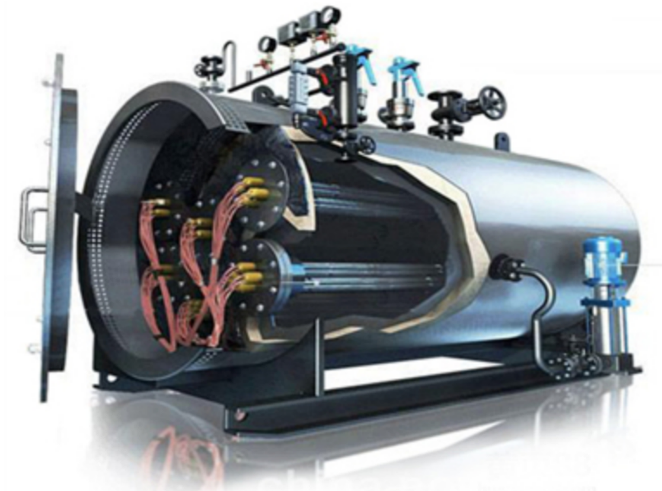


Figure 6: Electric Boiler [24]

Recharging Station

When using a CSP set up the recharging steam for the fireless locomotive will be taken from a heat exchanger and wet steam accumulator located within the switching yard. In this system, the steam accumulator acts as a storage vessel for the steam produced by the heat exchanger and acts as an energy storage system for times when solar irradiation is lacking. These steam accumulators should be sized based on the steam generation requirements of the heat exchanger, amount of time between recharging, and the amount of flash steam produced when the accumulator is discharged. Flash steam is produced when there is a pressure drop in the system as the steam accumulator is being discharged. In a PV set up a steam accumulator can be used depending on the amount of steam that needs to be produced, but is not necessary for efficiency standards.

The operator side of the recharging station for the fireless locomotive is a fairly simple operation. The locomotive has a charging port and pipe at the base of the locomotive that is connected to a pipe exiting the steam accumulator. A valve is opened on both the locomotive and the pipe from the accumulator allowing the steam to enter the storage tank onboard the locomotive. A pressure regulator on the pipe will drop or raise, depending on the operating pressure of the steam accumulator, the pressure of the steam to the locomotive's operating pressure before the steam enters the recharging pipe. Once the pressure in the line matches the pressure within the locomotive tank flow will stop. Since flow automatically stops, this process does not have to be supervised by someone. Prior operations used a rigid pipe for charging; however, due to advancements in materials technology, current pipes for charging are made from a lightweight flexible material allowing recharging to be accomplished by a single person [7]. This material is also insulated to prevent burns to the operator after the steam passes through the pipe into the locomotive. This charging process is a quick process taking only 15-35 minutes depending on the size of the tank needing to be filled, and can be seen below in figure 7 [7].

Figure 7: Fireless locomotive being recharged at DLM switching yard [7]

Subsystem 3: Fireless Locomotive

The fireless locomotive was created in 1872 with widespread production and use until the 1960s when diesel locomotives took over the market. While these fireless locomotives are not commonly seen, especially in the United States, Germany still uses many of the fireless locomotives that were built in the 1980s and are currently producing new fireless locomotives [25]. The fireless locomotive runs similarly to the traditional steam engine, but with one key difference: the steam is not generated on board the locomotive. The removal of the boiler system gives the fireless locomotive its name. Figure 8 shows a cross-sectional view of a standard steam locomotive versus a fireless locomotive [4]. The engine of the fireless locomotive is a large steam accumulation tank located at the front of the locomotive. This tank is filled to 75% of its total capacity with hot water and is recharged with steam from an external source through a charging pipe on the bottom of the locomotive [25] . The steam is controlled by a throttle and transported down a pipe to the piston cylinder where the reciprocating motion of the pistons push and pull the rods connected to the driving wheels, providing the force needed to make the locomotive move. Further advantages to the fireless steam locomotive engine are the absence of a gear box, minimal to no electronic devices, and minimal to no noise from the steam storage tank.

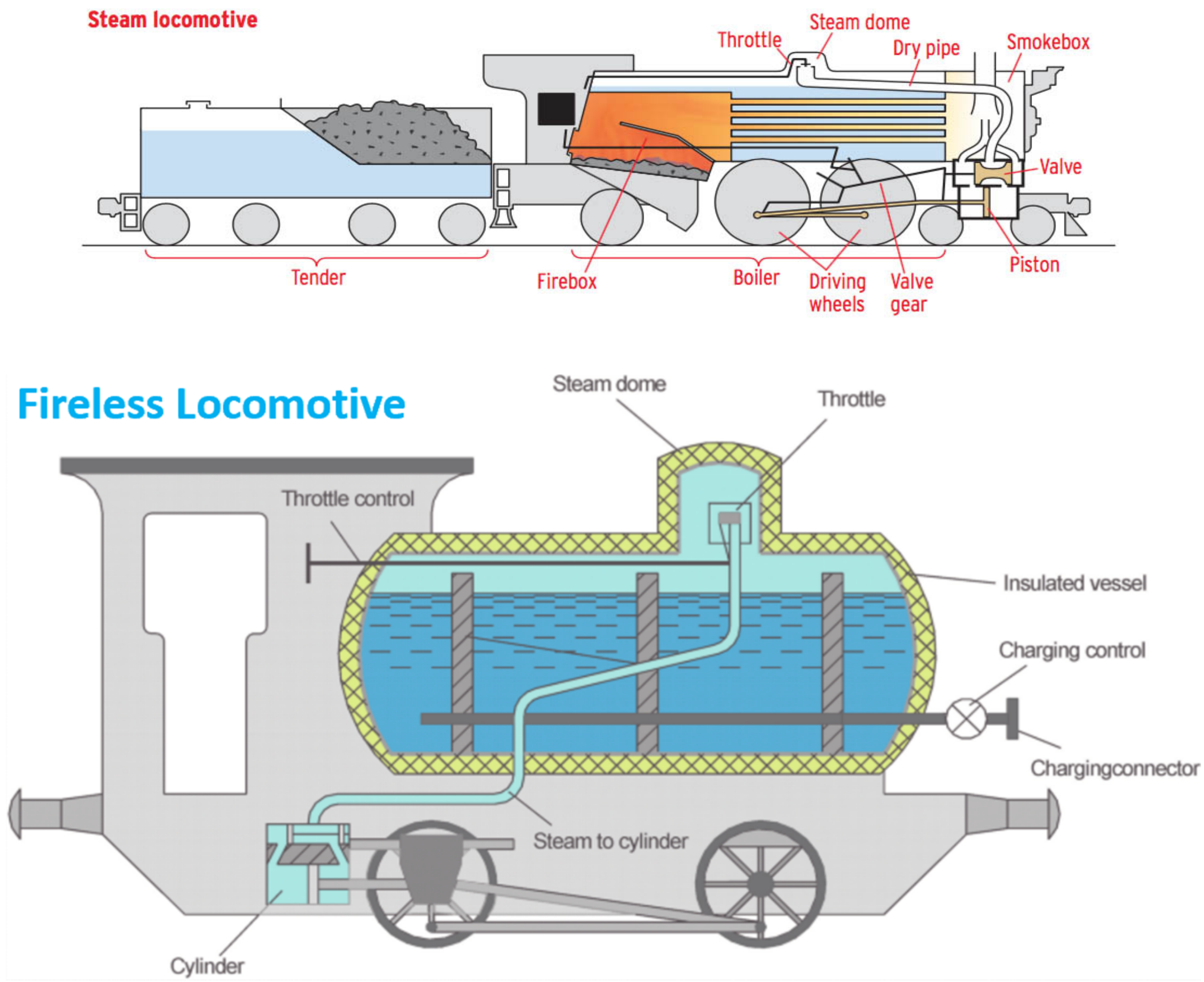


Figure 8: Cross-sectional view of Steam Locomotive (Top) and Fireless Locomotive (Bottom) [4].

The direct drive clutch and absence of a gear box and electronics, reduces moving parts and areas the engine can fail or require maintenance [9]. The onboard steam accumulation tanks are rated to withstand pressures up to 110 bar (1595 psi), with a maximum operating pressure of 20 bar (290 psi) for a full size application and 6 bar (87 psi) for the 1:8 scale application, these locomotives are essentially explosion proof, further increasing the safety of their operation. These advantages in safety and simplicity do not require a sacrifice of power. The power output of an engine in a car or truck is commonly measured in horsepower; while locomotives do consider this measurement as a baseline for their operational performance, for a switching locomotive it is far more valuable to determine the tractive effort produced by the engine. The tractive effort of a locomotive is the pulling and pushing capacity of the locomotive. The maximum tractive effort of a locomotive occurs at the initial moment of motion and decreases as the speed of the train increases. In terms of a full size switching locomotive, which operates at speeds between 5-7 miles per hour, the maximum tractive effort can be as low as 8000 lbs while rarely exceeding 30,000 lbs, depending on the size and steam storage tank capacity of the locomotive [28]. Since the tractive effort and size of the locomotive are a linear relationship the maximum running time of the locomotive remains unchanged for each sized locomotive. The demand of the user will determine the size of the solar field needed to generate steam for these locomotives.

Stakeholder Analysis

The goal of our primary client, Ted Delphia, is to use the 1:8 scale model generated by this project to educate and invigorate change within the locomotive industry. With this end goal for our project sponsor in mind, we evaluated the stakeholders on a full scale level as well as analyzing the stakeholders for the 1:8 scale application.

Freight transportation touches every corner of the United States, and when changing the way freight transportation operates, there would not be a single person who is not impacted by those changes. Some industries will be impacted positively (solar companies, heat exchanger, steam accumulator, and thermal energy storage companies) where others would see a negative impact due to the change (diesel locomotive manufacturers, diesel fuel suppliers, diesel mechanics). To take a better look at the different groups of people that would be affected by this project, we separated them into five distinct groups.

1. *Clients and Consumers:* Clients are companies and industries that use trains to transport their goods across the country. These stakeholders would include coal companies, foods like corn and soybeans, construction materials, and automobiles just to name a few. Consumers are people who purchase products that are transported by these trains. Since such a wide variety of products are transported by train the majority of the United States, or any country that uses trains for freight transportation, will be affected.

2. *Society and Environment:* For this project, society is defined as cities and towns that are immediately surrounding these rail yards and the people who live and work in these cities and towns. Environment is defined as the impacts to the air, water, and land surrounding the rail yards. This section would also include railroad societies as well as environmental groups.

3. *Government:* The government creates regulations and standards for all industries operating inside the United States, ensuring fair practices are maintained. They also create for environmental standards and regulations for industries as well. Examples of these stakeholders would include the Environmental Protection Agency (EPA), local and federal governments, and the American Railroad Association.

4. *Manufacturing and Suppliers:* A myriad of manufactures and suppliers are required to make a locomotive and a rail yard function. Stakeholders for producing a switching locomotive would include the manufacturers, material suppliers, and fuel suppliers, depending on the type of fuel used (diesel, steam, electric). This would also include the people and companies who maintain these locomotives and fuel systems. The manufacturers would include companies for train manufacturers such as Siemens and DLM in Switzerland, or solar companies to develop the solar generator like LG Solar and SunPower.

5. *Rail Companies and Rail Yards:* This group would include the companies who own and operate the switching yards and the locomotives that would be impacted by this project. The top three rail companies in the United States are Union Pacific, Kansas City Rail Lines, and Norfolk Southern.

Since there are so many people and groups that are impacted by this project, we determined five different criteria of this project that would have an impact on each of these groups.

1. *Environmental Impacts:* Due to the production of NOx, CO2, and SO2 from diesel emissions. These emissions can cause respiratory issues, acid rain, and even lung disease [5]. The noise pollution caused by loud engines is also a rising concern of continued use of diesel engines.

2. *Upfront Costs:* The cost of changing the fleet from diesel to steam will have a cost. This cost will also include installing the solar generators, boiler and steam accumulation tanks, as well as recharging stations on these switching yards. Upfront costs would also include training costs to teach employees how to use these new locomotives and recharging stations. Any downtime incurred from the transition would also be applied to upfront costs.

3. *Operational Costs:* The daily operating costs of a switching yard include, maintenance, energy costs, and employee wages, these will be carefully considered when determining the feasibility of this project. A change in operational costs will affect the bottom line of the rail companies, changes in the bottom line, whether good or bad, could be reflected in costs for clients and consumers raising.

4. *Job Creation/Loss:* By changing from a diesel system to a fireless steam system, there could be some job losses or creation. Switching to a fireless steam system would remove the need for diesel maintenance mechanics and need for diesel fuel could impact jobs outside of the rail yards.

5. *Working Conditions:* Changing to a different fuel source would directly change the working conditions inside the rail yard and the operators/employees risks due to dangerous machinery and hazardous working conditions caused by the emissions and noise from diesel engines.

In figure 9 below, a gradient is applied to the chart to indicate how important these criteria are to each group of stakeholders. The darker the color the more important and impactful the criteria is to that stakeholder group, the lighter the color the less important and impactful the criteria is.

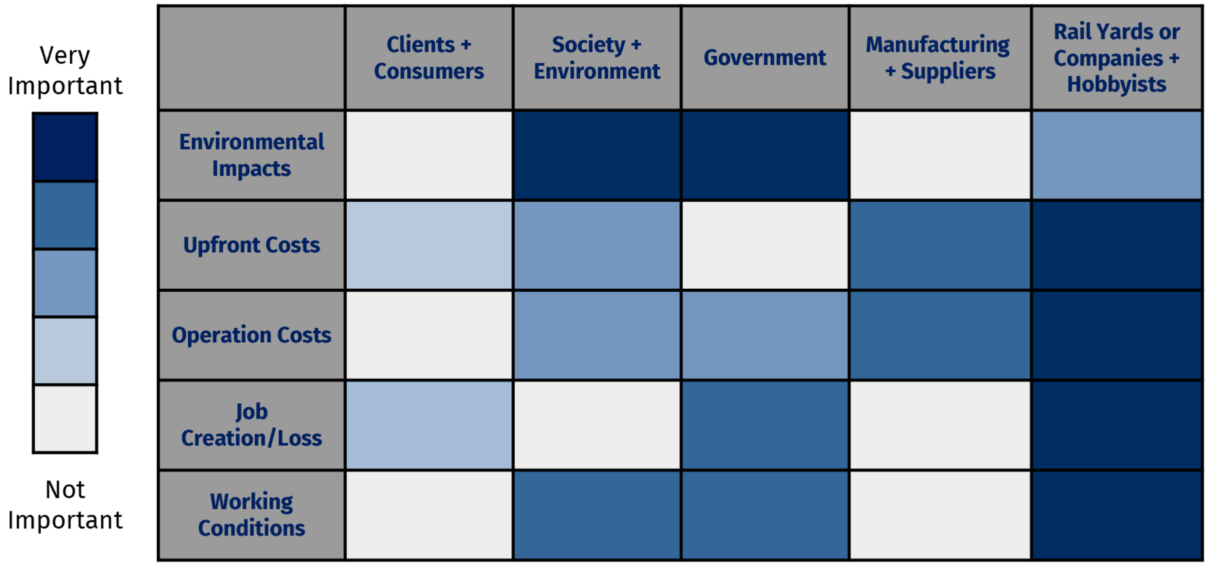


Figure 9: Full Scale Solar Fireless Locomotive: Shared value chart for stakeholders

In a 1:8 scale application, our primary focus is on the Society and Environment, with an emphasis on the environmental impacts, upfront costs, and operational costs of the project for the hobbyist (Companies and Hobbyists). Our primary stakeholders are Ted Delphia and the Southern Michigan Rail Society as well as locomotive enthusiasts who already own a scale locomotive and those looking to purchase. Secondary stakeholders are educational facilities like museums, schools, and science centers looking to educate people on the advantages of steam locomotion powered by renewable clean energy. Solar photovoltaic panel manufacturers, distributors, and installers and maintenance workers, electric steam generator manufacturers and installation and maintenance staff, and the energy supply companies that purchase excess power generated from the solar panels are also secondary stakeholders for the 1:8 scale application. Tertiary stakeholders include the rail companies, who in the small scale this does not impact directly, but this project could be used to educate and invigorate change within their companies. Tertiary stakeholders could also include environmental organizations that advocate for the use of renewable energy to power homes and businesses, as well as government organizations that regulate and provide financial incentives for people to put solar panels on their homes.

Problem Description

Intellectual Property Considerations

Currently, intellectual property plays no role in this project; however, there is long-term potential for a patent on the solar to steam methodology or technology. Although the fireless steam locomotion technology is well-documented, there are no clear examples of CSP nor solar PV being used to create steam in this context. The modeling tool also has the potential for intellectual property considerations if it were to be expanded on to include commercial scale applications (i.e. full-scale, low-speed operations).

Design Process

As we work towards our goal of developing a solar-based, steam powered locomotive for use in switching/shunting yards, we planned to utilize a design process that focused on iterative design since we wanted to be able to reevaluate our project requirements and design whenever the need of more exploration was identified. Ultimately, the specific design process that we chose to follow is illustrated below in figure 10. This design process is a variation of the standard ME 450 design process, where Need/Problem Identification and Realization were outside the scope of our project. However, we received a defined problem alongside the need, so we needed to strongly explore our project's need/problem first as we were unfamiliar with the engineering background of it. This is why the Analysis of Need/Problem step was added to the design process. Another addition is Initial Engineering Analysis because we needed to conduct the mathematical/engineering analysis before selecting any concepts. This is why the next sections are Selected Concept(s) and Detailed Analysis of Concepts(s) since we were then able to choose and do more analysis on the practicality of each concept. Just like the standard ME 450 process, if any potential areas are identified that need more research or development, our process allows for us to go back to any step as needed.

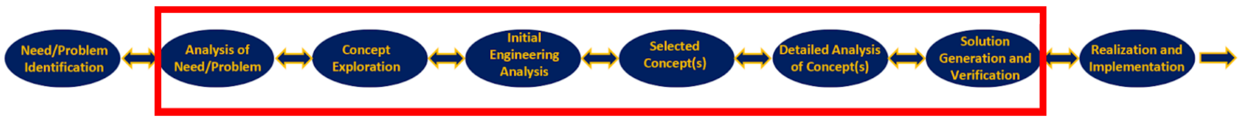


Figure 10: Illustration of design process to be followed for our project.

The first step of our design process within the scope of our project is Analysis of Need/Problem, where we perform an exhaustive analysis and literature review of the project's background information, based on the provided need and problem. This is also where we determine an initial project scope and final deliverables. The next step was Concept Exploration in which we conducted a broad stakeholder analysis, an initial development of user requirements and engineering specifications, which was then used to generate several concepts. This was followed by Initial Engineering Analysis, where an initial set of calculations were performed to guide our selection process in the Select Concept(s) step. Following this, an in-depth analysis of the selected concepts occured in the Detailed Analysis of Concept(s) step. Multiple iterations of this step were anticipated and once we settled on an Alpha concept, we moved onto the Solution Generation and Verification step. In this step, we developed and tested the deliverables based on the specifications set and went back when specifications needed to be reevaluated. Finally, we progressed into the Realization and Implementation step, where we presented the finalized deliverables and our conclusions/determinations on the final outcome. The next section will provide a detailed overview of exactly how we proceeded with each step of our design process.

Design Process in Review

The design process outlined above was used throughout all phases of this project. We began with going through the Analysis of Need/Problem step, where we successfully finalized our project scope to be three deliverables for Ted Delphia. We then completed our background research and reviewed our recommended approach to the project provided to us by our project sponsor. We determined that our project would need to involve three subsystems and have three final deliverables, all of which are explained later in this report. They include a system conceptualization via an Excel modeling tool, the creation of a baseline of how low speed rail operations currently work, and this final report summarizing our findings, analysis, and recommendations. We also went through several iterations of concept exploration, initial engineering analysis, selecting a concept, and detailed analysis of concept steps, where we conducted a stakeholder analysis, defined our requirements and specifications, devised multiple concepts centered around solar as a renewable energy carrier, and performed several rounds of engineering analysis on them to select a finalized concept. We then completed the solution generation and verification step by using our modeling tool to determine practical scenarios and applications, and started developing deliverables. For our most recent iteration, we explored more iterations of concept exploration and transitioned to a solar PV energy generation subsystem to sustain an 1:8 scale locomotive for hobbyist purposes. Now that we are fully satisfied with the final design concept, we reassessed several of our engineering specifications in order to account for the necessary inputs and assumptions for our end-to-end analysis. All of these steps occurred during Phases 1- 5 of the project plan; these phases and their timelines are further explained in the Project Plan section of this report. All deliverables were completed by April 22nd.

Information Sources

Much of our information, especially regarding solar energy carriers and locomotive practices, have come from government resources such as the National Renewable Energy Laboratory (NREL), the Environmental Protection Agency (EPA) and the United States Department of Energy (US DOE) as well as DLM. These agencies generally offer immense data sets or comprehensive documentation detailing statistics regarding aspects of our project, such as solar irradiance data for the US, that have been gathered with significant sample sizes. This has helped us establish benchmarks for our system performance and allowed us to anticipate the conditions a solar to steam system might experience based on its geographical location.

Since nearly all components of our system are available commercially, we have made liberal use of spec-sheets and industry data over the course of the semester. Having reliable, experimentally verified data directly from product manufacturers enabled us to design our system with confidence in how each part would theoretically perform.

We did encounter some difficulty finding statistics regarding switching locomotives in the US. Switching is a relatively niche industry and there is little data publicly available. The scant information we could find on the subject was sometimes out of date by several years, requiring an immense amount of research for little return. The best source of this information came from the EPA in the form of articles detailing the pollution from idle switcher locomotives.

Section 2: User Requirements and Engineering Specifications

To gain a better understanding of each aspect of this project, we broke the overall system down into three subsystems: energy generation, steam generation and recharging, and the fireless locomotive. Each of these subsystems will have its own set of user requirements and engineering specifications. User requirements were determined by using stakeholder feedback from our project sponsor as well as a switching yard operator. Relevant engineering targets were then determined by conducting research on each of the subsystem's limitations. As our specifications were created with existing products in mind, related products and processes compare very similarly since we would not be redesigning any specific technology.

Subsystem 1: Energy Generation

In order to leverage the renewable energy offered by the sun, a solar collector is necessary to harness the sun's solar radiation to generate steam. Specifically for this application, steam will be generated from harnessed electricity produced with solar photovoltaic (PV) modules, which are then grouped together into solar photovoltaic systems to generate the necessary direct current (DC) electricity output. The total collector plate area is determined by the number of solar PV modules needed to generate the necessary steam to power the fireless locomotive. For this system, a direct current (DC) to alternating-current (AC) inverter is needed to convert the produced DC electricity output into the AC electricity required by the steam generator. The system must have a comparable lifetime to the average existing solar panel lifetime, and will also need to be serviced with a similar frequency to existing solar PV systems. While the user requirements remained the same throughout the duration of the semester, the specifications changed several times as the group iterated through locomotive sizes. Beginning with the full-scale switching locomotive, several of these engineering specifications such as collector plate total area began on the magnitude of several acres. Furthermore, the initial goal was to use CSP to power the system instead of PV; however, it became apparent that CSP would not be practical for a 1:8 scale application.

Table 1: Requirements and Specifications for the energy generator

Requirement Category	Requirement	Specification	Priority
Performance	Collector Plate Total Area	30 - 50 square feet	High
Efficiency	Inverter efficiency factor	94%	High
Durability	On par with current solar panel lifetime	25 - 30 years	Medium
Serviceability	Days of Maintenance Service	≤ 30 days/year	Medium
Conformance	Renewable Clean Energy	Solar Photovoltaic (PV)	Medium

Subsystem 2: Steam Generation and Recharging Station

Steam Generation

Originally, the engineering specifications for steam generation were tailored for a full-scale switching locomotive in which a heat exchanger and steam accumulator would be used to convert the energy in molten salts to steam generation. As the project scope shifted to a 1:8 scale locomotive, the heat exchanger and steam accumulator were dropped in favor of an electric steam generator. For generating steam in a photovoltaic solar power system, an electric steam generator simplifies the process. An electric steam generator uses a set of tubes called a heating element inside of a tank of water. These heating elements heat the water until steam is produced. Electric steam generators can be sized for virtually any required amount of steam generation. When properly sized, these electric steam generators can perform with 98% - 100% efficiency [22]. Electric steam generators are also equipped with multiple safety mechanisms to ensure user safety. A pressure relief valve will release excess steam if the pressure in the tank rises to 20% above the operating pressure. A water level float tells the operator the current water level inside the tank; for example, if the water is too low or too high, then the generator will not run until water is added to or removed from the system. To ensure the steam generator can produce enough steam to power the 1:8 scale locomotive, it should generate enough steam for a full charge within one hour; however, this time metric can be changed in the modeling tool's user interface. A synthesized chart of the requirements and specifications can be found below in table 6.

Table 2: Requirements and engineering specifications for Steam Generation

Requirement Category	**Requirement**	**Specification**	**Priority**
Capacity	Steam Generation: Produce enough steam for locomotive fully charge locomotive in one hour	0.3-2.8 (kg/h)	High
Efficiency	Overall Steam Generation Efficiency	85% - 100%	High
Steam Retention	Maximum Time before Steam Condenses	> 8 hrs	Medium
Safety	Pressure Relief Valve	> 105 psi	High

Recharging Station

To refuel these fireless locomotives, the steam tanks on the locomotives must be recharged with steam and hot water. A 1:8 scale fireless locomotive is able to maintain its 'charge' for up to 30 minutes of operation. On a typical day, users such as hobbyists or museum operators will want to run these machines multiple times within a few hours. To recharge the locomotive, an EPDM rubber hose is attached to the electric steam generator which is then secured to the recharging port on the locomotive. After the hose is attached to the locomotive, the valves on the hose and the locomotive can be opened to allow the steam to flow from the steam generator into the locomotive's tank. This process is a very similar process to refueling a car, except the steam is exiting the hose at a very high temperature and pressure which creates several potential safety hazards that had to be addressed in the user requirements for this subsystem. The pressure regulator at the exit of the steam generator changes the pressure of the steam in the hose to match the operating pressure of the locomotive. Once the pressure in the hose matches the pressure inside the tank, equilibrium is reached and the flow of steam will stop automatically [2]. This, in addition to the flexible hose design, makes the recharging of the locomotive a very user-friendly experience. Table 7 below shows the requirements and corresponding specifications for the recharging station.

Table 3: Requirements and Engineering specifications for the Recharging Station

Requirement Category	Requirement	Specification	Priority
Safety	Heat Protection - Low Thermal Conductivity	0.02 - 0.147 W/m·K	High
	Pressure Protection	98 psi	
	Misfire Protection	Valve will only open when securely fastened on the charging valve on the locomotive	
Usability	Single Person Operation	Flexible hose	High
	Exit Pressure - Pressure Regulator	87 psi	
	Time to refill tank	15-35 minutes	
Efficiency	Due to heat loss within the pipe and escaped steam	80%	Medium

Subsystem 3: Fireless Locomotive

The fireless locomotive has been in production since the 1900s, and some of the locomotives manufactured in the 1940s-1960s are currently in use today [7]. The design for these locomotives has not changed much in the 60 to 80 years since, with exception of materials used for constructing the steam accumulator tanks. New tanks are lined with a film that prevents heat dissipation, increasing the efficiency of these machines from 85% to greater than 90% [9]. For this project we will focus on the 1:8 scale fireless locomotive. Table 8 below outlines the requirements and engineering specifications for the fireless locomotive. In addition to the performance parameters we also need to ensure the safety of the users and the workers. Each locomotive has a maximum working pressure of 87 psi, and will be equipped with a pressure relief valve that is designed per railway safety standards to release the pressure inside the tank when it reaches no more than 6 psi above the maximum working pressure. Since there is no onboard heating, overheating the system and creating excess pressure is not a concern in a fireless locomotive. In any case, the steam accumulator tanks on the locomotives are rated to withstand pressures of up to 137,000 psi, essentially making them ‘explosion proof’.

Table 4: Requirements and Engineering specifications for the Fireless Locomotive

Requirement Category	Requirements	Specifications	Priority
Performance	Maximum Tractive Effort	53-350 lbs	High
	Minimum Efficiency	80%	
Safety	Explosion proof design	91 psi [39]	High
	Working Pressure	87	
Steam Retention	Maximum Time before steam condenses	> 1 hr	Medium
Environment	Emissions should fall within or below EPA guidelines	Tier IV Guidelines ● Nitrous Oxide - 1.3 g/bhp-hr ● Particles - 0.03 g/bhp-hr ● HydroCarbon - 0.14 g/bhp-hr ● Carbon Dioxide - 2.4 g/bhp-hr	High

Section 3: Concept Generation

Although the overall concept for this project was clearly given to the team by the project sponsor, several concept generation methods were used to explore alternative solutions to what was initially proposed. Specifically, Team 26 implemented functional decomposition, a morphological chart, and design heuristics to identify complementary concepts to our initial proposed concept while leveraging our previous knowledge and extensive benchmarking of solar to steam.

Method 1: Functional Decomposition

We began by listing the necessary functions of our subsystems as shown below to identify the roles we'd need possible concepts to be able to perform. Our energy generation system's subfunctions focus on not only creating energy using solar power, but also being able to transport that energy via heat transfer fluid. Our steam generation subsystem would then take that thermal energy and use it to boil water into steam. This steam would then be passed to our third subsystem, which both stores and dispenses steam for our locomotive. The train itself would convert that steam into tractive effort to actually move things about a switching yard. Some of these functions, particularly those in energy generation, are somewhat restrictive of possible solutions, but this is due to our final design having the requirement of using solar energy. The chart of these sub functions can be found below in Table 9.

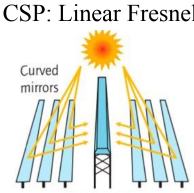
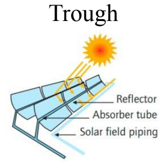
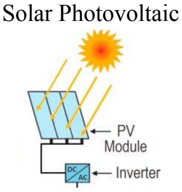
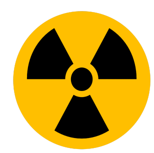
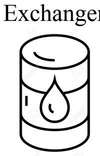
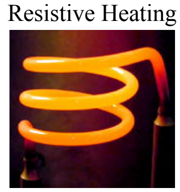
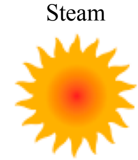
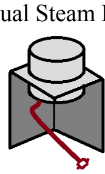
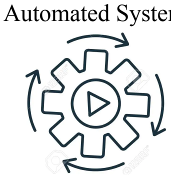
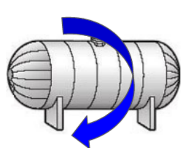
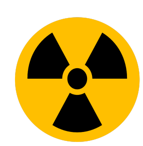
Table 5: Chart of Sub Functions

Subsystem	Subfunction #1	Subfunction #2	Subfunction #3	Subfunction #4
Energy Generation	Track the Sun	Focus Solar Energy	Heat Transfer Fluid	Pump out Transfer Fluid
Steam Generation	Circulate Heat Transfer Fluid	Intake Water	Generate Steam	Transfer Steam to Recharging
Recharging System	Intake steam	Dispense Steam	Function Safely	Store Steam
Fireless Locomotive	Intake Steam from Nozzle	Store Steam	Convert Steam to Tractive Effort	Carry Load

Method 2: Morphological Chart

To generate a morphological chart, we began by creating a list of each subsystem and the role in which it plays within the overall system. Then, focusing on one subsystem at a time and not the system as a whole, we generated a list of different potential solutions to satisfy the subsystems role. We then created a morphological chart, with the different subsystems in the left column and their potential solutions in the corresponding rows. This allowed us to generate as many potential solutions as possible, even if some of them were lacking in practicality. The Morphological chart can be seen below in table 10, and a complete list of all 20 potential solutions can be found in Appendix F.

Table 6: Morphological Chart of possible solutions.

Subsystem	**Solutions →**					
Energy Generation	CSP: Linear Fresnel 	CSP: Power Tower 	CSP: Parabolic Trough 	CSP: Parabolic Dish 	Solar Photovoltaic 	Nuclear 
Steam Generation	Synthetic Oil Heat Exchanger 	Molten Salt Heat Exchanger 	Traditional Boiler 	Resistive Heating 	Direct Solar to Steam 	Direct Nuclear to Steam 
Recharging Station	Manual Steam Hose 	Automated System 	Molten Salt 	Track Recharging 		
Fireless Locomotive	Traditional Fireless 	Tank Changing 	Supplementary Steam 	Compressed Cartridge 	Onboard CSP 	Onboard Nuclear 

Method 3: Design Heuristics

A methodology that we had employed in past design & manufacturing courses at the University of Michigan was the use of design heuristics. For context, design heuristics provide 77 specific strategies to help project teams generate novel designs that clearly differ from each other [54].Using a random assortment of the 77 heuristic cards to find new inspiration for innovative concepts, we were able to conclude our brainstorming session using this methodology. Specifically, we made use of the '2. Add motion', '5. Adjust function through movement, '21. Change product lifetime', and '42. Make components attachable/detachable' heuristic cards, seen below in figure 11. The 'make components attachable/detachable' card is what inspired us to identify new fireless locomotive concepts such as tank-changing or compressed cartridges. Furthermore, the second design heuristic inspired the idea for using CSP energy generation onboard the locomotive itself. Although these ideas did not make it to our final five concepts, they presented clever subsystem concepts that stepped outside the predefined project scope. Lastly, the twenty-first design heuristic to 'change product lifetime' inspired the track recharging concept for the recharging station subsystem. Most concepts that were initially discussed centered around a limited period of time associated with a charge; however, if the switching locomotive was constantly being recharged, then this could allow for an infinite 'lifetime'. The locomotive would only need to return to its docking station for maintenance or during down periods.

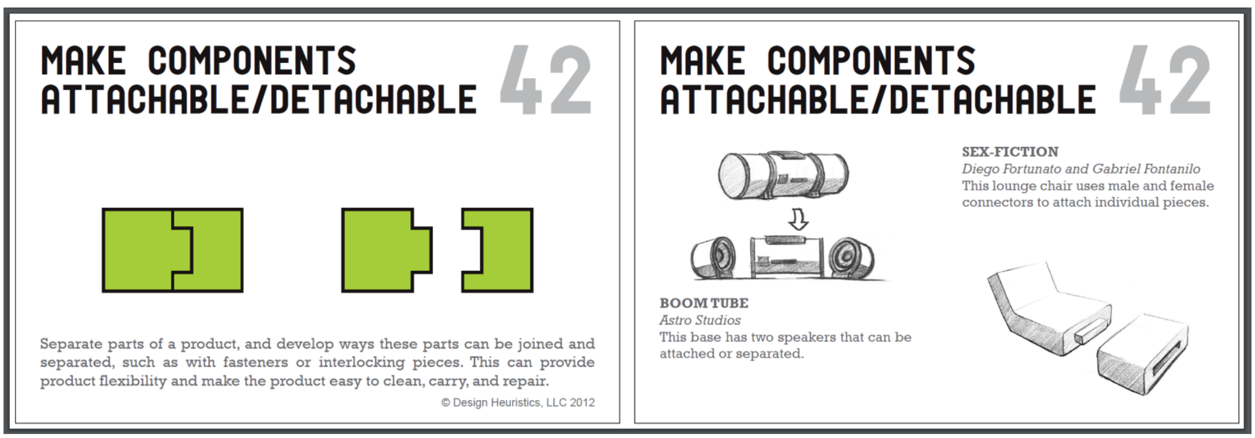


Figure 11: An example of a design heuristic, specifically 42) Make Components Attachable/Detachable [54].

Our Five Main Concepts

When evaluating all of our brainstormed concepts and cross-checking these with our project sponsor and advisor, it became apparent that in order to achieve Ted Delphia's goal of using solar energy, there was a clear domino effect for subsystems 2 and 3. Overall though, subsystem 2 would need to use resistive heating if it were to be intaking power from the solar PV option while a heat exchanger would instead be used for the four CSP concepts. Furthermore, the recharging station would need to be a manual steam hose to avoid costly system concepts that based on preliminary cost analysis would only be economically reasonable in large-scale applications such as a switching yard. Lastly, subsystem 3 would need to be an 1:8 scale traditional fireless locomotive to operate in a safe, affordable, and land-efficient manner for the intended hobbyist application. All other subsystem concepts provided introduced intriguing ways to speed up the process for a large-scale system such as the Union Pacific Bailey Yard in North Platte, Nebraska. Based on this inevitable concept selection for subsystems 2-4, subsystem 1 was the only subsystem that could consider various concepts without changing one or two of the other subsystem concept selections while also meeting Ted Delphia's goals. Thus, five main concepts emerged that highlight the various types of concentrated solar power (CSP) as well as solar photovoltaic (PV) technology. All concepts incorporate the 1:8 scale traditional fireless steam locomotive that uses an electric steam generator as well as a high-pressure hose and pressure relief valve to connect to the locomotive; however, as previously mentioned, main concepts 1-4 would require a heat exchanger while main concept 5 would use a resistive heater.

Main Concept #1 - Linear Fresnel CSP
A linear Fresnel solar collector uses long reflecting mirrors at the base of the system to focus sunlight into an absorber located at the focal line of the mirrors to concentrate energy into it. Representing approximately 1% of the world installed capacity of CSP, the technology is largely unproven, but has proven effective in its limited projects. With respect to our project, linear Fresnel CSP becomes a better choice the smaller the application is, thus a 1:8 scale locomotive is ideal for this technology.

Main Concept #2 - Power Tower CSP
The power tower CSP has become far more popular in recent years as it offers higher temperature operation than competing CSP technologies such as parabolic troughs, thus achieving higher efficiencies. Furthermore, this technology is much more commonplace worldwide with several notable projects in California, Spain, and China. The technology features a receiver atop a central tower which absorbs reflected sunlight from dual-axis tracking reflectors that are also known as heliostats. The central tower receiver contains a heat-transfer fluid such as molten salt or oil that is used as a heat transfer fluid to exchange heat in a heat exchanger. Most current applications are used in large plants since 2010 (over 50 MW).

Main Concept #3 - Parabolic Trough CSP
The most common CSP technology in practice, parabolic trough CSP makes up 87% of the world's installed capacity. This concept features a parabolic trough that uses a set of concave mirrors that concentrate sunlight onto a central receiver tube. The receiver tube contains a heat transfer fluid that absorbs the thermal energy from the reflected rays and is pumped through a heat exchanger where water is turned into steam to power a steam turbine to generate electricity. The introduction of heat transfer fluids such as synthetic oils or molten salts allow for a maximum attainable temperature of 600°C. With respect to a fireless locomotive, the steam turbine would be eliminated and replaced with the hose refueling and steam accumulator.

Main Concept #4 - Parabolic Dish CSP
The least common of the four mainstream CSP technologies, the parabolic dish represents less than 1% of the world's installed capacity. Featuring a parabolic mirror (or multiple mirrors) arranged in a shell that reflects light onto a central receiver unit, parabolic dishes are most effective when pointing directly at the sun. Thus, they are often mounted on single or dual axis trackers to ensure optimal alignment throughout the day. Because of their point focus, this concept allows heat transfer fluids to reach upwards of 1500°C. Given its ability to produce high temperatures with only a single shell, the parabolic dish concept offers a lot of potential in the scope of our 1:8 model.

Main Concept #5 - Solar PV

Veering away from concentrated solar power, our fifth main concept uses solar photovoltaic for energy generation. Photovoltaic solar modules absorb the energy from the sunlight and convert it to electricity using semiconductor materials within the solar panel. Furthermore, these panels are frequently constructed with smaller PV cells that generate 1-2 Watts each. Thus, this concept is easily scaled up or down depending on the user's energy requirements. Limitations occur with the amount of space and land a person has to add solar panels.

Section 4: Concept Selection Process

Even with heavy sponsor influence we took a multistep process to bring our 20 design concepts down to one alpha design. This process started with a gut check to take 20 concepts to 10 concepts, Those ten were then ranked based on feasibility and project sponsor influence and narrowed down to 5 concepts. Through engineering analysis these top five concepts were narrowed down to one alpha design.

Methodologies for Selecting Optimal Concepts

Despite heavy sponsor influence and desire, we wanted to give each of our generated concepts the consideration it deserves before eliminating it altogether. To do this we took our list of 20 concepts and picked our top ten based on a gut check of feasibility and separated them based on feasibility and projected sponsor engagement. The higher on the chart the greater likelihood our sponsor would be receptive to it, the further left on the chart the greater our confidence that this would be able to be physically constructed in the future. This ranking can be seen below in figure 12.

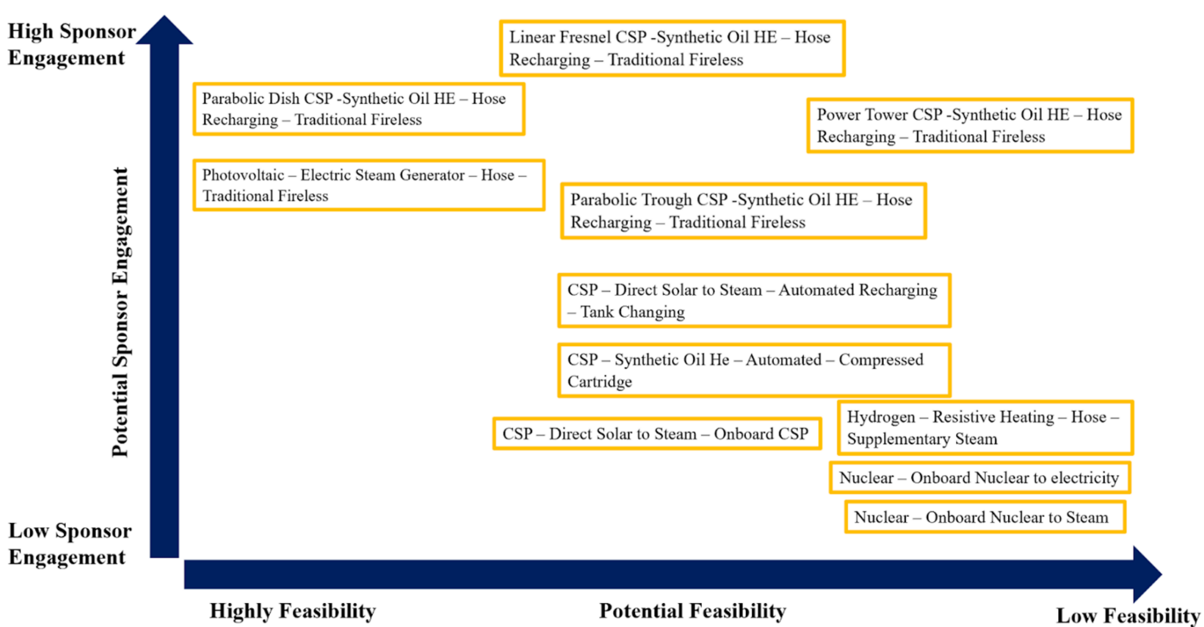


Figure 12: Sponsor Engagement and Feasibility Chart

Advantages and Disadvantages of Top Five Concepts

Main Concept #1 - Linear Fresnel CSP

One of the key advantages to this system is its higher efficiency based on existing projects. According to our model, this technology requires the smallest solar field size with regards to the demo application. Furthermore, it is fairly affordable and can be easily purchased online. However, as noted earlier, this technology is not commonly used in practice and represents approximately 1% of the world's installed CSP capacity.

Main Concept #2 - Power Tower CSP

One of the key advantages to this system is its scalability in large-scale applications. Power tower CSP technology is becoming increasingly popular in projects that exceed 50 MW due to the higher temperatures that its heat transfer mediums can reach; however, it is impractical for projects that do not meet the 50 MW threshold as it offers poor value.

Main Concept #3 - Parabolic Trough CSP

The main advantage of the parabolic trough is its prevalence worldwide. As it represents 87% of the world's installed capacity, its capabilities are well-documented and there are already various suppliers available to purchase the technology from. Continuing, the parabolic trough power plant has the advantage of being scalable to most applications and can meet even the most demanding switching yards from an energy standpoint. However, complexities that arise with the heat transfer fluids, heat exchanger, and steam turbine make this CSP technology complicated to implement in smaller scale projects.

Main Concept #4 - Parabolic Dish CSP

The main advantages to parabolic dish technology are its unit scalability and ability to heat fluid temperatures upwards of 1500°C. Given a dish's modularity, the subsystem can be easily scaled up or down to match a project's energy needs. Furthermore, if a switching yard were to decrease the number of active switchers, the yard could also decrease the number of dishes and resell them to recover a portion of their initial investment capital. In addition, the parabolic dish has a point focus which allows them to achieve working fluid temperatures upwards of 1500°C. On the contrary, the technology is uncommon in practice as it represents less than 1% of global installed capacity, thus it is difficult to find suppliers as well as individuals who are experienced with repairing parabolic dishes.

Main Concept #5 - Solar PV

The main advantage to solar PV is its widespread use in both commercial and residential applications. Solar PV panels are easy to purchase and install with minimal assistance from a professional, thus most users could handle this system setup. Furthermore, the cost of solar PV has significantly decreased over the past two decades, partially due to economies of scale and technological advancements. Thus, this concept is very practical in most solar applications.

Initial Engineering Analysis

To narrow down the top five designs to one alpha design we had to determine the energy output per acreage for each of the energy generation methods. For our stakeholders' needs, the acreage required for the solar field needs to be minimized. To accomplish this we took a bottom up approach following the reverse of the energy generation. Starting with the range of standard sizes for a fireless switching locomotive, we determined the amount of water and steam needed to power each individual locomotive. Next we used our knowledge of thermodynamics and enthalpy to determine the energy requirements to generate enough steam for one charge on the locomotive. The enthalpy of a system is the internal energy of a system, by taking the difference between the enthalpy of the water at its starting temperature (h_w) and the enthalpy of the water at the temperature in which it turns to steam (h_s), and multiplying it by the mass of the water to be heated (m_w), we are given the energy required to generate steam (Q_s), equation 1 [31]. A summary of these energy requirements can be seen in table B1 in appendix B.

$$Q_s = m_w(h_s - h_w) \quad \text{(Eq.1)}$$

For each of the energy generation options, we had to determine a baseline for the megawatt energy generated per area of land. For each of the concentrated solar power plants we found a range of plants that are currently operational. For each operational plant we determined the megawatt output and the area of the solar field and the location of the plant. In order to compare each of these plants and form a relationship between the energy output and the land size needed, we had to 'normalize' the plants like they were all from the same location. To do this we took the Direct Normal Irradiance of the location of the plant and the Direct Normal Irradiance of Michigan and created a ratio. This ratio is then multiplied by the megawatt per land size to form a range of capacities that can be compared to each other. Table 11 below shows an example of these calculations for the Linear Fresnel Concentrated Solar power plant.

Table 7: Currently Operating Linear Fresnel Solar Power Plants and Their Megawatt per Square Meter Normalized against Michigan's Direct Normal Irradiance

Existing Plants	**m^2**	**MW**	**m^2/MW**	**DNI**	**DNI:4.2 Ratio**	**Normalized m^2/MW**	**Normalized m^2**
1	400	0.3	1333	3.8	0.90	1206	362
2	18490	3	6163	5	1.19	7337	22012
3	25988	5	5198	7.5	1.79	9281	46407
4	170000	15	11333	3.5	0.83	9444	141667
5	302000	30	10067	5.4	1.29	12943	388286

These ranges of capacities and their land sizes were then plotted and a line of best fit was applied, seen in figure 13 for the Linear Fresnel System.

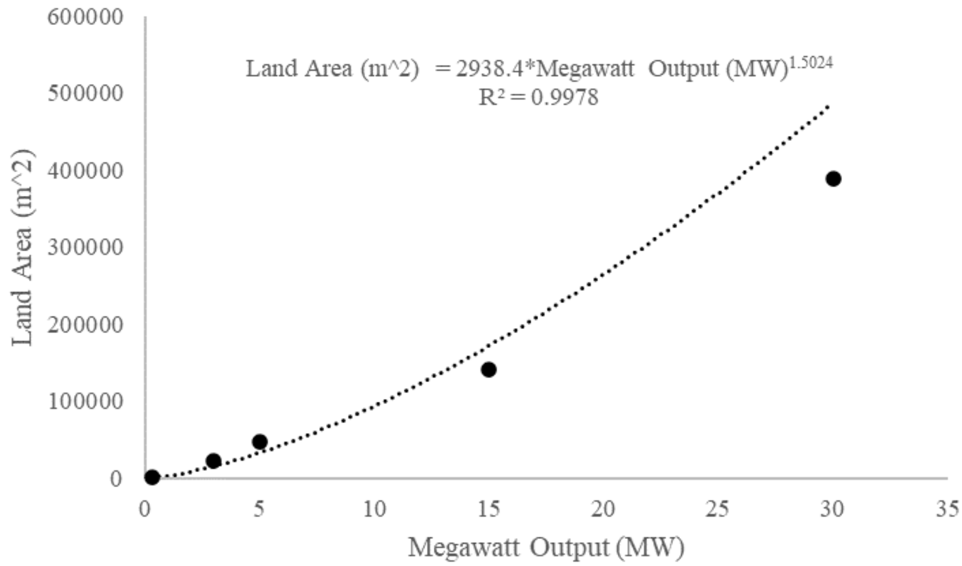


Figure 13: Plot of normalized Megawatt output and Land area needed for Linear Fresnel Concentrated Solar Power Plant with a power line of best fit.

Since switching yards vary in size and operational standards, we created a user interface to take these differences into account. In this user interface the user can input their specific needs for how many switchers are in use, hours the switching yard operates in a day, hours between charges, system location, and times of year they will be operating the locomotive. Additional optional inputs include the amount of water inside the locomotive, percent energy loss, and the maximum allowable acreage for the solar field. For these initial calculations we made the assumption for one switcher being used 14.5 hours a day with an 8 hour charge. To take into account energy loss due to heat loss we assumed an 80% overall system energy loss. We also did these initial calculations assuming the switcher will be used in Michigan year-round. To factor in the specific location of the switching yard, the equation generated from the graph is multiplied by the ratio of the normalized Direct Normal Irradiance (DNI_N) and the user specified Direct Normal Irradiance (DNI_U), forming equation 2.

$$Land\ Area\ =\ (2938.4\ *\ Megawatt\ Output^{\ 1.5024})\ *\ (\frac{DNI_N}{DNI_U}) \qquad \text{(Eq. 2)}$$

The complete calculations and results for the Power Tower, Parabolic Trough, and Parabolic Dish concentrated solar power plants, and the photovoltaic power plant can be found in appendix B.

After completing the calculations for a full size locomotive we determined that the power and land requirements needed are too large for the land available for our project sponsor, see table B8 in appendix B. We performed these same calculations for a 1:8 scale train that will be operated for 8 hours a day and has a charging capacity of 30 minutes[32]. The remaining use inputs stayed the same and a new set of energy output and land area needed was generated and can be found below in table 12.

Table 8: Summary of Land area needed for a Linear Fresnel Power Plant based on 1:8 Scale Locomotive Sizes.

Locomotive Tank Sizes (ft^3)	1.4	1.2	0.8	0.7	0.6	0.4	0.3	0.1
Power output Needed (kW)	0.53	0.43	0.31	0.27	0.22	0.17	0.10	0.05
Mirror Field Area (Acres)	0.31	0.23	0.14	0.12	0.08	0.06	0.02	0.01

Based on the recommendations from the project sponsor and the engineering analysis completed, our alpha design will be a 1:8 scale traditional fireless steam switching locomotive that incorporates linear Fresnel concentrated solar power, a synthetic oil heat exchanger, and hose refueling with a steam accumulator. Especially given the educational intention of this system, we believe that the selection of a 1:8 scale locomotive will be most practical while all other subsystem selections reflect the most efficient and effective concepts to be used with this size of locomotive. We have chosen these subsystem designs based on how they effectively interact with each other, recommendations from Ted and Professor Skerlos, as well as extensive engineering analysis using our system modeling tool. The Alpha design will be described further in detail in the next section.

Section 5: Concept Description - The "Alpha Concept"

After careful consideration of all generated concepts created from the three methodologies, we arrived at a preliminary "Alpha Concept": a 1:8 scale traditional fireless steam switching locomotive that incorporates linear Fresnel concentrated solar power, synthetic oil heat exchanger, and hose refueling along with a steam accumulator. Figure 14 below shows our selected design. The key to this selection was the size constraints for a hobbyist user. Since these 1:8 scale locomotives and power generation systems are built within the constraints of someone's home and property lines we chose the linear fresnel system to generate the needed thermal energy to generate steam. The hobbyist user only uses the system during the 'nicest' months based on where they live. For purposes of this project we assume regardless of area of residence the user will have three months of prime weather to use the locomotive and want to run the locomotive one to two times a week. Although the linear fresnel system is more complex than a photovoltaic system, these have been constructed by solar hobbyists and 'off the grid' people before, generating up to 50 watts of power. With this in mind we feel confident to move forward and dive into a deeper analysis for the Alpha Concept.

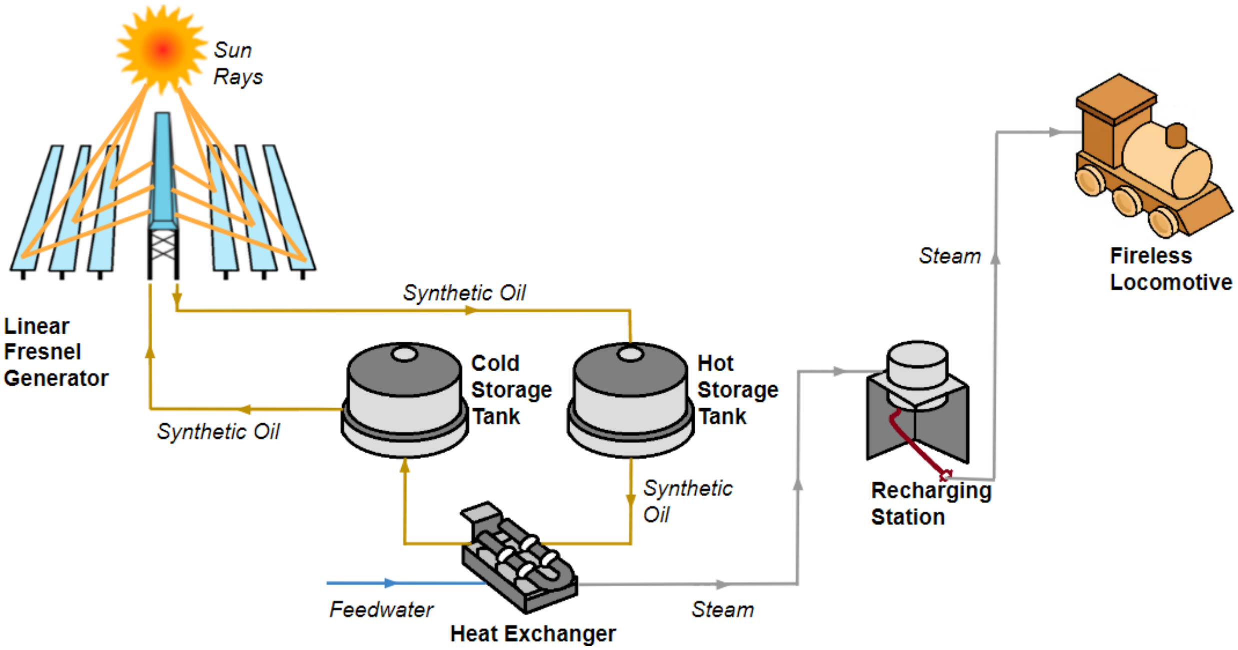


Figure 14: Alpha System Overview Diagram

Alpha Subsystem 1 - Energy Generation - Linear Fresnel Concentrated Solar Power

To generate the energy required for steam generation, we will utilize the linear Fresnel Concentrated solar power collector. Multiple reflecting mirrors will concentrate sunlight into an absorber tube that then transmits the concentrated energy into the synthetic oil heating fluid for steam generation [13]. These reflectors utilize a form of the Fresnel lens effect, which helps keep its size from getting too large. The reflecting mirrors will monitor the location of the sun using a computer solar tracking system and can adjust their angle of incidence accordingly to maximize the energy transfer. The absorber is an elongated, stationary assembly located at the focal line of the reflecting mirrors below it. It contains a collector plate in the middle that heats up the tube containing the heating fluid. Both the collector plate and tube are to be enclosed by a glazing cover, which reduces the heat loss by convection from the top of the absorber. The cold heating fluid coming from the steam generation subsystem will enter the receiver through the absorber tube and into the absorber, acquiring heat energy as they pass through and flowing back into the hot synthetic oil reservoir.

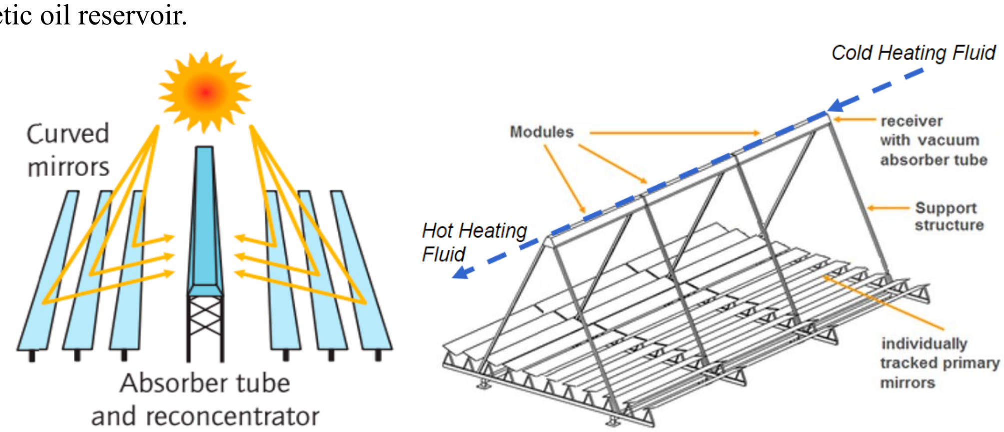


Figure 15: To the left, a simplified version of the subsystem showing the reflection of sunlight into the absorber. To the right, a more detailed diagram showing more components and the heating fluid flow.

To determine the solar field aperture area size, we first needed to determine a baseline for the megawatt energy generated per area of land. This meant researching currently operational linear Fresnel plants to determine their megawatt output and solar field aperture area, and create a mathematical model relating these values (illustrated in figure 13). This process is further explained in the engineering analysis section of this document. Following this, we determined the amount of energy needed to power the heat exchanger in the steam generation subsystem for different locomotive sizes. These calculations are explained below in the Alpha Subsystem 2 section. A summary of these areas can be found in Table 9 below.

Table 9: Summary of Land Area Needed for a Linear Fresnel Power Plant Based on the Required Heat Exchanger Power Needed for Different 1:8 Scale Locomotive Sizes.

Locomotive Tank Sizes (ft^3)	1.4	1.2	0.8	0.7	0.6	0.4	0.3	0.1
Power Required for Heat Exchanger (kWh)	0.62	0.51	0.36	0.32	0.26	0.20	0.11	0.06
Mirror Field Area (Acres)	0.31	0.23	0.14	0.12	0.08	0.06	0.02	0.01

Alpha Subsystem 2 - Steam Generation - Synthetic Oil Heat Exchanger

To generate steam to power the locomotive we will utilize a shell and tube heat exchange with a synthetic oil heat transfer fluid. The heat transfer fluid flows through the receiver tube on the solar concentrated power plant through a high temperature reservoir and into the tubes of the heat exchanger. The cylindrical tank is filled with water and the thermal energy from the higher temperature synthetic oil dissipates into the lower temperature water. Raising the temperature of the water and lowering the temperature of the oil. Using a u-tube design, the oil passes through the heat exchanger twice before exiting the exchanger and returning to the cold temperature reservoir and back into the receiver tube of the solar power plant. This process is illustrated in figure 16 below. The two pass system allows for a greater amount of heat transfer in a short period of time, allowing for more steam to be generated each hour [21]. The choice of heat transfer fluid is crucial to this system design as well. Due to the 1:8 scale, intermittent use, and location (Michigan), synthetic oil should be used as the heat transfer fluid. Unlike water and molten salts synthetic oil does not solidify until the temperature drops to below -30℃. Synthetic oil also has a high thermal conductivity and diffusivity increasing the heat transfer rate between the oil and the water [33]. In addition to selecting the proper heat transfer fluid, the insulation of these heat exchangers directly affects the efficiency of the system. When properly insulated these heat exchangers can operate with 90% efficiency or greater.

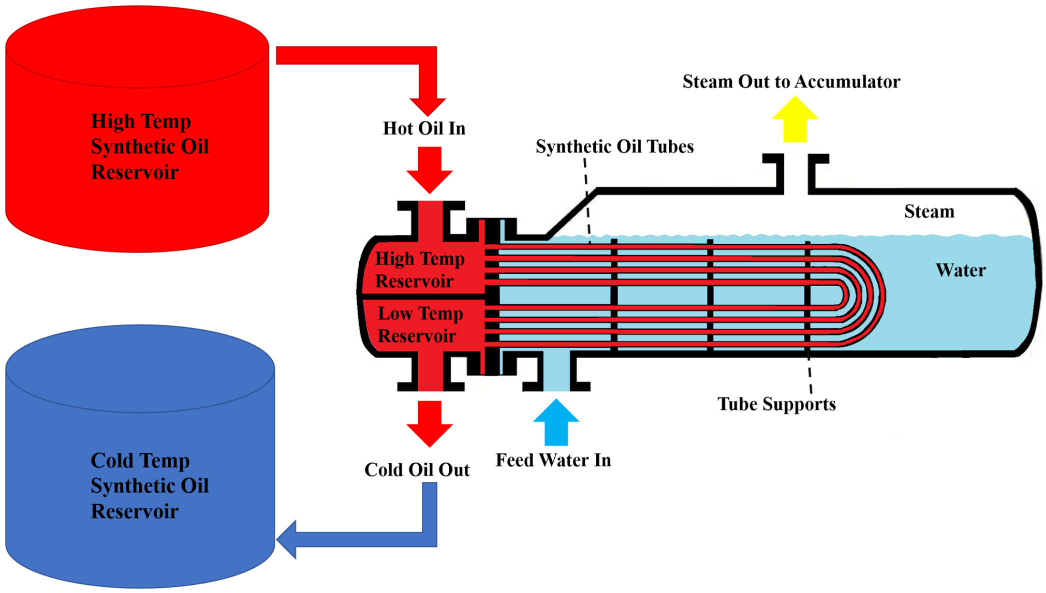


Figure 16: Synthetic Oil Heat Exchanger with Hot and Cold Reservoirs.

To determine the size and energy requirements of the heat exchanger we determined the mass of water within the range of locomotives and the amount of time between charges to determine the mass of water that needs to be heated per hour. The mass of water to be charged is determined based on the use needs of the locomotive user. In discussion with our project sponsor, the typical scale locomotive owner will run the train two or three times, once or twice a week during the "nice" months or their area. For our calculations we are using southeast Michigan as the location. These users would like to be able to have a full charge of steam within one hour. To make up for steam losses during recharging we estimated that 25% more water should be charged than what is actually required. The energy required (Q_s) to generate the proper amount of steam can be calculated by the mass of the water (m_w), the specific heat of the water (C_p), and the difference between the starting temperature (T_1) and evaporation temperature (T_2), using equation 3 [21].

$$Q_s = m_w * C_p * (T_2 - T_1) \quad \text{(Eq. 3)}$$

After determining the energy in J/h, this can be converted into the megawatt output needed. This calculated energy is used to calculate the area of heat exchange tubes needed. The area of the heat exchange tubes needed (A) is determined by the relationship between the energy per hour required (Q_h), the log mean temperature (ΔT), and the overall heat transfer coefficient (U), using equation 4 [21]. Calculations for the log mean temperature and overall heat transfer coefficient can be found in appendix C.

$$A = \frac{Q_h}{U * \Delta T} \quad \text{(Eq. 4)}$$

A summary of the energy required, area of heat exchange tubes needed, and the volume of the heat exchanger can be found below in table 14.

Table 10: Summary of Heat Exchanger Energy Requirements, Area of Heat Exchange Tubes, and Volume of Heat Exchanger for a Range of 1:8 Scale Locomotives.

Locomotive Tank Sizes (ft^3)	1.4	1.2	0.8	0.7	0.6	0.4	0.3	0.1
Mass of Water to be charged (kg)	33	27	19	17	14	11	6	2
Power Required for Heat Exchanger (kW)	0.62	0.51	0.36	0.32	0.26	0.20	0.11	0.06
Area of Heat Exchange Tubes (m^2)	466	381	270	241	192	147	85	46
Heat Exchanger Volume (ft^3)	36.4	30.6	22.6	20.0	16.3	13.0	8.0	4.6

Further analysis will need to be done considering heat loss of the system, overall system efficiency, and the cost of the system. The calculations above use the assumption of an 80% efficient system which will change once the shell and insulation heat transfer rates are considered.

After the steam is generated within the heat exchanger it will be sent to the steam accumulator at the recharging station.

Alpha Subsystem 3 - Recharging Station - Hose Refueling and Steam Accumulator

The recharging station is comprised of two parts, the steam accumulator attached to the heat exchanger and the hose used to transfer the steam from the accumulator to the locomotive. The steam accumulator serves as an energy storage tank to balance out excess steam generation during times of excessive sun and store steam when there is not enough solar irradiation to power the heat exchanger. A steam accumulator is a simple construction, as seen below in figure 17. The cylindrical tank has a pipe that brings steam in from the heat exchanger and injects it into the water of the accumulator through a row of injectors at the bottom of the tank. These injectors when sized properly supercharge the steam and improve the efficiency of the system [34]. The top of the tank has a steam steam outlet pipe that connects to the pressure regulator and the hose for recharging. Also on the top of the tank is a pressure relief valve that is used to prevent explosions and overfilling of the tank, protecting the users. Located on the bottom of the tank are the water inlet and outlet valves for purging and refilling the tank with water as needed.

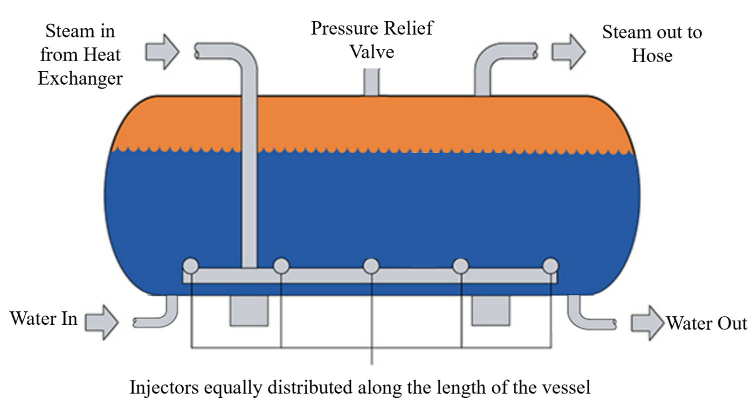


Figure 17: Diagram of Steam Accumulation Tank

The steam exchanger should be sized to hold enough steam for one full charge. To calculate the size of the exchanger we have to take into account the amount of flash steam that is generated from the pressure drop between the heat exchanger and the steam accumulator when steam is pulled from the accumulator into the locomotive. The proportion of flash steam generated (F_s) is calculated with equation 5, using the enthalpy of water at the steam accumulator pressure , the enthalpy of water at the discharge pressure which is the operating pressure of the locomotive, and the evaporation enthalpy of water at the steam accumulator pressure [23].

$$F_s = \frac{h_2 - h_1}{h_{fg}} \quad \text{(Eq. 5)}$$

This proportion of flash steam is then divided by the mass of steam storage required to get the mass of water needed. Since steam accumulator tanks are generally filled 90% full with water, the mass of water is divided by the percent it will be filled to get the mass of water of a 100% full tank. Using the density of water we can then determine the volume of a 100% full steam accumulation tank, which is equal to the total volume of the tank. A summary of these values, depending on locomotive size, can be found in Table 11 below.

Table 11: Steam Accumulation Tank Size Based on Locomotive Sizing and Flash Steam Generated.

Locomotive Tank Sizes (ft^3)	1.4	1.2	0.8	0.7	0.6	0.4	0.3	0.1
Minimum Steam Storage (kg)	2.3	1.9	1.3	1.2	0.9	0.7	0.4	0.2
Mass of Water at 90% Capacity (kg)	97	80	56	50	40	31	18	9
Steam Accumulator Volume (ft^3)	4.3	3.5	2.5	2.2	1.8	1.4	0.8	0.4

To recharge the tank on the locomotive the recharging hose connected to the steam accumulator is connected to the locomotive, once securely fastened a valve on the hose can be opened allowing steam to flow into the tank. When the steam exits the steam accumulator into the recharging hose it first passes through a pressure regulator. This pressure regulator drops the steam pressure from the steam accumulator's pressure of 10 bar to the locomotive's operating pressure of 6 bar. The steam will pass from the accumulator into the tank of the locomotive until the pressure within the hose matches that of the tank. Once this occurs equilibrium is reached and the steam will stop flowing automatically, allowing this to be a hands off operation for the user [2]. To further ease of use for the users and safety, the selection of the material for the hose is essential. Per our requirements and specifications this material needs to have a low thermal conductivity to protect the user from burns, and rated to withstand a pressure 10% greater than the operating pressure. This material should also be a lightweight, flexible material so only one person is needed to recharge the locomotive. Our initial engineering analysis and research has determined this hose should be made from the rubber compound Ethylene Propylene Diene Monomer (EPDM). EPDM steam hoses are currently used to transport steam in steel mills, refineries, shipyards, foundries, and chemical plants [35]. These steam hoses are available in a range of sizes and have a maximum working pressure of 17 bar and a thermal conductivity of 0.29 W/(m·K) [35].

Further calculations need to be made to determine the losses of the system and determine the proper efficiency. Through these calculations we will also determine the diameter of the recharging hose required and the proper pressure regulator and operating valve. After these determinations are made we can generate a detailed cost analysis and bill of materials for the project.

Alpha Subsystem 4 - Fireless Locomotive - 1:8 Scale Fireless Switching Locomotive
After evaluating the energy requirements for the full scale fireless locomotive, it was necessary to scale down to a 1:8 scale. This 1:8 scale fireless locomotive can eventually be built for the Southern Michigan Railroad Society to use as an educational and demonstration piece at their southeast Michigan railway museum. Using the standard full scale locomotive sizes, we scaled them down to the 1:8 scale and calculated the tractive efforts, or pulling power, for each new locomotive, equation 6. These new measurements can be found below in table 16. To further illustrate how powerful these small scale trains are, the tractive effort is converted to horsepower. For comparison, the average horsepower of a motorcycle is 79 hp and the average horsepower of a car is 200 hp [36]. On average one of these 1:8 scale trains can pull up to 20 adult passengers [37].

$$TE = \frac{K*P*CB^2*S}{D} \qquad \text{(Eq. 6)}$$

Table 12: 1:8 Scale Fireless Locomotive Engineering Specifications and Calculated Tractive Effort and Horsepower.

Storage Tank Size (Cubic Feet)	Cylinder Bore Diameter (in)	Stroke Of Piston (in)	Driving Wheel Diameter (in)	Maximum Tractive Effort (lb)	Horsepower
1.4	3.125	2.5	4.75	10136	184
1.2	2.75	2.25	4.25	7895	144
0.8	2.5	2.25	4.25	6525	119
0.7	2.3125	2	3.75	5624	102
0.6	2.125	2	3.75	4749	86
0.5	1.875	1.75	3.375	3595	65
0.3	1.5	1.25	2.875	1929	35
0.1	1.25	1.25	2.5	1541	28

The 1:8 scale fireless locomotive has the same driving components as a full scale locomotive, a throttle control arm, throttle valve, steam pipe, and piston cylinder connecting to the driving rods and wheels. Illustrated in figure 18 is a 1:8 scale fireless locomotive model and the internal components. The throttle arm is used by the operator to control the amount of steam allowed in the steam pipe and regulates the speed at which the piston cylinder moves. The 1:8 scale fireless locomotive operates at 7 bar (87 psi), the locomotive can reach a top speed of 10 mph, and a single charge can last for 30 minutes [37]. Many live steam 1:8 scale locomotives are available for purchase at hobby shops and specialty online retailers, including the 0-4-0 Switching locomotive we have used as a baseline throughout this project.

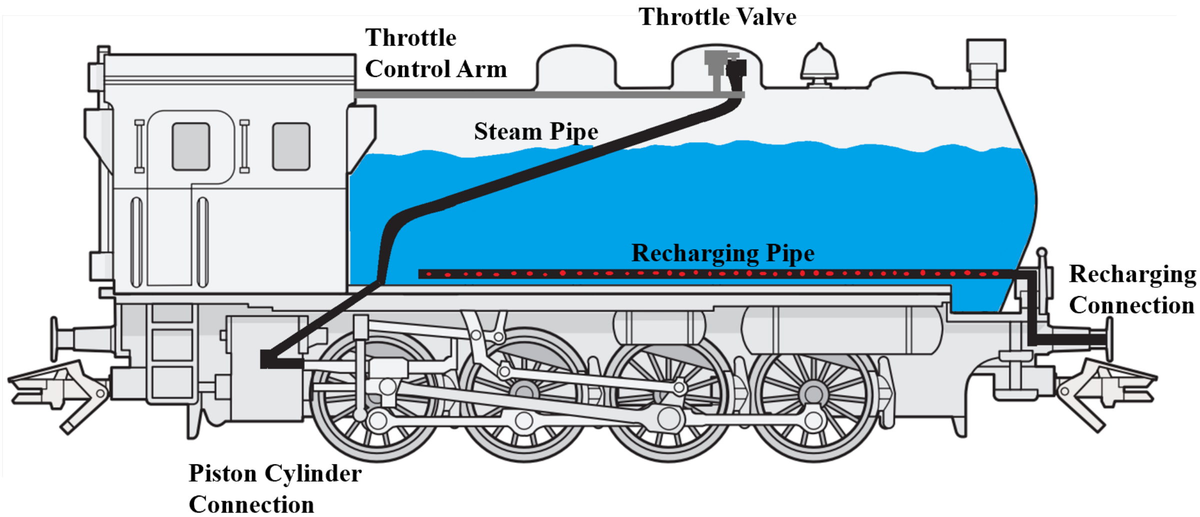


Figure 18: Fireless Steam Locomotive

After our initial engineering analysis we determined that a 1:8 scale train would be necessary for the feasibility of this project. After completing a more detailed analysis of the heat exchanger, the energy required to power the locomotive would allow for a 1:8 or 1:4 scale to be constructed. Due to our project sponsor's influence and the cost difference between the two scales, we have settled on the 1:8 scale locomotive. On average the 1:4 scale locomotive will cost $30,000, and the 1:8 scale locomotive will cost $18,000 [37]. Both scale locomotives use the same width track, and a one and quarter mile long track will cost $132,000 [38]. A breakdown of the bill of materials can be found in Appendix D.

Concept Analysis and Iteration

In order to meet the project sponsor's goals of creating a sustainable, educational demo that incorporates solar energy to power a fireless steam locomotive, the "Alpha Design" was assessed with respect to its ability to meet the requirements and specifications set forth by our team.

Specification Analysis

One of the most important specifications of the overall system is the total land area it requires. A large portion of this land area is to be occupied by our solar concentration system. This value affects not only the performance and capabilities of the system at any scale, but also the practical and financial viability of its implementation. We as a team have already determined a way to calculate the necessary area but need to communicate with our stakeholders about whether this number is realistic, and if it's not, determine how we might adapt our system to function given this constraint.

In order to meet the steam generation requirements of our system, we've opted to use a synthetic oil heat exchanger. We've determined that this technology is uniquely suited to our small scale application as it operates under the relatively low temperatures utilized by our system without seizing up. It is also more thermally conductive than water and requires replacement less frequently.

Our third subsystem uses a relatively simple tank and hose to store and dispense steam when necessary. So long as the tank is large enough and built of sufficiently strong material, it will be able to meet our specifications. Similarly, a hose of sufficient nozzle diameter and pressure rating will meet the needs of the system with ease.

Our fireless locomotive concept is more than sufficient to meet the required specifications, especially at the smaller scale we are now assumed to be operating under. So long as it is fed with sufficient energy from the previous three subsystems, it should provide the necessary tractive effort to accelerate itself over its tracks.

Engineering Fundamentals

In order to determine the optimal working fluid to carry thermal energy throughout the system, we've begun to look to our knowledge of both heat transfer as well as fluid dynamics to determine which substance has both good thermal conductivity as well as carrying capacity. Using computational fluid dynamic tools like Ansys is something we have little experience with and not enough time to familiarize ourselves with, so we intend to employ a first principles approach in Excel to determine the suitability of our chosen fluid.

We also intend to validate the specifications regarding our linear Fresnel energy generation subsystem using the mathematical model we've already created in Excel. Given the modularity of the tool we've created, we think it will prove simple to evaluate if the chosen technology achieves our specifications or to alter it if it doesn't.

Overall, we believe the selected "Alpha Design" to be well-enough defined to to analyze rigorously using engineering concepts. By splitting the overall system into individual subsystems, this has eased the interpretation of each step of this complex process and allowed us to break up our analysis accordingly. Most engineering concepts are fairly straightforward and can be calculated using values that are available to us online in the form of specification sheets or research papers, thus eliminating additional time spent communicating with industry experts.

Design Drivers and Challenges

The design drivers vary among the different subsystems. Furthermore, design decisions for each subsystem are reliant on each other. Beginning with subsystem 1, the most significant design drivers include the available land to place a solar farm, the available upfront capital to spend on a solar farm, as well as the local climate. For example, design decisions will vary depending on the average DNI experienced in a certain geography. Continuing with subsystem 2, the project scale will determine future iterations of the Alpha design. Although synthetic oils is the optimal design decision given the 1:8 scale locomotive model, if we were to pursue a larger locomotive size in the future, subsystem 2 would need to pivot to a different heat transfer fluid. Finishing with subsystem 4, the current 1:8 scale switching locomotive is optimal for the intended 'backyard' demonstration at the Southern Michigan Railroad Society; however, a pivot to a larger application would require a larger locomotive.

The most difficult aspects about the design are the high variability in sunlight in most geographic areas of the United States, the potential infrequent use of the locomotive, and the necessary capital investments. Beginning with the high variability in sunlight, a location such as Michigan experiences adequate sunlight in the summer months; however, those high levels of DNI quickly shrink to suboptimal levels in the autumn and winter months. Coupled with the shorter days, some geographies are more suitable than others for this project unless alternative methods of energy generation are considered. Continuing with the potential infrequent use of the locomotive, if the 1:8 scale demo is only used on certain days for short time periods and not being continuously run, then this adds the complexity of storing the heat transfer fluid from periods of intense sunlight. Concluding with the capital investments, each subsystem features a hefty price tag that could be daunting for most educational institutions. The design may not earn a profit unless a larger scale is pursued; however, the explicit purpose of our project is to focus on the environmental and sustainable aspects rather than profitability, thus these upfront costs are not as concerning in the scope of our project.

The major problems expected are related to weighting the various inputs in our system modeling tool and determining the tradeoffs that should be made based on those results. There are many key factors being considered such as cost, solar energy required, and locomotive tank size. This will be addressed by creating case scenarios to evaluate how our Alpha system would hold up in those situations.

Section 6: Engineering Analysis

After further research was conducted and we learned more about the needs and wants of our stakeholders, we decided the alpha concept chosen might not be the best outcome for this project. In a discussion with our project sponsor about system complexities and cost we decided to do more engineering analysis on the photovoltaic system. In this new concept a photovoltaic system is attached to the users home and is used to power the home and electric steam generator. In this analysis we also went deeper into the heat loss within the system and how that will affect the steam retention.

Steam Generation

Each locomotive has a certain amount of steam required to power the piston and cylinder to drive the locomotive forward. The amount of steam required is based on the working pressure of the steam tank on board the locomotive, overall tank volume, and the amount of water within the tank. A standard 1:8 scale Fireless locomotive has an overall tank volume of 1.4 cubic feet and is 75% full of water operating at 87 psi. To determine the mass of steam (m_{steam}) needed to power the locomotive we need the mass of the water (m_w), the enthalpy of water at the locomotive operating pressure(h_1) and the enthalpy of water at the electric steam generators operating pressure (h_2). Using equation 7 we are able to determine the mass of steam needed to power the train [23].

$$m_{steam}\,(kg) = \frac{m_w * (h_1 - h_2)}{h_2} \qquad \text{(Eq. 7)}$$

To determine the power requirements of the electric steam generator, we took a baseline of electric steam generators that are currently on the market. Graphing these generators based on the mass of the steam generated and the power required, we generated the following equation (equation 8) to determine the power needed for the 1:8 scale Fireless locomotive. A graph of the baseline electric steam generators can be found in Appendix E.

$$Power\ Required\ (kW) = 0.6454 * m_{steam} + 0.212 \qquad \text{(Eq. 8)}$$

To account for losses that can occur during recharging from escaped steam and heat loss through the recharging hose, we determined the steam generator should produce 25% more steam than the locomotive actually requires. The mass of steam and power required can be found in Table 13 below.

Table 13: Steam output and Power Requirements for Various Size 1:8 Scale Locomotives

Locomotive Tank Sizes (ft^3)	1.4	1.2	0.8	0.7	0.6	0.4	0.3	0.1
Mass of Steam Output (kg/h)	2.8	2.3	1.6	1.5	1.2	0.9	0.5	0.3
Power Requirements (kg/h)	2.0	1.7	1.3	1.2	1.0	0.8	0.5	0.4

Heat Loss

Unlike the full scale switching locomotive, the 1:8 scale switching locomotive is used intermittently and infrequently. Due to this intermittent use and variability of solar power generation, the user needs to be able to generate steam and retain it for a period of time until they would like to use it. To avoid adding further complexities and cost to the system, this steam retention should take place within the electric steam generator or the locomotive tank itself. To determine the amount of time each of these systems can retain the steam we needed to determine the heat loss for each system. For both of these systems the heat loss will occur primarily through the shell of the tank. For the electric steam generator heat loss will occur through the stainless steel shell and insulation into the atmosphere. The locomotive tank does not have insulation around the shell, typically constructed of brass, so heat loss will occur faster in comparison. First we need to analyze the heat transfer throughout the system. Figure 19, below shows a cut out view of the shells of each tank and how the heat will move through the system.

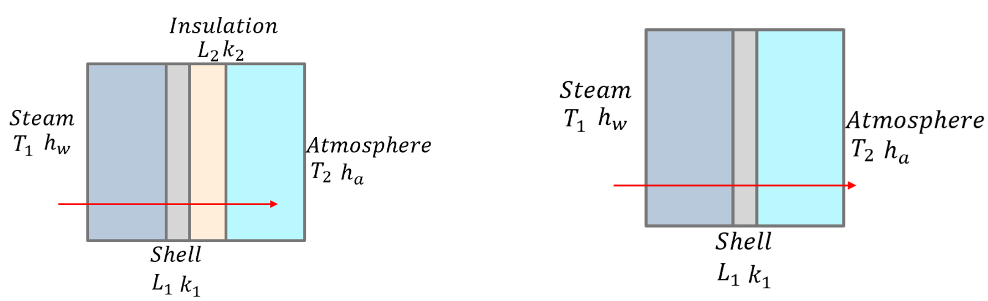


Figure 19: Flow of Heat Loss for Electric Steam Generator (Left) and Locomotive Tank (Right)

To determine the heat loss we first need to determine the overall resistance of the shell and insulation. The resistance (R_1) of the electric steam generator is determined by the cross sectional area of the tank initial temperature (T_1) and heat transfer coefficient of the water (h_w), the thickness (L_1, L_2) and thermal conductivity (k_1, k_2) of the shell and insulation, and the temperature (T_2) and heat transfer coefficient (h_a) of the air surrounding the system, Equation 9. Since the locomotive does not have insulation, resistance (R_2) is calculated with the cross-sectional area of the tank, the initial temperature of the steam and the heat transfer coefficient, the thickness of the shell and the thermal conductivity, and the ambient temperature of the air and its heat transfer coefficient, Equation 10 [55].

$$R_1 = \frac{1}{\pi(D/2)^2}\left(\frac{1}{h_w} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{1}{h_a}\right) \quad \text{(Eq. 9)}$$

$$R_2 = \frac{1}{\pi(D/2)^2}\left(\frac{1}{h_w} + \frac{L_1}{k_1} + \frac{1}{h_a}\right) \quad \text{(Eq. 10)}$$

After calculating the resistance of each system we can calculate the rate of heat loss, equation 11. This heat loss is determined by the difference in the steam temperature and the ambient temperature outside the tank. This heat loss will change depending on the location the tank is held and the time of year. For this project we are assuming the electric steam generator and the locomotive are outside or within an unheated garage.

$$Heat\ Loss = \frac{T_1 - T_2}{R} \quad \text{(Eq. 11)}$$

To determine the time it takes for steam to condense, we need to determine the amount of energy that the steam needs to lose before it condenses back into water. This happens in two stages, first the cooling stage where the temperature drops to just above the saturation temperature. The energy to cool the steam (q_1) is calculated using the mass of the steam, the difference in temperature, and the heat capacity of steam (C_p), equation 12 [56]. The second stage is when the steam condenses back into water. The energy to condense (q_2) is calculated using the specific enthalpy of saturated steam and the mass of the steam, equation 13. Totaling both these values together and dividing by the heat loss rate, we can determine the amount of time it takes for the steam to condense [56].

$$q_1 = m_s * C_p * (T_2 - T_1) \quad \text{(Eq. 12)}$$

$$q_2 = m_s * h_g \quad \text{(Eq. 13)}$$

Through these calculations we determined steam can be held within the electric steam generator between 4 and 9 hours depending on the size of the steam generator. The fireless locomotive tank, without insulation, holds steam for much less time, ranging from 30 to 45 minutes. Due to the short time to hold steam within the locomotive the user would need to add insulation around the tank if they do not plan on running the locomotive immediately after filling. The exact values and detailed calculations can be found in Table XX of appendix E. Since neither of these tanks are 100% filled with steam this calculation should not be used as an exact term for how long the steam can be held, heat transfer through the water and out of the tanks will cause some disparity within the calculations.

Solar Power Generation

The performance of photovoltaic solar panels is greatly affected by the solar radiation and temperature of the cells within each panel. Since solar radiation and temperature are driving factors for the performance of solar panels no system will perform the same as another. This variability comes from the solar radiation of the area, the ambient temperature that changes due to humidity and wind speed, cloud coverage, and shade. To properly size a solar field for this project we needed to understand how solar radiation and temperature affects the panels power output. Since the analysis for a photovoltaic power system changes based on the location, we chose to do our initial engineering analysis for a system in Michigan operating Year-Round. We chose this location due to the fact that our stakeholders and primary customer would be building this system in Michigan.

To begin our analysis we needed to determine how solar irradiance is impacted by cloud coverage. A common weather indicator for cloud coverage is the clearness index. The clearness index $[C]$ is the fraction of solar radiation $[Q_o]$ that is transmitted through the atmosphere that comes into contact with the earth's surface [homer]. Using this relationship seen in equation 14, we can calculate the 'actual' solar radiation for the area for a specified month of the year [homer].

$$Q = (1 - C) * Q_o \qquad \text{(Eq. 14)}$$

After calculating the 'actual' solar radiation, we then calculated the ambient temperature $[T_a]$. The ambient temperature can sometimes also be referred to as the feels like temperature. This is the temperature of a certain area due to the humidity $[H]$ and wind speed $[W]$. Depending on the humidity and wind speed this ambient temperature can be higher or lower than the measured dry bulb temperature $[T_M]$. This relationship is seen below in equation 15[apparent temp calc].

$$T_a = T_M + 0.348 * H - 0.7 * W * \left(\frac{Q}{W+10}\right) - 4.25 \qquad \text{(Eq. 15)}$$

Once we have determined the ambient temperature we can now determine the photovoltaic cell temperature $[T_C]$. This change in cell temperature will change the indicated operating current $[I]$ and indicated operating voltage $[V]$ as given by the solar panel spec sheets. As current $[I_a]$ and voltage $[V_a]$ change the actual power generated $[P_a]$ will change [design]. The actual power generated by the panels is also impacted by the Fill Factor $[FF]$ given by the spec sheet, and the Derating Factor $[DF]$. The derating factor takes into account losses generated by dirt and matter covering the panel (soiling), reduction in solar radiation caused by shadows (shading), Snow coverage, electrical losses from manufacturing imperfections (mismatch), resistive losses from DC and AC wiring (wiring), resistive losses from electrical connections (connections), reduced efficiency from degradation after the first few months of use (Light-Induced Degradation), losses as determined by the specific manufacturer (Nameplate Rating), Age of the panels, and losses incurred by system down time from power outages, maintenance or other unscheduled outages (Availability) [61]. The standard Derating Factor is 14% and for simplicity was used in these calculations. Equation 16 shows how the actual power generated was calculated.

$$P_a = FF * I_a * V_a * DF \qquad \text{(Eq. 16)}$$

The number of panels $[N]$ required to power a given load is determined by equation 17. The number of panels needed to generate enough power to power an electric steam generator and home Year-Round in Michigan can be found in table 14 below. This table shows the power and panel requirements for a range of possible 1:8 scale fireless locomotives. Complete calculations can be found in appendix E.

$$N = \frac{P_s + P_h}{P_a} \qquad \text{(Eq. 17)}$$

Table 14: Hourly Power (kW) Requirements and Number of Solar Panels Needed to Power Both a Home and Electric Steam Generator

Locomotive Tank Sizes (ft^3)	1.4	1.2	0.8	0.7	0.6	0.4	0.3	0.1
Total Power Needed (kW/h)	2.7	2.4	2.0	1.8	1.6	1.5	1.2	1.1
Number of Panels Needed	21	19	15	14	13	12	10	9

Cost Analysis

Concluding with a cost analysis, this modeling tool made it apparent that even the smaller scale 1:8 locomotive solar-to-steam system may not be economically feasible for the average hobbyist. While the scope of the project specifically requested a focus on feasibility, it's important to consider that the intended cost of this system is approximately $20,000, based on discussions with our project sponsor. However, the analysis shown in figure 20 uncovered an approximate $45,000 project cost using fairly standard assumptions.

Solar to Steam Cost Calculator (1:8 Model)

User Inputs

Subsystem 1: Energy Generation			
Select a State	Michigan	Years of Use	20
Wattage Needed (kW)	2.39		

Subsystem 2: Steam Generation & Recharging	
Steam Generation Needed (kg/hr)	2.3
Length of EPDM Hose Needed	80

Subsystem 3: Fireless Locomotive			
Track Length (feet)	330	Type of Train	GP20 basic detailed all steel engine with controller & batteries ready-to-run
		Add Paint?	Yes - Add paint & lettering (up to 3 colors)
Number of Track Switches	4	Add Sound?	Yes - Add Large Scale Phoenix Sound system including enclosed subwoofer and 100 watt amp

Cost Outputs

Subsystem 1	
Installation Cost	$6,727.55
Lifetime Cleaning Cost	$8,000.00
Total Subsystem 1 Cost	$14,727.55

Subsystem 2	
Electric Steam Generator Cost	$1,377.02
Fittings Cost	$300.00
Hose Cost	$400.00
Total Subsystem 2 Cost	$2,077.02

Subsystem 3			
Number of Track Panels	33	Train Paint Cost	$750.00
7.5" Gauge Track Cost	$7,590.00	Train Sound Cost	$550.00
Train Cost	$14,000.00	Switch Cost	$5,000.00
Total Subsystem 3 Cost	$27,890.00		

Total System Cost
$44,694.57

Figure 20: Solar to Steam Cost Calculator for an 1:8 Scale Locomotive

Before explaining the analysis itself, it's important to first understand the assumptions made in calculating the overall system cost. Solar PV cost data in the units of $/kW for all fifty states was used to approximate the installation costs [57], while lifetime maintenance costs were based on annual panel cleaning/maintenance costs [71]. Furthermore, the tool's steam generation analysis was used to determine the steam generation needed for subsystem 2. From there, the tool outputs the electric steam generator cost based on cost vs. steam generation data gathered from Amerec electric steam generators on the market [69]. The fittings costs were fixed values based on McMaster-Carr prices [58] and the hose cost was variable depending on the length needed from McMaster-Carr. With regards to subsystem 3, it was assumed that the hobbyist would construct a 1/16 mile track which requires 330 feet of track. It was also assumed that the hobbyist implements four switches into their track. Train costs were used from Backyard Train Co [59] while track and switch costs were used from RMI Railworks [65].

In this cost calculator, the overall system cost has been segmented into individual subsystem costs before being totaled at the bottom. All user inputs are made in the user interface which then outputs the cost of subsystem 1 as well as the total system cost directly to the user interface. Beginning with the energy generation subsystem, a user selects the US state they intend to build their solar to steam system in and then the wattage they will need to power it while also considering the amount of power the user's house is using in tandem with the steam generation. Based on those two inputs, an installation and lifetime maintenance cost are calculated. In this scenario, those two costs equate to approximately $15,000. Moving onto steam generation and recharging, a user inputs the hose length that they need and the calculator determines the electric steam generator, fittings, and hose costs. This ends up totaling $2,000 or approximately five percent of the total system cost. Lastly, for the fireless locomotive subsystem, a user inputs the track length and number of switches they plan on using and these inputs then calculate the variable costs of the subsystem. The 1:8 scale train cost is fixed and allows a user to select from several locomotive options. In this example, over half of the cost comes from the fireless locomotive subsystem and less than a third of the cost comes from the solar panel installation and maintenance.

The team believes an appropriate level of detail was chosen for this calculator as it is intended to approximate the total costs within 20% of the actual cost, so essentially a $10,000 buffer in either direction. Given this range, the team also has significant confidence in the accuracy of this cost calculator while acknowledging that system costs will most often be offset by the solar PV's household energy applications. Furthermore, lifetime maintenance costs are difficult to predict depending on future instances of extreme weather conditions such as droughts, hurricanes, and blizzards. In a future iteration of this modeling tool, more cost analysis is needed to consider the previously mentioned home power requirements, the solar array space limitations, as well as other scales such as a 1:4 model or full-scale switching locomotive.

Engineering Analysis: Final Thoughts

At the conclusion of this engineering analysis the photovoltaic system appears to be the better option for the home user. Depending on the home power consumption and the solar array set up the user will be able to generate enough power to compensate for the power draw caused by the steam generator when it is in use. This allows the user to meet the goal of a green train set up. In addition to generating enough power to power the train the user gains further benefit from the photovoltaic array being connected to their home and powering their everyday life. While the cost of the system is still large it is much less than the linear fresnel application. Assuming the locomotive enthusiast already owns the 1:8 scale train they would like to power, the upfront cost is reduced by more than half. Though this engineering analysis can be improved further, the under assumption of power generation gives us the confidence that this will be a viable system for the hobbyist user.

Section 7: Final Concept

Our final design is comprised of three different subsystems: energy generation, steam generation and recharging, and the fireless locomotive itself. As shown by figure 21, energy flows in the form of sunlight to the photovoltaic panels which convert it into electricity. This electricity then powers an electric steam generator which intakes feedwater and boils it to create steam that is then used to power our 1:8 scale steam locomotive.

System Overview

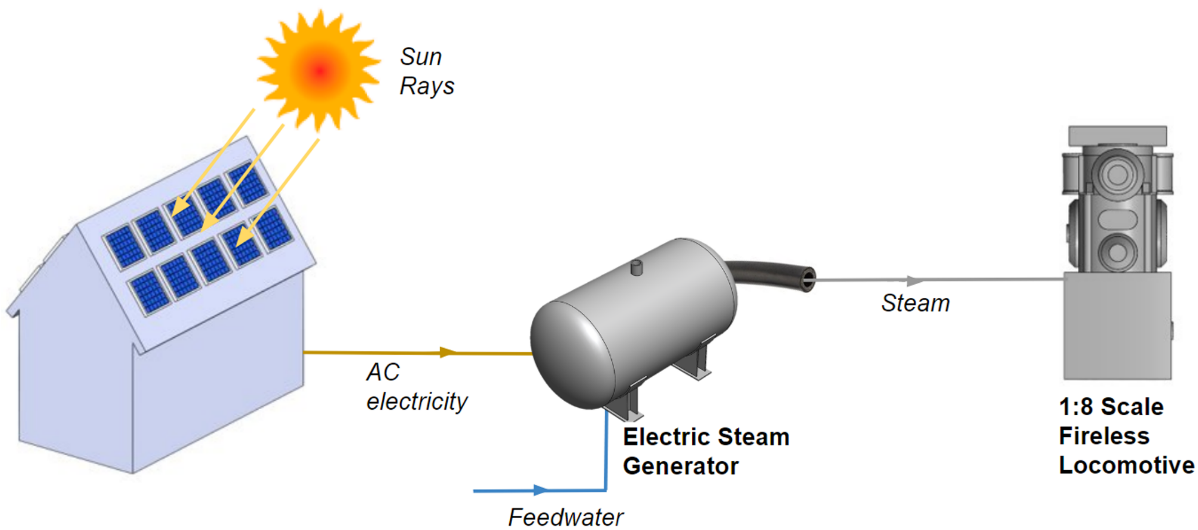


Figure 21: System Overview

Photovoltaic Energy Generation

The energy generation subsystems primary function is to facilitate the conversion of sunlight into a useful form of energy. We have opted to use photovoltaic panels (PV panels) to provide the necessary energy to power our other subsystems. These panels will be statically mounted on the roof of the house of the end user in such a way that they are exposed to as much direct sunlight as possible throughout the day as seen in figure 22. Using PV panels offers several advantages to the end user. They are widely available and easy to install. They are also relatively low maintenance when compared to other solar energy capture methods like concentrated solar power collectors. PV panels also allow us to use an electric resistive heater, which greatly simplifies the process of steam generation. Critically, when the system is idle, PV panels can be used to generate electricity either for domestic use or to sell in order to help offset the acquisition cost of the system.

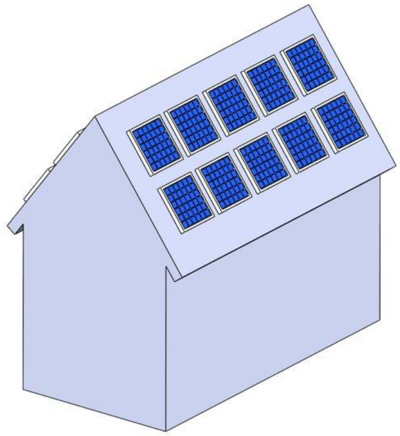


Figure 22: Photovoltaic CAD/Engineering Drawing

Electric Steam Generator and Recharging Hose

The steam generation and recharging subsystem consists of an electric resistive heating element with a steel steam accumulator tank (figure 23) and an EPDM hose with several fittings (figure 24) to transport steam from this subsystem to the following one. The resistive heating element is cheaply purchasable off the shelf and provides a low maintenance yet adequate option to use the electricity from our PV panels and boil water into steam within the accumulator. Our final design incorporates a commercially available accumulator tank fit to handle the pressures and temperatures associated with steam. The steam hose comes standard with common 1" NPT threading that can interface easily with the steam tank aboard the locomotive.

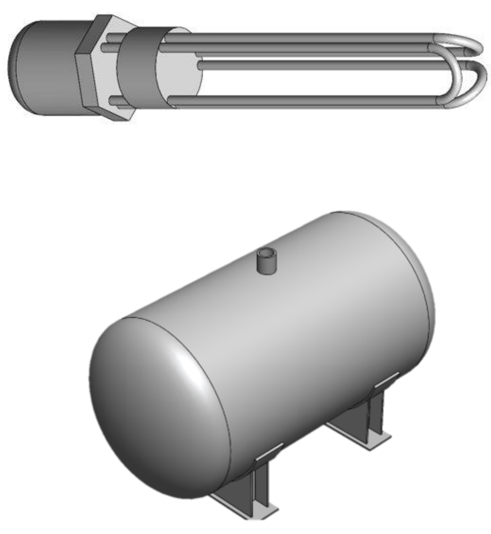


Figure 23: Electric Steam Generator (Bottom) and Heating Element (Top) CAD Drawings

Figure 24: Recharging Hose (Left), NPT Threaded Port (Center) and Pressure Regulator (Right) CAD Drawing

1:8 Scale Fireless Locomotive

Our fireless locomotive subsystem seen in figure 25 features a 1:8 scale steam locomotive typically used in a hobbyist context. It intakes steam from our previous subsystems hose via an NPT threaded port, which it then converts to mechanical work. This smaller train is suitable for our application as it is far less expensive than a full scale system and is much easier to acquire. It also has immensely smaller energy needs while offering the tractive effort necessary for “backyard” use. This lower energy requirement also greatly reduces the size of our first subsystem, requiring only a roof’s worth of area rather than several acres.

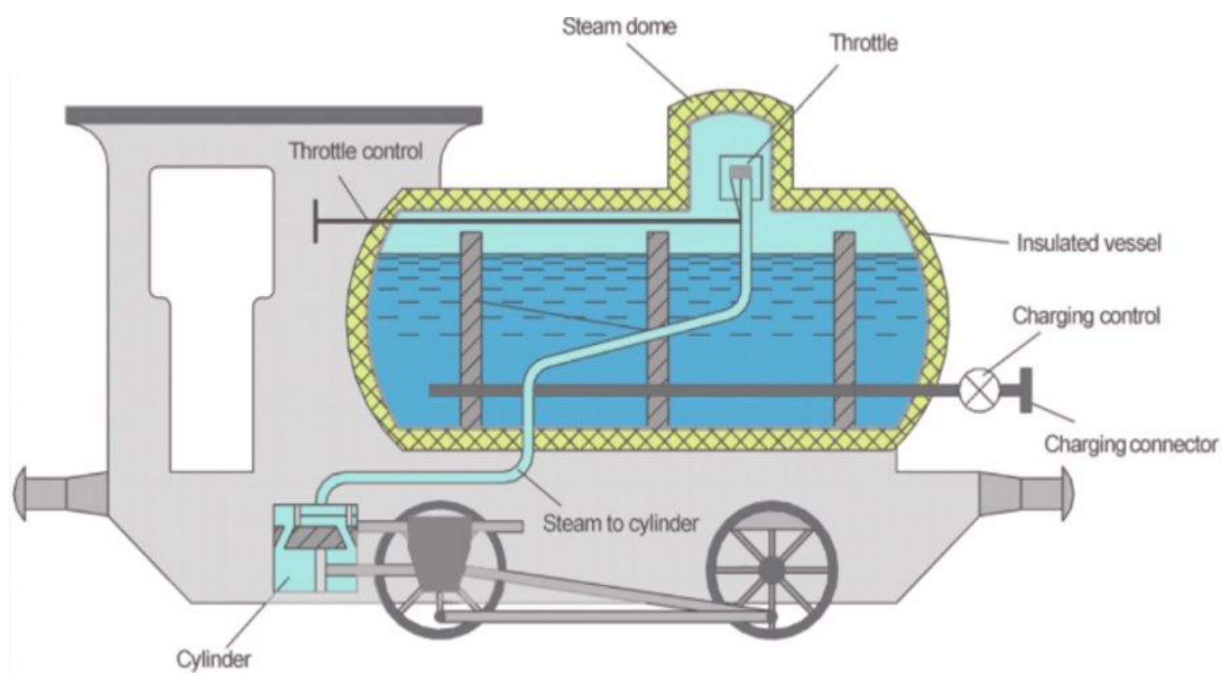


Figure 25: Fireless Locomotive Engineering Drawing

Our energy generation subsystem saw several revisions over the course of the semester before we finally settled on photovoltaic panels. Our initial designs were focused on concentrated solar power (CSP) systems such as linear fresnel collectors. Such systems were not readily available, extremely expensive, fragile, and required more area than PV panels. They also had little to no use outside of powering the steam train, making their cost a heavy burden on potential users. We initially focused on CSP because of the desires of our sponsor, but through engaging with him we eventually came to the conclusion that it was impractical and pivoted to the use of PV panels.

Section 8: Final Design Description - Solar to Steam Modeling Tool

The final design and goal of this project is a computer model of the selected concept, in the form of a system design and cost calculator. This computer model will need to take into account different user defined variables and make calculations based on those selections for the steam generation, heat loss, and power generation needs. It will perform these calculations and tell the user the minimum steam output and power required for an electric steam generator and the minimum number of solar panels they would need to purchase as well. This calculator will serve as a tool to help hobbyists build their green fireless locomotive set up and a starting point to help educate people and the industry to how solar power can be used to power the fireless locomotive.

User Interface

The main sheet users will interact with is the User Interface. This sheet will have the user input information about their specific system in order to make the proper calculations. Certain inputs will be required and others will be optional, seen below in figure 26. The required inputs are in red, optional inputs are in yellow, and the system outputs/calculations are in green.

User Interface							
Required User Inputs: Enter Required Specifications in Red Boxes							
1:8 Locomotive Accumulator Tank Size (Cubic Feet)	1.2	**Select A State**	Michigan	**Number of Track Switches**	4	**Track Length (feet)**	330
Number of 1:8 Locomotives in Use	1	**Select A Month or Season For Operation**	Year-round	**Type of 1:8 Locomotive**	GP20 basic detailed all steel engine with controller & batteries ready-to-run unpainted		
Number of Full Charges Needed	1	**Years of Anticipated System Use**	20	**Add Sound System to Locomotive**	Yes - Add Large Scale Phoenix Sound system including enclosed subwoofer and 100 watt amp		
Time Allowed for Steam Generation (Hours)	1	**Length of Hose for Recharging**	80	**Add Paint to Locomotive**	Yes - Add paint & lettering (up to 3 colors)		
Optional User Inputs: Enter Additional Parameters as Needed in Orange Boxes.							
Capacity of Water in Locomotive Tank (%)	75%	**Annual Home Energy Usage (kWh)**	6000	**PV Percent Loss from Shading**	5%		
Model Outputs: Green boxes are model outputs.							
Power Required For Steam Generation (kW)	**1.71**	**Total Power Requirement (kW)**	**2.39**	**Number of Panels Needed**	**19**	**Cost of Panels, Installation, and Lifetime**	**$14,727.55**
						Total System Cost	**$44,694.57**

Figure 26: User Interface for Steam and Solar Power Needs for 1:8 Scale Fireless Locomotive

User inputs include information necessary to perform calculations about steam generation and retention, power consumption, and power generation. These user inputs include the size of the locomotive accumulator tank, number of trains that need to be powered, how many times they will need to be powered in a 24 hour period, how long the user is willing to wait for steam to be generated, and where and what period of the year the user will want to generate steam.

Since this tool is meant to be used independent of this report or additional documentation, some technical language and specific locomotive language needs to be defined. Even though we wanted to include definitions and reasoning behind each of the user inputs, we did not want to 'clutter' the interface with paragraphs of text. To add these definitions we leveraged the 'Notes' tool within google sheets. This allows the user to hover their cursor over a box and a small window will appear with a definition or recommendation about what should be entered into the box. This will help those who are just starting out in the locomotive and solar world, without being cumbersome to a more experienced user. An example of these notes can be seen below in figure 27.

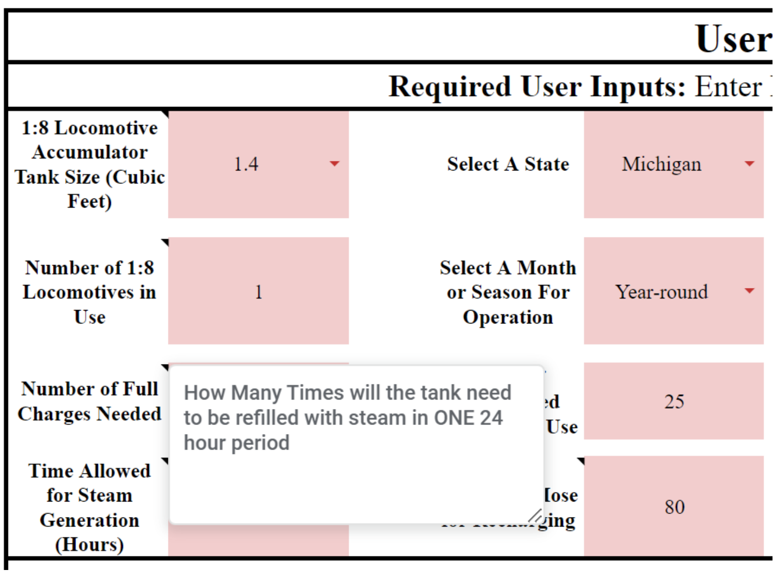


Figure 27: Solar to Steam Modeling Tool, Additional Notes Example

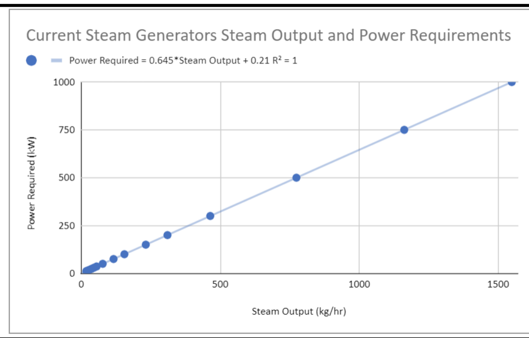
After the user updates the inputs to their required specifications, the user interface will display the key model information. These are highlighted in green, as shown above in figure 27. These key figures include the power required to generate steam, the total power the solar panels need to generate, quantity and size of panels, and the cost. The User Interface is intended to be a 'one stop shop' for users, giving them all the key information in one easy to read location.

Additional Sheets

The modeling tool will comprise multiple different sheets, each of which are performing their own calculations for the model, or contain information that will be called upon to make the proper calculations. Sheets will include, Cost, Locomotive sizing, steam generation, heat loss, power generation, cost and weather information. These sheets are not meant to be edited by the general user. Although these sheets are not meant to be edited they still need to be designed so users can follow the math and engineering logic. Each sheet will contain sections that define the nomenclature, variables, and equations used to make calculations, and the step by step process taken to make the calculations. An example of this can be seen in figure 28 below.

Steam Generation

Current Steam Generators	
Power Required (kW)	**Steam Output (kg/hr)**
12	18
15	23
18	28
24	37
30	46
36	55
50	77
75	116
100	155
150	232
200	310
300	464
500	774
750	1162
1000	1549



Nomenclature

$m_s, m_w, m_{wg} = Mass\ of\ Steam, Mass\ of\ water,$ $and\ Mass\ of\ water\ within\ the\ Steam\ Generator\ all\ in\ kg$

$h_1, h_2 = Enthalpy\ at\ steam\ generator\ operating\ pressure,$ $and\ Enthalpy\ at\ Locomotive\ operating\ pressure$

$V, L, D = Steam\ Generator\ Volume, Length\ and\ Diameter$

Equations

$$Mass\ of\ Steam\ (m_s) = \frac{(h_1 - h_2) * m_w}{h_1}$$

$$Power\ Required\ (kW) = 0.645 * m_s + 0.21$$

$$Volume\ (ft^3) = \frac{m_{wg}}{\rho_w} * 35.315$$

$$Length\ (ft) = \left(\frac{36V}{\pi}\right)^{1/3}$$

$$Diameter\ (ft) = \frac{L}{3}$$

1. Each locomotive has a certain amount of steam required to power the piston and cylinder to drive the locomotive forward. The amount of steam required is based on the working pressure of the steam tank on board the locomotive, overall tank volume, and the amount of water within the tank. A standard 1:8 scale Fireless locomotive has an overall tank volume of 1.4 cubic feet and is 75% full of water operating at 6 bar. The mass of steam required is calculated for each locomotive using the equation above.

2. The mass of steam needed perhour is calculated based on the user inputs for Number of Charges Required and the Time allowed for steam generation.

3. To determine the power required to generate the mass of steam necessary, an assortment of electric steam generators currently for sale power requirements and mass of steam generated per hour were graphed. A line of best fit was generated and that equation was used to determine the power needed.

4. To calculate the overall volume of the electric steam generator the mass of steam equation is rearranged to to find the mass of the water. This mass of water is then divided by the % capacity of the tank. This determines the mass of water to fill the tank 100% full of water. This mass can then be divided by the density of water and multiple by 35.315 to determine the volume of the tank in cubic feet.

5. To properly maintain its shape and keep the material from buckling, cracking, or failing an optimal pressure cyclinder has a length that is three times that of it diameter. Using this relationship, as shown in the equations above, the overall length and diameter of the electric steam generator is calculated.

Figure 28: Solar to Steam Modeling Tool, Steam Generation Sheet Nomenclature, Equations, and Steps Taken

Below the nomenclature, equations, variables, and instructions are tables performing the necessary calculations. These tables include a row for the user selected locomotive as well as all the other size locomotives. This will allow the user to compare each locomotive side by side if they choose to do so. An example of these tables of calculations can be seen below in figure 29.

Steam Mass in Locomotive Tank								
Tank Capacity (Cubic Feet)	Design Pressure (Bar)	Tank capacity in liters	Density of water at 10 bar	Mass of water in kg	Mass of water at % Capacity	Enthalpy of Water at 10 Bar	Enthalpy of water at 6 bar	Steam storage capacity (kg)
1.4	**6**	**40.4**	**0.882**	**35.6**	**26.7**	**762.6**	**698**	**2.3**
1.4	6	40.4	0.882	35.6	26.7	762.6	698	2.3
1.2	6	33.2	0.882	29.3	22.0	762.6	698	1.9
0.8	6	23.5	0.882	20.7	15.5	762.6	698	1.3
0.7	6	21.0	0.882	18.5	13.9	762.6	698	1.2
0.6	6	16.6	0.882	14.6	11.0	762.6	698	0.9
0.4	6	12.7	0.882	11.2	8.4	762.6	698	0.7
0.3	6	7.5	0.882	6.6	4.9	762.6	698	0.4
0.1	6	3.9	0.882	3.4	2.6	762.6	698	0.2

Electric Steam Generator Power Requirements and Sizing								
Locomotive Tank Size (Cubic Feet)	Mass of Steam (kg)	Mass of Steam output kg/hr	Power Requirements (kW)	Mass of Water Needed (kg)	Volume of Tank (Cubic Feet)	Length (ft)	Diameter (ft)	Cross Sectional Area (ft2)
1.4	**2.3**	**2.8**	**2.0**	**33.4**	**1.8**	**2.7**	**0.9**	**0.7**
1.4	2.3	2.8	2.0	33.4	1.8	2.7	0.9	0.7
1.2	1.9	2.3	1.7	27.4	1.5	2.6	0.9	0.6
0.8	1.3	1.6	1.3	19.4	1.0	2.3	0.8	0.5
0.7	1.2	1.5	1.2	17.4	0.9	2.2	0.7	0.4
0.6	0.9	1.2	1.0	13.7	0.7	2.0	0.7	0.4
0.4	0.7	0.9	0.8	10.5	0.6	1.9	0.6	0.3
0.3	0.4	0.5	0.5	6.2	0.3	1.6	0.5	0.2
0.1	0.2	0.3	0.4	3.2	0.2	1.3	0.4	0.1

Figure 29: Solar to Steam Modeling Tool, Steam Generation Sheet Calculation Tables For Full Range of 1:8 Scale Fireless Locomotives.

Section 9: Verification and Validation Approaches

As we moved forward with our design process and analysis, we had to devise methods to confirm how our chosen specifications are being met, and if our final prototype had successfully addressed our problem statement and satisfied our user. To do so, we developed verification and validation approaches, to ensure that our deliverables are up to standards. Given that our project approach is to generate virtual tools for sizing the solar steam locomotive system, all the verification methods performed were a combination of analytical tests and our validation approach was informed by our main stakeholder.

Verification Plan

For this project, each individual subsystem had its own verification process. Since none of our deliverables involve any physical builds, most of verification testing methods are based on Analysis and Virtual tests. This test method involves a mathematical based analysis of the specification being tested to determine whether or not it meets the requirements set. This is done through computer modeling, simulations and analytical tools. If a future project is to take place, it will be able to take our virtual tests to inform their own physical testing, and utilize the suggestions described below for physical testing.

Solar Array Size and Power Generation

To verify our system we first needed to confirm the calculations we made are close to calculations and estimations made by solar system modeling software. Since the team did not have access to an existing solar field and its data, nor a budget or time to buy a solar panel and gather data, we were able to source this information from the National Renewable Energy Laboratory (NREL) PV Watts Calculator. With this calculator the user inputs an address or location they would like to build a solar array and define the size of the array by drawing an area on the map, as seen in figure 21 below. For this project we chose a 900 square foot home in Michigan with a standard sized two car garage. The garage roof top was selected as the area to build the solar array, illustrated in the two red boxes in figure 30, both boxes representing the north side and a south side of said roof, together making 32 square meters of available area for the solar panels. This is within our panel area range for our specifications. Additionally, this area allows for a maximum of 18 panels using an average panel size of 1.7 square meters.

Figure 30: NREL PV Watts Calculator Solar Array Sizing Tool

PV watts then prompts the user to define some of the variables for the system they would like to build, DC System Size is automatically determined by the physical size of the system chosen by the user in figure 30 above. The module type can be selected to be Standard, Premium, or Thin Film. Each of these module types have their own efficiencies, Standard 15%, Premium 19%, and Thin Film 10%. For this project we chose to use the Standard Module type since it is the most common type in production today. Array Type will change depending on the placement of the array (roof or ground), system complexity as determined by the user, and cost determined by the user. These options include Fixed Roof Mount, Fixed Open Rack, 1-Axis and 2-Axis Tracking, and 1-Axis Backtracking. Axis tracking results in higher power generation since the panels will move following the sun's path, while fixed mounting is a cheaper option it does not yield as much power generation [61]. For the rooftop location, we chose to keep this a fixed roof mount system. To determine system losses there is an additional calculator where the user can input the percentage of losses due to dirt and matter covering the panel (soiling), reduction in solar radiation caused by shadows (shading), Snow coverage, electrical losses from manufacturing imperfections (mismatch), resistive losses from DC and AC wiring (wiring), resistive losses from electrical connections (connections), reduced efficiency from degradation after the first few months of use (Light-Induced Degradation), losses as determined by the specific manufacturer (Nameplate Rating), Age of the panels, and losses incurred by system down time from power outages, maintenance or other unscheduled outages (Availability) [61]. NREL provides a few default losses that are incurred in most solar systems, each of these losses is then averaged together for an overall system loss. The tilt and azimuth angle depend on the location and construction of the roof the system is being placed upon.

After the user inputs all of the data described above, PVWatts pulls weather data for the previous year. This weather data includes temperature, wind speed, precipitation, and cloud coverage. Using this information in conjunction with the user inputs, PVWatts calculates the monthly and hour energy generation for the system. The PV Watts calculator estimated that at its peak, the 18 panels would be able to output 2.0 kWh of energy, or 0.11 kWh per panel.

Table 15: NREL PV Watts Power Generation for Southeast Michigan Home vs Engineering Analysis

	Number of Panels	Maximum Energy Generated (kWh)	Energy Generated Per Panel (kWh)
PV Watts	18	2.0	0.11
Engineering Analysis	21	2.7	0.13

The PV watts calculator takes a few variables into account that our engineering analysis does not. While the PV watts calculator is more accurate because it accounts for tilt, azmuth, and directional orientation (North, South, East, and West) the difference in energy generation between our engineering analysis is only 0.02 kWh. This small difference verifies the accuracy of our engineering analysis and calculation methods, allowing us to use those calculations within the final deliverable, the Solar to Steam Modeling Tool.

Electric Steam Generator and Recharging Hose

For the steam generator, the calculations are verified by matching the calculated kg/hr of steam generation and the power requirements with a commercial product specification. Table 16 below takes the values calculated in the engineering analysis section above. For our chosen locomotive tank size of 1.4 ft^3, our calculated power consumption for the steam generator would be 2 kW and for a mass of steam output of 2.8 kg/h. Our chosen electric steam generator is a Reimers Model JR Steam generator [69]. According to the specifications of this specific model pictured in Table 16 below, it would need a power of 1.5 kW to generate a steam capacity of 2.27 kg/h, which provides close values to our calculated model and satisfies the specifications set.

Table 16: Steam Generation and Power Consumption for Standard 1:8 Scale Fireless Locomotive

Calculated		Reimers Model JR Specifications	
Calculated Heating Power (kW)	**Steam Capacity (kg/h)**	**Heating Power (kW)**	**Steam Capacity (kg/h)**
2	2.8	1.5	2.27

The safety of the system was verified by ensuring that both the generator and the recharging hose have the necessary safety labels and standards due to the high temperature and pressure involved. The steam retention time of less than 8 hours can be compared to those of current owners of the commercial product, and in a similar way, the refilling tank time can be compared.

1:8 Scale Fireless Locomotive

The performance requirement of a 53 to 350 lbs of tractive effort can be verified through a comparison of the detailed analysis of the selected locomotive performed in the engineered analysis versus actual owners data. The safety of the system was verified by ensuring that the locomotive is given the necessary maximum pressure to ensure no explosions. Finally durability can be ensured through another comparison with existing owners of the selected locomotive.

Validation Plan

Given the long time-frame this project requires to achieve its end goal of a full-scale fireless steam switching locomotive powered by renewable energy, we recognized the importance of splitting the validation plan into short-term and long-term validation. Due to the nature of our project being mostly based on models and theories, our short-term validation is primarily based on our sponsor's feedback to our modeling tool. Using this tool, we met with our sponsor in April 2022 to show him how to use it and create various scenario-based examples that output key data to guide future system decisions. With regards to long-term validation, this would be based on how a hobbyist uses our tool to construct their own 1:8 scale solar to steam locomotive system in different climates, geographies, and other various circumstances. The final component of long-term validation consisted of evaluating whether or not the hobbyist use of our solar to steam system inspired the creation of a 1:4 scale or full-scale application. Furthermore, the validation plan was broken down by the subsystem. The next few paragraphs describe the design cycles we experienced during our project as well as how we validate that the subsystem solution addresses the design problem we set out to solve.

Solar Photovoltaic Energy Generation

Our decision to pursue solar photovoltaic for the purpose of generating energy took several iterations as the project scope adjusted to meet realistic client goals. Originally, the intended solution would generate enough energy to operate a full-scale switching locomotive for upwards of 18 hours per day and 7 days per week. As the team and project sponsor realized in tandem that this would be a long-term approach and a smaller scale locomotive would first be necessary to demonstrate the concept to train hobbyists, energy requirements were significantly reduced. Thus, the validation for our current system would drastically change if the locomotive size was scaled up as most specifications would need to be increased to match the energy demand. For this project in the context of an 1:8 scale locomotive, validation of the solar PV energy generation will be completed by using our end-to-end modeling tool to evaluate various hobbyist scenarios across the United States. The modeling methodologies of these diverse depictions of solar availability will be shown to the project sponsor and we will seek feedback from him. If our assumptions, inputs, and/or outputs do not match his plan for convincing hobbyists to install a solar to steam system themselves, then we will need to iterate through a new design cycle of the modeling tool. Furthermore, an eco-audit could be conducted on the solar photovoltaic system to ensure that the system's long-term reduction in energy consumption and carbon emissions exceeds the same variables associated with a diesel locomotive model.

Electric Steam Generator and Recharging Hose
As previously mentioned above, specifications for each subsystem will significantly change depending on the scope of the locomotive application. Since the final project scope for the short-term is an 1:8 scale fireless locomotive for the purpose of hobbyist use, an electric steam generator and recharging hose were selected as the optimal subsystem design. To validate this subsystem in the short-term, the end-to-end modeling tool will once again be used to evaluate various hobbyist scenarios across the United States in tandem with the first subsystem's scenario-based analysis. These scenarios will then be presented to our project sponsor and course professor to ensure we have reviewed a diverse enough pool of possibilities. Another step of the validation process will be to see how Ted uses the tool himself and whether or not it is intuitive enough for his understanding.

1:8 Scale Fireless Locomotive
Concluding with the third subsystem, validation of the 1:8 scale fireless locomotive is dependent on the data outputs from the scenario-based approaches of subsystems 1 and 2. It will be necessary to consult with Ted as well as other train enthusiasts to gauge whether or not a 1:8 scale fireless locomotive will achieve the end goal of inspiring the creation of a full-scale solar to steam switching locomotive. As the long-term goal of this project is to replace diesel with renewable energy for the purpose of fueling switching locomotives, it must be evaluated whether or not it is reasonable to assume that this solution will successfully address the design problem we set out to solve: creating a less energy-intensive and carbon-intensive rail industry. This can only be validated by consulting locomotive experts such as Ted and other hobbyists who are familiar with the bureaucracy and underlying goals of the industry's largest players.

Subsystem	Validation Method	Date / Results
1 - Energy Generation	Using modeling tool to show sponsor various solar PV scenarios around country.	April 14 – completed
2 - Steam Generation & Recharging	Using modeling tool to show steam generation potential based on various solar PV scenarios.	April 14 – completed
3 - Locomotive	Using subsystem 1 and 2 data to demonstrate ability to power 1:8 scale steam locomotive.	April 14 – completed

Figure 32: Overview of the validation methods for each subsystem.

Section 10: Discussion
Although the overall design process structure was given to us by the ME450 instruction team, we believe that we should have tried narrowing down our design process to match this semester. By broadly iterating through our modeling tool designs based on different locomotive sizes, we often lost track of what we should be working on to be most effective. If we had initially taken the time to assign dates to the various iterations within our chosen design process, we would have been able to delegate tasks much more effectively while possibly coming to the realization earlier that a full-scale or 1:4 scale locomotive would not be an effective application at this stage of the technology.

Problem Definition
There are numerous areas that the team believes would benefit from exploring further in-depth. First, the team believes it would be necessary to engage with more train hobbyists to gauge if they realistically would use this modeling tool to build their own 1:8 scale solar to steam system in their backyard. This

would help us assess the practicality of our tool as well as how it should be modified to help the end user. Through the Southern Michigan Railroad Society, we could get in contact with other volunteers who share a passion for trains. Second, the team believes that it should review other 'green' locomotive designs. While the fireless steam locomotive certainly offers a more sustainable return to steam locomotion, the US Department of Energy and US Environmental Protection Agency are currently exploring other forms of sustainable locomotion, none of which include the fireless steam locomotive. We could collect first-person interview data from getting in contact with relevant experts from either agency to gauge the long-term practicality of this technology. Third, the team believes that it would greatly benefit from reaching out to switching yard operators and owners to see how often technological changes are made as well as how they would go about funding a full-scale solar to steam system. Lastly, the team believes that the problem could be better defined by visiting a concentrated solar power plant to better visualize how the technology is used in practice. Specifically the linear fresnel system would be intriguing to view up close.

Design Critique

This project took many turns throughout the semester and scope was hard to identify. Since the scope was not defined until later in the semester the amount of time spent on the final design was significantly less than what was necessary. The majority of the semester was spent figuring out which system to model and how to do so. While this is essential since the modeling tool is based on this concept and calculations, not enough time was spent considering what was going into this tool, how it would be used, and who would be using it. Excel and google sheets are a robust tool for many different calculations and design scenarios and accessible to virtually anyone. Though it does have limitations when it comes to performing calculations based on a wide variety of scenarios. The final design and modeling tool illustrates and explains each step in detail allowing the user maximum understanding. But is limited to design scenarios as predefined in the tool. For instance, the tool allows you to determine the amount of solar panels you need to power your system, but it does not allow you to calculate the size of the system based on the maximum allowable area a user has for solar panels to be installed. The modeling tool performs all the necessary calculations and shows the end user the key elements needed for their system, but needs fine tuning to determine what inputs and outputs are the most important for the user. If this project were to continue, or we had to start again, we would spend more time engaging with stakeholders outside of the project sponsor to determine how the modeling tool would be used and what is most important to the user.

Section 11: Reflection

Public Health, Safety, Welfare, and Other Societal Impacts

Public Health and Global Context

By introducing this modeling tool to locomotive hobbyists, we help start a path towards a safer work environment in switching yards while also reducing the amount of greenhouse gas emissions associated with switching locomotives. A switching yard that relies on renewable energy carriers such as solar photovoltaic will create a healthier environment for all primary stakeholders.

In the global marketplace, the transportation sector makes up a significant portion of all greenhouse gas emissions and specifically the train industry uses a substantial amount of petroleum based fuels. By introducing an alternative method of train locomotion, regions that benefit from high amounts of sunlight can use this solar to steam design to reduce operating costs.

Potential Social Impacts from System Manufacturing, Use, and Disposal
Manufacturing of these solar to steam systems still require several heavy metals such as steel, so there isn't necessarily a potential social impact associated with the manufacturing process with respect to how locomotives are currently manufactured. However, there will be less manufacturing of petroleum based fuels which could reduce the likelihood of future oil spills.

As hinted at before, the use case has the most potential to positively impact society as a solar to steam design would drastically reduce the greenhouse gas emissions associated with locomotion. As has been widely documented by the Council on Foreign Relations, the best way to tackle climate change is by keeping fossil fuels in the ground [62]. Thus by reducing the amount of fuel demanded by the global rail industry, the world moves closer to achieving carbon neutrality and preventing the worst effects of a changing climate. Specifically, a solar to steam fireless locomotive would reduce carbon emissions and dependency on non-renewable fuels such as diesel, thus reducing air pollution in local communities. Furthermore, this technology would increase worker safety by eliminating harmful particulate matter in the switching yard that can cause long-term damage to an individual's heart and lungs, as noted before.

While the model itself does not have a disposal component, the solar to steam system that it recommends has several key components that all have well-defined lifetime. First, the energy generation subsystem will eventually need to be disposed of as the photovoltaic cells lose their effectiveness over time. According to the Environmental Protection Agency (EPA), solar panel recycling is becoming more prevalent and is expected to be widespread by the time one of these systems reach the end of their life in 20+ years [63]. Furthermore, locomotives such as 1:8 scale can be stripped down to recycle certain parts for the manufacturing of new locomotives. Overall, the disposal of these systems will have a decreasingly negative impact on the environment as PV recycling practices become more widespread.

Potential Economic Impacts from Design Manufacturing, Use, and Disposal
The manufacturing of these solar to steam systems will create more jobs related to solar photovoltaic panel and locomotive manufacturing. Perhaps with this less fuel intensive technology, it will be cheaper and more energy efficient to ship more products by locomotive. This could also incentivize the US government to invest more in building new railroads around the country, thus leading to more manufacturing jobs.

Because this technology eliminates fuel use and replaces it with solar energy, the use of this system technically has a negative direct economic impact; however, it makes up for it indirectly by incentivizing investments in more renewable energy carriers.

As previously mentioned, this technology has the potential to expand the PV recycling industry, thus having a positive economic impact on companies that deal with recycling and other waste practices.

Tools Used to Characterize Potential Societal Impacts of System
Our stakeholder analysis and ecosystem map were evaluated to characterize the potential societal impacts of our design. We recognized the importance of taking into account all stakeholders at every level (primary, secondary, and tertiary) in the context of this technology while considering both the short and long term. For example, we evaluated the tradeoffs of introducing solar to steam systems to the rail

industry for stakeholders such as switching yard operators. While in the immediate future, the technology will need to gain traction among hobbyists before scaling to a full-scale operation, a conservative technology introduction timeline of ten years could result in operators having plenty of time to understand how their responsibilities differ for maintaining a fireless steam locomotive. On the flip side, there's the possibility that in the long-term, this solar to steam technology could speed up the transition to automated switching yards.

Cultural, Privilege, Identity, Stylistic, and Power Dynamics

As evident by the varying team member bios in Section 16, all team members came from very different backgrounds. We are all mechanical engineering students at the University of Michigan with at least three and a half years of college experiences to guide our approaches to this project; however, we were all members of different organizations, several of us had transferred from other schools, and one of us even had several years of full-time work experience. Thus, these cultural, privilege, identity, and stylistic differences influenced our approach to the project as some of us felt more comfortable designing client facing deliverables such as the modeling tool and design review presentations while others gravitated towards writing more parts of the design reports. In terms of similarities, all of us felt comfortable using resources such as CAEN to CAD a system output of our modeling tool in SolidWorks, but we delegated this task to Nick who felt most comfortable with computer aided design software. Furthermore, our similarities and differences also helped us during our stakeholder analysis as several of us were much more familiar with the responsibilities of a switching operator, for example. And with regards to stylistic differences, some members relied on their full-time work experience to show other members how to produce user-friendly deliverables that could be easily interpreted by a wide range of identities. Overall, we relied more heavily on our collective differences as a group to bring unique perspectives to group discussions while using our similarities as a way to initially connect as a group and build psychological safety. As one group member had previously learned in a class on management and organizations, a group's collective intelligence will always be greater than the sum of its individual intelligences due to synergies among members.

With regards to our project sponsor Ted Delphia, cultural, privilege, identity, and stylistic similarities and power differences heavily influenced our design processes and final design. Our group members had little in common with Ted other than our association with the University of Michigan. In terms of differences, Ted was an avid train enthusiast who studied a non-engineering major at Michigan and is several decades older than all of us, thus we relied heavily on him to describe what he was looking for in a successful deliverable. Additionally, there was a strong power difference between the group and him as we lacked any familiarity with train technology before the project began; however, this power difference was reduced by our frequent communication with each other.

Inclusion and Equity

Power Dynamics Among Stakeholders, End Users, and Other Team Members

As there was minimal interaction between our team and our stakeholders outside of our project sponsor, there were no observable power dynamics. This benign said, we would anticipate significant power dynamics between our team members and decision makers within the rail industry. Many of these individuals have spent the majority of their careers in the rail industry, thus it can be difficult to introduce new perspectives if the business case cannot be clearly understood. As the project wraps up, the power dynamics between team members and hobbyists have been addressed as we now fully understand the rail industry as well as how our modeling tool can improve the industry's environmental impact.

With regards to end users, Ted doubled as an example of an end user, thus there was a medium power dynamic between the team members and him. His industry knowledge and experience exceeded all of ours combined, so we relied on our conversations with him and his interpretation of how other hobbyists would use our model to guide the creation of our research and deliverables.

Among team members, there was certainly a power dynamic depending on the topic. A couple members had previously completed coursework related to renewable energy carriers such as solar and so they felt much more versed in determining relevant variables and their associated units. Other team members felt much more comfortable interacting with Professor Skerlos and Ted which created a power difference based on who interacted with our two advisors the most. These power dynamics still exist among the team members as two of the four members led nearly all of those discussions as well as internal group discussions.

Identities and Experiences Shaping Perspectives

In the context of our project, our own identities and experiences certainly shaped our perspective compared to the end users of our product. For the modeling tool, those that will be using the modeling tool are hobbyists who are typically several decades older than our team members. As previously stated, we had far less exposure to the rail industry as none of us grew up riding trains that often other than the occasional trip to a city or regional Amtrak ride. When compared with other team members, Joey had a lot of prior experiences with sustainability oriented coursework, creating client presentations for his business classes and consulting club, and leading team discussions. Thus, his perspective was that this project presented an enormous opportunity to reduce fuel consumption within the transportation sector. Halie had a lot of prior experience working in a couple full-time roles while also owning a house which offered a new perspective as to how a hobbyist would install one of these systems in their backyards. Keith had previous experiences with graphic design and so he was able to leverage his visualization skills by creating some nice images for presentations. Nick had experience using CAD software, so he was able to create a holistic depiction of what a backyard solar to steam system would look like. Compared to the end users of this project, our budding identities and smaller list of experiences made this an eye-opening experience in terms of learning how train hobbyists spend their free time. In terms of long-term end users, we learned that our collective identity offered a good perspective as to how this technology could make the world a better place in which our society is less reliant on the oil industry.

Ethics

Future Ethical Dilemmas

There were minimal ethical dilemmas faced in the design of this project as it mostly centered around the modeling of a system that uses solar energy to generate steam and then power a fireless steam locomotive. As the end use of this deliverable will not be fully attained for at least five years, ethical dilemmas did not have to be considered too much. However, we did take into account the amount of land that the energy generation plants would require to be effective. This land could belong to communities that might rely on it more than the rail industry and future railroads could be built across other civilizations' land. As we've seen with the controversy surrounding the expansion of the Keystone XL Pipeline, ethical dilemmas can derail expensive infrastructure projects that aim to connect far away places. Since the rail industry aims to bring packages and persons all over the world, the locations of their railroads are bound to stir controversy. Because we did not face ethical dilemmas in the immediate context of this project, we did not have to manage them; however, there are obviously long-term implications of expanding the transportation sector with a more sustainable fuel source.

Personal Ethics vs. Professional Ethics

As a group, our personal ethics are fairly aligned with the professional ethics that we are expected to uphold by the University of Michigan. We are in agreement that as engineers we hold ourselves to the highest standard in which we must use our knowledge and skill sets to make the world a better place while taking into consideration all stakeholders. Whether that be end users, the environment, small communities, or future generations, we believe that we act with integrity while maintaining our commitment to positive societal change. These beliefs fall in line with the University's and we would hope they fall in line with future employers as well. However, we also recognize that the University and its leaders do not always act in the best interest of their stakeholders as evidenced by the past few years, thus we must do our best to change that reputation. With respect to future employers, we also recognize that not all companies act in good faith for their employees, the environment, or end users. Even the most notable companies have not been susceptible to scandals and while corporate leaders might place pressure on its employees to act in bad faith, we must always remember our personal ethics and why we became engineers in the first place. Before making major decisions in future jobs, we must recognize the impact of that decision on vulnerable communities and society as a whole.

Changes in Perspective

The team's assessment of how this technology would impact society grew enormously throughout the semester as we interacted with our primary stakeholders more. We initially thought that we could immediately impact stakeholders such as switching operators, communities that live near switching yards, and the rail industry. As we moved along further, we recognized the limitations of our four member team, the short timeline to complete the project, as well as the bureaucracy of the rail industry. It would take years of developing the solar to steam system so that it could be applied at the commercial scale. In place of our massive expectations, we realized that we could inspire grass roots interest in the technology's potential by creating a sound modeling tool that hobbyists could use to create 1:8 scale systems in their backyards. To conclude, our perspective changed in scope for a single semester, but our ambition to drive positive change remained as we pursued our deliverables with a priority on user friendliness.

Challenges Faced

Some of the biggest challenges that the team faced were related to validating that our subsystems met the necessary engineering specifications. Given the complexity of this system, tradeoffs had to be made between user requirement categories such as performance, cost, and efficiency. Specifically, we had to consider how much a train hobbyist is willing to spend on a backyard system. Ted initially stated that a hobbyist would only be interested in spending about $20,000; however, that would barely cover the expenses necessary for a 1:8 scale locomotive and its track setup. From there, we faced a difficult tradeoff between additional maintenance costs and upfront system quality. This being said, the switch from CSP to PV introduced a new opportunity to have the system serve a dual purpose as a means for generating energy for household use as well. As our goal is for a future ME450 team to use our work to build a functional 1:8 scale prototype for the Southern Michigan Railroad Society, we had to ensure our team was considering all possible use cases such as expanding the potential for this energy generation to accommodate the museum's other energy needs.

Another major challenge was narrowing down our project scope. This caused issues throughout the entirety of the project as it was unclear how in-depth our modeling tool should be to consider other renewable energy carriers, locomotive sizes, and methods of transportation. As the team began with a full-scale application, it became apparent that it was not initially feasible to power a switching yard with current CSP technology. From there, the group had to repeat its analysis for a 1:4 scale locomotive and then a 1:8 locomotive which completely eliminated the switching yard application from our work this semester. Although our work was meant to inspire switching yards to eventually adopt this technology, it was unclear how this would actually take place as well as why no interaction with rail industry professionals would be necessary to gauge the practicality of this technology.

Lastly, it was not immediately clear why there was such a specific focus on using solar energy and why the application should be for fireless steam locomotion. Although there exists immense loyalty to steam locomotion among train hobbyists, its potential for reintroduction does not appear to be realistic among industry experts. Had the project scope allowed for us to compare solar with another renewable energy carrier technology such as nuclear or geothermal, perhaps there would have been more potential for a report that could be distributed to industry experts or academics focusing on renewable energy.

Section 12: Recommendations

In terms of our recommendations, we have divided this section into short-term and long-term recommendations. The short-term can be thought of as the next two years (April 2022 - April 2024) while the long-term can be thought of as the following decade (April 2024 - April 2034). As our deliverables focused on a grass-roots approach to introducing this technology to hobbyists (short-term), we felt that this would better be evaluated separately from introducing the technology to the seven major railroad companies in the United States (long-term).

Short-Term Recommendations

In the short-term, our team has developed a number of recommendations for improving the potential for this technology to have a lasting societal impact. Specifically, there are XX recommendations: promoting the modeling tool among the Southern Michigan Railroad Society and other hobbyists, continuing this project with another ME450 team in which you construct a 1:8 scale system for the Southern Michigan Railroad Society, determine the most practical source of energy generation as it does not appear to be solar CSP, contact rail industry experts or Department of Energy officials to gauge the practicality of widespread fireless steam locomotion given the massive manufacturing process changes that would be required, and determining how much switching yards would save on energy expenses by eliminating fuel costs.

First, the team recommends the promotion of the modeling tool among the Southern Michigan Railroad Society and other hobbyists. As the purpose of the tool is to garner support among train enthusiasts such as Ted Delphia, this should be a top priority as in order to receive the necessary funding to create one of these 1:8 scale systems, there will need to be passionate donors willing to devote their time, energy, and money to the solar to steam cause. Because the Southern Michigan Railroad Society is within a thirty minute drive of the University of Michigan - Ann Arbor campus, future groups could interact with the society further and develop a better understanding of the rail industry as a hobby.

Second, the team recommends continuing this project with another ME450 team in a future semester in which the team constructs a 1:8 scale system for the Southern Michigan Railroad Society using our modeling tool. By leveraging the Society's deep knowledge of the industry and the mechanical engineering department's vast knowledge of solar photovoltaic systems, there's potential for this system to actually be implemented in its desired 1:8 scale.

Third, the team recommends determining a more practical source of energy generation for full-scale locomotion. As switching locomotives are often operating nearly 24 hours per day, they require a reliable source of energy that does not vary so significantly throughout the course of the day. If solar CSP or solar PV were to be pursued, then massive investments would need to be made on energy storage. Instead, a more reliable alternative such as geothermal or nuclear should be considered in the context of this application.

Fourth, the team recommends contacting rail industry experts or Department of Energy officials to gauge the practicality of widespread fireless steam locomotion. Given the costly retooling and infrastructure changes that would be necessary to accommodate this technology, it seems that the world's largest rail companies would only consider the most efficient and sustainable locomotive designs. Thus, this begs the question of whether or not there's truly a reason for a major rail company to use a fireless steam locomotive while there are already hybrid locomotives being pursued that significantly reduce fuel needs and carbon emissions. Overall, it appears that the long-term project goal may need to be shifted to a purely educational stance while other types of clean locomotion can be pursued for long-term switching applications, among other low-speed rail operations.

Fifth, the team recommends determining how much switching yards would save on energy expenses by eliminating fuel costs. Although the environmental and societal factors are major components of this project and our goals within the scope of mechanical engineering, a major switching yard will likely not consider retooling their entire business unless a sound business case can be made. If fuel costs can be drastically reduced while also decreasing the switcher downtime, then the yard stands to save on recurring expenses. However, if maintenance and cleaning of photovoltaic or concentrated solar power systems require larger investments than refueling switching locomotives with diesel fuel, then the technology needs to be re-evaluated for how we make the business case for a switching yard.

Long-Term Recommendations

Looking beyond the immediate use case of our system as a technology demonstrator, there are two recommendations that our team would make for long term development and application of the technology. Among them are the continued analysis of power generation methods, as well as the identification and analysis of other non-switching use cases for fireless locomotion.

Although CSP technologies are not necessarily new, they are constantly being researched and improved upon. As new energy generation technologies emerge over the next decade, it would be prudent to be on the lookout for any that might be applicable to locomotion. Hydrogen fuel cell technology, for example, is already being explored as an option to produce electricity to generate traction on board locomotives, having an energy density of around 34 kWh/kg compared to diesel's 12-14 kWh/kg [79]. Such technology may eventually become developed enough for use in systems such as a technology demonstrator or even for full-scale industrial use.

Although switching yards are one of the most prominent scenarios in which low speed fireless locomotion appears to be viable, we recommend searching for other applications where the low speed and sometimes intermittent availability of fireless locomotion might be better suited. Localized rail transports around a campus or a park is one such application that our team has identified for possible future development.

Section 13: Conclusions

Current diesel engines used in switching applications are inefficient and a fireless steam locomotion presents an attractive alternative. There exists a variety of possible concepts for how solar to steam can be achieved in the context of fireless locomotion within a switching yard. Ideally, solar concentrators are used to heat water in an accumulator to generate steam, which is then stored in pressurized tanks. It is then transferred to a locomotive where it is used by the onboard engine to do mechanical work. However, any new system must not only match the capabilities of existing systems, but also do so safely and offer some marginal benefit to its user. Whether that comes in the form of reduced operating costs or eliminating harmful emissions, a fireless locomotive would need to be sufficiently powerful to perform any task it might encounter in a typical switching yard.

Developing a prototype of a full-scale industrial system over the course of only a semester was obviously an unreasonable proposition both in terms of time and cost. Even physically building a 1:8 scale hobbyist model was beyond the scope of the project. Ultimately, we decided to focus on the more achievable goal of building a mathematical model to simulate a 1:8 scale solar fireless system. This model takes into account multiple different factors such as environmental conditions, geographic location, and cost considerations as user inputs and in turn calculates data on system performance.

In order to develop a model of a system, we first needed to define what that system looked like. Our design uses photovoltaic panels to power a resistive heating element. This heating element generates steam which is then used to power a commercially available 1:8 scale locomotive. Reducing the overall size of the system was critical to ensuring that the system is realistic to physically implement in the future, as it lowers the overall system cost from hundreds of thousands to roughly fifty thousand dollars. Using photovoltaics panels instead of concentrated solar power was also key in increasing the feasibility of the system. Not only are photovoltaics significantly more accessible than CSP options, they can also be used to recuperate the acquisition costs of the system by passively generating electricity for the user's residence.

To quantify the effectiveness of our design, we developed a set of requirements based on research as well as stakeholder input. From these requirements, we developed a set of engineering specifications to ensure that the system was operating satisfactorily. We then verified these specifications both by using industry benchmarks for things like our photovoltaic specifications and by using mathematical analysis. We also continuously engaged with our project sponsor to determine the direction our design would take. We were unable to verify every aspect of the system as we did not have a physical prototype to conduct experiments with. Some specifications, like the operational time of our system on a single charge, are things that can be estimated but are only certain once actual tests are undertaken.

The model we developed based on our system design does provide reasonable estimates of system parameters. We cross referenced the data generated by our model with industry standards to confirm its validity. For example, we looked at industry data for energy requirements for steam accumulators and plotted our own system against several commercially available ones to see how it performed. Our solution provides a tool to model the ultimate goal of our sponsor: a small-scale educational demonstrator of solar fireless locomotion.

Section 14: Acknowledgments

We would like to acknowledge the constant guidance from our project sponsor, Ted Delphia, and for the passion instilled by him into us for bringing back steam to the locomotive industry in a sustainable manner. We'd also like to thank Professor Skerlos for both his mentorship and his support for our project, especially in periods of uncertainty for our team.

Section 15: References

[1] Association of American Railroads. "Technology Helps Freight Rail Combat Climate Change." Accessed March 12, 2022. https://www.aar.org/sustainable-technology/.

[2] DLM - MODERN STEAM. "Vorführungen Der DLM-Speicherlokomotiven in Schaffhausen," November 2, 2012. https://dlm-ag.ch/en/presentation-of-dlms-fireless-locomotives-at-schaffhausen/.

[3] "Diesel Locomotives Of The 1930's, 1940's, 1950's, 1960's," *American-Rails.com*. https://www.american-rails.com/diesel.html (accessed Feb. 10, 2022).

[4] "How a steam locomotive works | Trains Magazine," *Trains*. https://www.trains.com/trn/train-basics/abcs-of-railroading/how-a-steam-locomotive-works/ (accessed Feb. 13, 2022).

[5] O. US EPA, "Learn About Impacts of Diesel Exhaust and the Diesel Emissions Reduction Act (DERA)," Jul. 24, 2015. https://www.epa.gov/dera/learn-about-impacts-diesel-exhaust-and-diesel-emissions-reduction-act-dera (accessed Feb. 09, 2022).

[6] "Emission Standards: USA: Locomotives." https://dieselnet.com/standards/us/loco.php (accessed Feb. 09, 2022).

[7] “Fireless technology,” *DLM - MODERN STEAM*. https://dlm-ag.ch/en/fireless-technology/ (accessed Feb. 09, 2022).

[8] “Switcher,” *Wikipedia*. Feb. 04, 2022. Accessed: Feb. 09, 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Switcher&oldid=1069768175

[9] “Vorführungen der DLM-Speicherlokomotiven in Schaffhausen,” *DLM - MODERN STEAM*, Nov. 02, 2012. https://dlm-ag.ch/en/presentation-of-dlms-fireless-locomotives-at-schaffhausen/ (accessed Feb. 09, 2022).

[10] “PV Cells 101: A Primer on the Solar Photovoltaic Cell,” *Energy.gov*. https://www.energy.gov/eere/solar/articles/pv-cells-101-primer-solar-photovoltaic-cell (accessed Mar. 14, 2022).

[11] “REN21 - Renewables 2013 Global Status Report.” [Online]. Available: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf. (accessed: 05-Apr-2022).

[12] “Photovoltaic Energy Factsheet | Center for Sustainable Systems.” https://css.umich.edu/factsheets/photovoltaic-energy-factsheet (accessed Mar. 14, 2022).

[13] A. Berrada, K. Loudiyi, and R. El Mrabet, “Chapter 1 - Introduction to hybrid energy systems,” in *Hybrid Energy System Models*, A. Berrada and R. El Mrabet, Eds. Academic Press, 2021, pp. 1–43. doi: 10.1016/B978-0-12-821403-9.00001-9.

[14] C. J. Dey, “Heat transfer aspects of an elevated linear absorber,” *Solar Energy*, vol. 76, no. 1, pp. 243–249, Jan. 2004, doi: 10.1016/j.solener.2003.08.030.

[16] L. Valenzuela, “12 - Thermal energy storage concepts for direct steam generation (DSG) solar plants,” in *Advances in Concentrating Solar Thermal Research and Technology*, M. J. Blanco and L. R. Santigosa, Eds. Woodhead Publishing, 2017, pp. 269–289. doi: 10.1016/B978-0-08-100516-3.00012-5.

[17] S. Karellas and T. C. Roumpedakis, “Chapter 7 - Solar thermal power plants,” in *Solar Hydrogen Production*, F. Calise, M. D. D’Accadia, M. Santarelli, A. Lanzini, and D. Ferrero, Eds. Academic Press, 2019, pp. 179–235. Doi: 10.1016/B978-0-12-814853-2.00007-2.

[18] P. Blanc *et al.*, “Direct normal irradiance related definitions and applications: The circumsolar issue,” *Solar Energy*, vol. 110, pp. 561–577, Dec. 2014, doi: 10.1016/j.solener.2014.10.001.

[19] M. Sengupta, Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby, “Solar Resource Maps and Data,” *The National Solar Radiation Data Base (NSRDB)*, Jun-2018. [Online]. Available: https://www.nrel.gov/gis/solar-resource-maps.html. (accessed: 05-Apr-2022).

[21] “Steam Consumption of Heat Exchangers | Spirax Sarco.” https://www.spiraxsarco.com/learn-about-steam/steam-engineering-principles-and-heat-transfer/steam-consumption-of-heat-exchangers (accessed Mar. 09, 2022).

[21] “3-s2.0-B9780123847003000062-f06-10-9780123847003.jpg (622×548).” https://ars.els-cdn.com/content/image/3-s2.0-B9780123847003000062-f06-10-9780123847003.jpg (accessed Mar. 15, 2022).

[21] S. Lingeswara, R. Omar, and T. I. M. Ghazi, “Reliability analysis on a shell and tube heat exchanger,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 36, p. 012012, Jun. 2016, doi: 10.1088/1755-1315/36/1/012012.

[22] “Boiler Equipment,” *WARE*. https://www.wareinc.com/boiler-equipment (accessed Mar. 17, 2022).

[23] “Steam Accumulators | Spirax Sarco.” https://www.spiraxsarco.com/learn-about-steam/the-boiler-house/steam-accumulators (accessed Mar. 10, 2022).

[24] “Electric Steam Boiler | ACME Engineering Products,” *ACME Engineering*. https://www.acmeprod.com/electric-steam-boilers (accessed Mar. 17, 2022).

[25] “Modernising the Fireless Steam Accumulator Locomotive.” https://www.internationalsteam.co.uk/trains/newsteam/modern21.htm (accessed Feb. 09, 2022).

[26] J. G. Hook, “Fundamentals of Steam Locomotive Tractive Force,” p. 15.

[27] “Wet Steam - Quality vs. Dryness Fractions.” https://www.engineeringtoolbox.com/wet-steam-quality-d_426.html (accessed Feb. 10, 2022).

[28] “Locomotive Power Calculations - Greenville, South Carolina - Republic Locomotive.” http://www.republiclocomotive.com/locomotive-power-calculations.html (accessed Feb. 10, 2022).

[29] http://www.rr-fallenflags.org/porter/porter-pd.html (Accessed Feb. 10, 2022).

[30] “Heat Transfer Fluids for Solar Water Heating Systems,” *Energy.gov*. https://www.energy.gov/energysaver/heat-transfer-fluids-solar-water-heating-systems (accessed Mar. 09, 2022).

[31] “Heat, Work and Energy.” https://www.engineeringtoolbox.com/heat-work-energy-d_292.html (accessed Feb. 23, 2022).

[32] P. Cohen, “Frontier / Columbia 2-4-2 Narrow Gauge Live Steam Locomotive by RMI Railworks,” *Roll Models Ind. RMI Railworks*. http://www.rmirailworks.com/Frontier.asp (accessed Mar. 09, 2022).

[33] “High temperature heat transfer fluid | Heat transfer fluids | HTFs,” *Global Heat Transfer Fluid*. https://globalhtf.com/heat-transfer-fluids/high-temperature-fluid/ (accessed Mar. 17, 2022).

[34] “Improvements in or relating to apparatus for electrically heating high-pressure steam generators or high-pressure steam accumulators,” GB629296 (A), Sep. 16, 1949 Accessed: Feb. 11, 2022. [Online]. Available: http://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=19490916&DB=EPODOC&locale=&CC=GB&NR=629296A&KC=A&ND=1

[35] “Steam Hose, Hose Tube Material Chlorobutyl, Hose Cover Material EPDM,” *Grainger*. https://www.grainger.com/product/CONTINENTAL-Steam-Hose-48XU79 (accessed Mar. 16, 2022).

[36] “What is the Average Car Horsepower?,” *Autolist*. https://www.autolist.com//guides/average-car-horsepower (accessed Mar. 16, 2022).

[37] “Railroad Supply Company Inc.” http://www.railroadsupply.com/view10.php (accessed Mar. 16, 2022).

[38] P. Cohen, “Steam Locomotive Kits,” *RMI Railworks*. https://www.rmirailworks.com/SS-Steam-Kits.asp (accessed Mar. 09, 2022).

[39] “2GS12B-TIER-IV-SWITCHER_rfs.pdf.” Accessed: Feb. 09, 2022. [Online]. Available: https://nre.com/wp-content/uploads/2020/09/2GS12B-TIER-IV-SWITCHER_rfs.pdf

[40] L. Valenzuela, “12 - Thermal energy storage concepts for direct steam generation (DSG) solar plants,” in *Advances in Concentrating Solar Thermal Research and Technology*, M. J. Blanco and L. R. Santigosa, Eds. Woodhead Publishing, 2017, pp. 269–289. doi: 10.1016/B978-0-08-100516-3.00012-5.

[41] “49 CFR Part 229 -- Railroad Locomotive SAFETY Standards.” https://www.ecfr.gov/current/title-49/subtitle-B/chapter-II/part-229 (accessed Feb. 09, 2022).

[42] G. Paul and V. Karl, “Charging crane for fireless locomotives,” US2313013A, Mar. 02, 1943 Accessed: Feb. 11, 2022. [Online]. Available: https://patents.google.com/patent/US2313013/en

[43] “Coal and the environment - U.S. Energy Information Administration (EIA).” https://www.eia.gov/energyexplained/coal/coal-and-the-environment.php (accessed Feb. 10, 2022).

[45] “Code of Federal Regulations.” https://www.govinfo.gov/content/pkg/CFR-2017-title49-vol4/xml/CFR-2017-title49-vol4-part230.xml#seqnum230.23 (accessed Feb. 14, 2022).

[46] “history of technology - Steam locomotive | Britannica.” https://www.britannica.com/technology/history-of-technology/Steam-locomotive (accessed Feb. 09, 2022).

[47] G. S. W. Calder, “Maintenance of Diesel and Electric Motive Power,” p. 2

[48] “Researching The Ultimate Fireless Steam Locomotive.” https://www.internationalsteam.co.uk/trains/newsteam/modern35.htm (accessed Feb. 09, 2022).

[49] “Researching the Ultimate Fireless Steam Locomotive - Part 3.” https://www.internationalsteam.co.uk/trains/newsteam/modern39.htm (accessed Feb. 09, 2022).

[50] “Researching the Ultimate Fireless Steam Locomotive - Part 11.” https://www.internationalsteam.co.uk/trains/newsteam/modern38.htm (accessed Feb. 09, 2022).

[51] “Researching the Ultimate Fireless Steam Locomotive – Part 4.” https://www.internationalsteam.co.uk/trains/newsteam/modern48.htm (accessed Feb. 09, 2022).

[52] R. Ahluwalia and A. N. Laboratory, “Total Cost of Ownership for Line Haul, Yard Switchers, and Regional Passenger Locomotives: Preliminary Results,” p. 11.

[53]S. I. Sadaq, S. N. Mehdi, and L. Kumari, “PERFORMANCE ANALYSIS OF SOLAR FLAT PLATE COLLECTOR,” vol. 3, no. 5, p. 6.

[54] “Home,” *Design Heuristics*. [Online]. Available: https://www.designheuristics.com/. (accessed: 15-Mar-2022).

[55] Bergman , T., & Lavine, A. (2017). *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons, Inc.

[56] BORGNAKKE, C. L. A. U. S. (2020). *Fundamentals of thermodynamics*. WILEY.

[57] “How much do solar panels cost in 2022?,” *How much do solar panels cost? (2022)*, 17-Feb-2022. [Online]. Available: https://www.marketwatch.com/picks/guides/home-improvement/solar-panel-costs/. [Accessed: 07-Apr-2022].

[58] “McMaster-Carr Heat Exchangers and Parts,” *McMaster*. [Online]. Available: https://www.mcmaster.com/shell-and-tube-heat-exchangers. [Accessed: 07-Apr-2022].

[59] “Pricing,” *Backyard Train Co.* [Online]. Available: http://backyardtrainco.com/pricing. [Accessed: 07-Apr-2022].

[60] “Common Sizes of Solar Panels – Brightstar Solar.” https://brightstarsolar.net/common-sizes-of-solar-panels/ (accessed Mar. 17, 2022).

[61] *PVWatts - NREL*. PVWatts Calculator. (n.d.). Retrieved April 7, 2022, from https://pvwatts.nrel.gov/

[62] “To tackle climate change, keep fossil fuels in the ground,” *Council on Foreign Relations*. [Online]. Available: https://www.cfr.org/article/tackle-climate-change-keep-fossil-fuels-ground. [Accessed: 22-Apr-2022].

[63] “Solar Panel Recycling,” *EPA*. [Online]. Available: https://www.epa.gov/hw/solar-panel-recycling. [Accessed: 22-Apr-2022].

[64] 2022 M. D. C. L. March 15, “What is the keystone XL pipeline?,” *NRDC*, 15-Mar-2022. [Online]. Available: https://www.nrdc.org/stories/what-keystone-pipeline. [Accessed: 22-Apr-2022].

[65] P. Cohen, “RMI Railworks Miniature Railroad locomotives, cars and equipment,” *RMI Railworks*. [Online]. Available: https://www.rmirailworks.com/. [Accessed: 22-Apr-2022].

[66] “Union Pacific Bailey Yard,” *Visit North Platte*, 12-Oct-2021. [Online]. Available: https://visitnorthplatte.com/directory-posts/union-pacific-bailey-yard/. [Accessed: 22-Apr-2022].

[67] “McMaster-Carr EPDM Rubber Hose,” *McMaster*. [Online]. Available: https://www.mcmaster.com/epdm-rubber-hose/connection-style~threaded/high-temperature-steam-hose-with-male-and-female-threaded-fittings/. [Accessed: 22-Apr-2022].

[68] “2022 solar panel maintenance costs: Solar PV maintenance cost,” *Fixr.com*, 29-Nov-2021. [Online]. Available: https://www.fixr.com/costs/solar-panel-maintenance#cost-to-remove-solar-panels. [Accessed: 22-Apr-2022].

[69] “Amerec steam generators | qualitybath.com.” [Online]. Available: https://www.qualitybath.com/brands/11/amerec. [Accessed: 22-Apr-2022].

[70] “1.5/1.6 Locomotive Pricing,” *Backyard Train Co.* [Online]. Available: http://backyardtrainco.com/pricing. [Accessed: 22-Apr-2022].

[71] “Solar panel installation and maintenance,” *GreenMatch*. [Online]. Available: https://www.greenmatch.co.uk/blog/2014/09/solar-panel-installation-and-maintenance. [Accessed: 22-Apr-2022].

[72] “SteamSpa STMKIT installation kit for steam,” *Build.com*. [Online]. Available: https://www.build.com/product/summary/1236434?uid=2958067&jmtest=gg-gbav2_2958067&inv2=1&

&source=gg-gba-pla_2958067%21c1707632291%21a68158365498%21dc%21ng&gclid=Cj0KCQjw3v6SBhCsARIsACyrRAkn9WJGqimGm6j59RTHYu8IvFAfEiniFYjoGqapXKciTwJqRtKFsNcaAm6PEALw_wcB&gclsrc=aw.ds. [Accessed: 22-Apr-2022].

[73] P. Cohen, "RMI Railworks Miniature Railroad locomotives, cars and equipment," *RMI Railworks*. [Online]. Available: https://www.rmirailworks.com/. [Accessed: 22-Apr-2022].

[74] "High-Pressure On/Off Valve with Lockable Lever Handle, Steel Body, 1-1/2 NPT Female," *McMaster-Carr*. [Online]. Available: https://www.mcmaster.com/49355K87/. [Accessed: 22-Apr-2022].

[75] "Solar panel kit: 600 W nominal output power, 12V DC, 3 solar panels, 20.3V DC," *Grainger*. [Online]. Available: https://www.grainger.com/product/60UR11?ef_id=Cj0KCQjwpImTBhCmARIsAKr58cw_2ctPgg5H7iLefJl1joFnwRe9yyXFPDxy-H9zgDnNmTJxFvmjtuIaAsGqEALw_wcB%3AG%3As&s_kwcid=AL%212966%213%21281698275264%21%21%21g%21470148536790%21&gucid=N%3AN%3APS%3APaid%3AGGL%3ACSM-2295%3A4P7A1P%3A20501231&gclid=Cj0KCQjwpImTBhCmARIsAKr58cw_2ctPgg5H7iLefJl1joFnwRe9yyXFPDxy-H9zgDnNmTJxFvmjtuIaAsGqEALw_wcB&gclsrc=aw.ds. [Accessed: 22-Apr-2022].

[76] "DC to AC Transformer with 3 Outlets, 700W, and 5.8A Output," *McMaster-Carr*. [Online]. Available: https://www.mcmaster.com/6987K29/. [Accessed: 22-Apr-2022].

[77] "MC4 Connector, contact material: Copper, male and female," *Grainger*. [Online]. Available: https://www.grainger.com/product/26KH80?ef_id=Cj0KCQjwpImTBhCmARIsAKr58cyYLPkO9s3p_9k91p4tex_a0YZeUw-ffbWGZJtPh9YvUJSrqz0xMmcaArY9EALw_wcB%3AG%3As&s_kwcid=AL%212966%213%21264955915673%21%21%21g%21461787465034%21&gucid=N%3AN%3APS%3APaid%3AGGL%3ACSM-2295%3A4P7A1P%3A20501231&gclid=Cj0KCQjwpImTBhCmARIsAKr58cyYLPkO9s3p_9k91p4tex_a0YZeUw-ffbWGZJtPh9YvUJSrqz0xMmcaArY9EALw_wcB&gclsrc=aw.ds. [Accessed: 22-Apr-2022].

[78] "Electric boilers - steam - Reimers electra steam," *Electric Boilers - Steam - Reimers Electra Steam*. [Online]. Available: https://www.reimersinc.com/electric-steam-boilers. [Accessed: 23-Apr-2022].

[79] Patrick Molloy, "Run on Less with Hydrogen Fuel Cells," *RMI.org.* [Online]. Available: https://rmi.org/run-on-less-with-hydrogen-fuel-cells/#:~:text=By%20contrast%2C%20hydrogen%20has%20an%20energy%20density%20of,which%20only%20holds%20about%2012%E2%80%9314%20kWh%20per%20kg. [Accessed: 22-Apr-2022].

Section 16: Bios

Keith Brañes is a senior studying Mechanical Engineering and minoring in Electrical Engineering at the University of Michigan. He grew up in Lima, Peru and moved to New Jersey with his family when he was 15 years old. Growing up Keith was always always fascinated with robots and admired the work his father did as an engineer, ultimately inspiring him to pursue a degree in STEM. Since high school, Keith has been heavily involved with engineering through his FIRST Robotics team, leading their build team in assembling robots for annual competitions. This experience prompted his undergraduate degree choice, and he hopes to use his degree and passion for mechatronics to design robotic systems in the future that can help people with disabilities in everyday life in an ethical way. He is currently the Marketing Director of the Society of Hispanic Professional Engineers, applying his graphic design passion through the role. Some of Keith's hobbies include collecting Transformers figures, freelance graphic design, reading comics and discovering new music. Keith hopes to pursue a Masters degree in Robotics and work for a company that focuses on positively integrating robotics and mechatronics into society and help solve disparities through their application.

Halie Kelly is a senior from Walled Lake, Michigan, studying Mechanical Engineering at the University of Michigan. Halie is a first generation college student who never anticipated being in school for engineering. Halie has always wanted to be a leader of people and motivate and drive those around her to pursue their dreams and make plans to reach their goals. Translating this drive to help others make things happen into a career, Halie strives to become a Project Manager and an engineering leader. Her prior experience in leadership include office management for the Oakland County Communicable Disease Unit where she organized and assisted on multiple high scale disease outbreaks within the county and state coordinating efforts between multiple agencies and the public. During her time in school she has interned with OHM Advisors, a Michigan based Engineering Management Company, expanding her skills in Project Management working alongside the Mechanical, Electrical, and Plumbing Team to coordinate and design projects for companies such as DOW Chemical, Notre Dame Stadium, and Local Municipalities. In addition to her work and studies, Halie enjoys traveling across the country on the motorcycle with her fiance, enjoying the great outdoors and letting the road take her wherever it may. This is probably the only thing in her life she does not plan out, they pick a direction, pack a bag and head out exploring.

Joey Self is a fifth year senior from Nashotah, Wisconsin studying Mechanical Engineering and Business Administration at the University of Michigan. From a young age, Joey developed a love for the FIRST robotics program, and subsequently mechanical engineering, as a result of competing in FIRST Lego League, FIRST Robotics Competition, as well as FIRST Tech Challenge throughout grade school and high school. Following several work experiences in the medical device and semiconductor industries, he will be completing one last internship with Boston Scientific this summer before graduating at the end of 2022 and beginning his full-time career in management consulting with McKinsey & Company. Although he will not be pursuing a full-time career in mechanical engineering, he hopes to work in renewable energy development or climate change policy in the future. Outside of work and school, Joey enjoys exploring new places and is aiming to visit every state (37 of 50 right now) and every national park (currently at 10) before the end of the decade. He is also a proud co-owner of the Green Bay Packers and an avid fan of the 2x World Champion Milwaukee Bucks.

Nick Weller is a senior from Moorestown, New Jersey studying Mechanical Engineering at the University of Michigan. His interest in engineering stems from his lifelong love of building things, from desks to aerial photography drones. He has completed an internship with Sage Technologies, a small defense firm specializing in digital thermal optic development. After his graduation in 2022, he will start a full-time position as a systems engineer for Lockheed Martin's Rotary and Mission Systems division, working on the Aegis missile defense program. Academic and career aspirations aside, Nick is a varsity athlete for the Michigan men's rowing team and has represented the university in races across the country. When he's not training, he enjoys running and plays several instruments to varying degrees of success.

Section 17: Appendices

Appendix A: Locomotive Sizing Calculations

The maximum tractive effort of a locomotive occurs at the initial moment of motion and decreases as the speed of the train increases. The maximum tractive effort (TE) is calculated with the maximum pressure (P) inside the tank, the diameter of the cylinder bore (CB), the stroke of the piston (S), the thermal efficiency of the tank (K), and driving wheel diameter (D) [26], seen below in Equation A1 [54].

$$TE = \frac{K*P*CB^2*S}{D} \quad \text{(Eq. A1)}$$

The horsepower is calculated by using the tractive effort, the average operating speed of the locomotive, and the horsepower constant 550, using equation A2.

$$Horsepower = \frac{TE*Average\ Speed}{550} \quad \text{(Eq. A2)}$$

Table A1: Full Size Fireless Locomotive Engineering Specifications and Calculated Tractive Effort and Horsepower

Locomotive Tank Size (Cubic Feet)	Cylinder Bore Diameter (in)	Stroke Of Piston (in)	Driving Wheel Diameter (in)	Maximum Tractive Effort (lb)	Horsepower
730	25	20	38	81086	2949
600	22	18	34	63162	2297
425	20	18	34	52200	1898
380	18.5	16	30	44994	1636
300	17	16	30	37994	1382
230	15	14	27	28758	1046
135	12	10	23	15433	561
70	10	10	20	12325	448

Table A2: 1:8 Scale Fireless Locomotive Engineering Specifications and Calculated Tractive Effort and Horsepower

Locomotive Tank Size (Cubic Feet)	Cylinder Bore Diameter (in)	Stroke Of Piston (in)	Driving Wheel Diameter (in)	Maximum Tractive Effort (lb)	Horsepower
1.43	3.125	2.5	4.75	10136	184
1.17	2.75	2.25	4.25	7895	144
0.83	2.5	2.25	4.25	6525	119
0.74	2.3125	2	3.75	5624	102
0.59	2.125	2	3.75	4749	86
0.45	1.875	1.75	3.375	3595	65
0.26	1.5	1.25	2.875	1929	35
0.14	1.25	1.25	2.5	1541	28

Appendix B: Initial Engineering Analysis

This appendix outlines the initial engineering analysis done to determine the energy required to produce enough steam to charge a full scale fireless locomotive, and the solar field requirements based on the energy needed to generate steam.

Energy Requirements

To determine the energy required to charge a fireless locomotive we first converted the tank size from cubic feet to gallons, equation B1.

$$Tank\ Capacity\ (Gallons)\ =\ Tank\ Capacity\ (Cubic\ Feet)\ *\ 7.48 \quad \text{(Eq. B1)}$$

A standard fireless locomotive is 75% full of water. To calculate the amount of water within the tank we multiplied the percentage the locomotive is filled to by the maximum capacity. The mass of the water to be charged was calculated using equation B2.

$$Amount\ of\ Water\ to\ be\ Charged\ (kg/h)\ =\ Amount\ water\ (gallons)\ *\ 3.785 \quad \text{(Eq. B2)}$$

Using our knowledge of enthalpy and an assumed starting temperature of 70°F and the evaporation temperature of 212°F, we calculated the energy required (Q) to generate the correct mass of steam, equation B3. This equation requires the mass of the water (m), enthalpy of water at 70F (h_1), and the enthalpy of water at 212F (h_2).

$$Q\ =\ m(h_2 - h_1) \quad \text{(Eq. B3)}$$

From there the kJ energy requirement is converted to kilowatts (kWh), equation B4, and megawatts (MW). A summary of these values can be found in Table B1.

$$kWh\ =\ kJ\ *\ 0.000277778 \quad \text{(Eq. B4)}$$

Table B1: Full Size Fireless Locomotive Energy Requirements for Steam Generation for a Single Charge

Tank Capacity (Cubic Feet)	Tank Capacity (Gallons)	Amount Water (Gallons)	Amount Water (kg)	Energy Required (MJ)	Energy Required (MWh)
730	$5.5*10^3$	$4.1*10^3$	$1.6*10^4$	$3.4*10^4$	9.4
600	$4.5*10^3$	$3.4*10^3$	$1.3*10^4$	$2.8*10^4$	7.7
425	$3.2*10^3$	$2.4*10^3$	9.010^3	$2.0*10^4$	5.5
380	$2.8*10^3$	$2.1*10^3$	$8.1*10^3$	$1.8*10^4$	4.9
300	$2.2*10^3$	$1.7*10^3$	$6.4*10^3$	$1.4*10^4$	3.9
230	$1.7*10^3$	$1.3*10^3$	$4.8*10^3$	$1.1*10^4$	3.0
135	$1.0*10^3$	$7.6*10^2$	$2.9*10^3$	$6.2*10^3$	1.8
70	$5.2*10^2$	$4.0*10^2$	$1.5*10^3$	$3.2*10^3$	0.9

Using the assumption that a single charge lasts 8 hours and the locomotive is run for 14.5 hours a day, we calculate the energy required to charge the locomotive for a full day's use. To account for inefficiencies we assumed an 80% heat loss, determining the locomotive needs to be recharged 3.5 times a day, allowing for 4.2 hours between charges. A summary of these values can be found in Table B2.

Table B2: Full Size Fireless Locomotive Energy Requirements for Steam Generation for A Full Day Use.

Tank Capacity (ft^3)	Tank Capacity (Gallons)	Amount Water (Gallons)	Amount Water (kg)	Energy Required create Steam (MJ)	Energy Required (MWh)
$2.4*10^3$	$1.8*10^4$	$1.6*10^4$	$5.1*10^4$	$1.1*10^51$	31
$2.0*10^3$	$1.5*10^4$	$1.1*10^4$	$4.2*10^4$	$9.1*10^4$	26
$1.4*10^3$	$1.0*10^4$	$7.9*10^3$	$3.0*10^4$	$6.5*10^4$	18
$1.3*10^3$	$9.4*10^3$	$7.0*10^3$	$2.7*10^4$	$5.8*10^4$	17
$1.0*10^3$	$7.4*10^3$	$5.6*10^3$	$2.1*10^4$	$4.6*10^4$	13
$7.6*10^2$	$5.7*10^3$	$4.3*10^3$	$1.6*10^4$	$3.5*10^4$	10
$4.5*10^2$	$3.3*10^3$	$2.5*10^3$	$9.5*10^3$	$2.1*10^4$	6
$2.3*10^2$	$1.7*10^3$	$1.3*10^3$	$4.9*10^3$	$1.1*10^4$	3

Solar Field Sizing

For each of the five solar power plant types (Linear Fresnel, Power Tower, Parabolic Trough, Parabolic Dish, and Photovoltaic) the megawatt output per land area was determined using the same method. For each type of power plant we found at minimum five different power plants that are currently in operation. Creating a table of each plant's megawatt output, land area it occupies, and the direct normal irradiance of the region it is currently operating in. Before we could accurately calculate the relationship between the energy output and the land area needed we needed to simulate each of the plants operating within the same region. To do this we generated a ratio of the direct normal irradiance (DNI) and multiplied it by the land area per energy output, equation B5.

$$Normalized\ \frac{m^2}{MW} = \left(\frac{DNI_{Power\ Plant}}{DNI_{Michigan}}\right) * \frac{m^2}{MW} \quad \text{(Eq. B5)}$$

These calculations can be found in the tables below for each of the five power plants.

Table B3: Linear Fresnel Power Plant Land Area per Megawatt Output and Normalized Values

Land Area (m^2)	Energy Output (MW)	Land Area per Energy Output (m^2/MW)	DNI	Ratio	Normalized (m^2/MW)	Normalized Land Area (m^2)
400	0.3	1333	3.8	0.9	1206	362
18490	3	6163	5	1.2	7337	22012
25988	5	5198	7.5	1.8	9281	46407
170000	15	11333	3.5	0.8	9444	141667
302000	30	10067	5.4	1.3	12943	388286

Table B4: Power Tower Power Plant Land Area per Megawatt Output and Normalized Values

Land Area (m^2)	Energy Output (MW)	Land Area Per Energy Output (m^2/MW)	DNI	Ratio	Normalized m2/MW	Normalized Land Area (m^2)
15000	1.1	13636	4.8	1.14	15584	17142.4
175375	10	17538	4.5	1.07	18790	187900
516000	50	10320	4.8	1.14	11794	589700
1400000	100	14000	4.5	1.07	15000	1500000
1197148	110	10883	7.5	1.79	19434	2137740
1312000	150	8747	6.6	1.57	13745	2061750
2600000	377	6897	7.5	1.79	12315	4642755

Table B5: Parabolic Trough Power Plant Land Area and Megawatt Output

Energy Output (MW)	1	5	10	20	35	50
Land Area (m^2)	8132	33590	57281	96804	148963	204575

Table B6: Parabolic Dish Power Plant Land Area per Megawatt Output and Normalized Values

Land Area (m^2)	Energy Output (MW)	Land Area per Energy Output (m^2/MW)	DNI	Ratio	Normalized (m^2/MW)	Normalized Land Area (m^2)
6300	1.5	4200	6.1	1.5	6100	9150
6879	1.5	4586	5.9	1.4	6442	9663
12200	3	4067	6.1	1.5	5906	17719
40000	10	4000	6.1	1.5	5810	58095
180000	50	3600	6.1	1.5	5229	261429

Table B7: Photovoltaic Power Plant Land Area per Megawatt Output and Normalized Values

Energy Output (MW)	20	50	24	60	98
Land Area (m^2)	96000	192000	121600	268800	2300000
Land Area per Energy Output (m^2/MW)	4800	3840	5067	4480	23469

After Normalizing the land area per megawatt output the land area versus megawatt output was plotted. For each plot a line of best fit was applied and the equations generated were used to calculate the land area needed for each of the locomotives for a single charge and multiple charges. These graphs and summary tables can be found below.

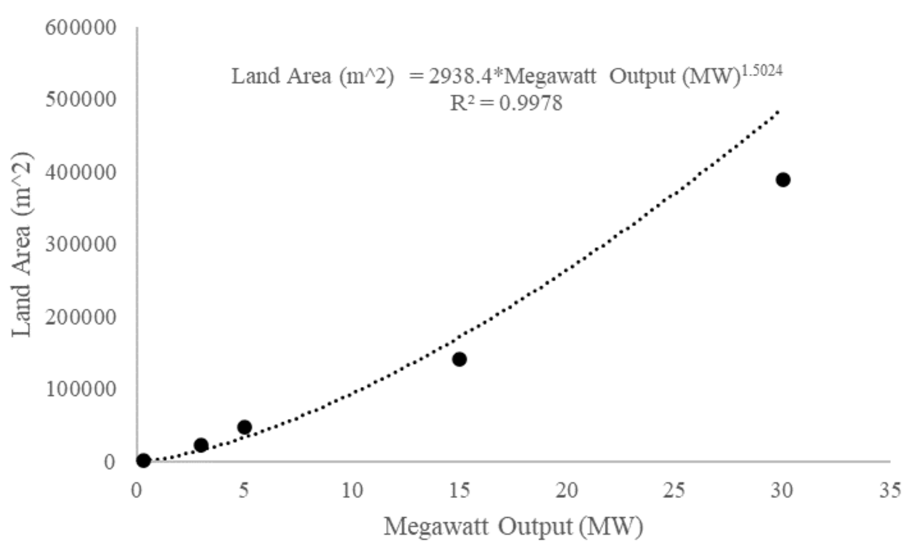


Figure B1: Linear Fresnel Power Plant Land Area versus Megawatt Output

Table B8: Linear Fresnel Power Plant Land Area Required for a Range of Locomotive Sizes for a Single and Multiple Charges.

Locomotive Tank Capacity (Cubic Feet)	Energy Required For Single Charge(MW)	Land Area Required For Single Charge (Acres)	Energy Required For Multiple Charges (MW)	Land Area Required for Multiple Charges (Acres)
730	9.4	23.5	31	140.9
600	7.7	17.4	26	108.2
425	5.5	10.5	18	62.3
380	4.9	8.9	17	57.2
300	3.9	6.3	13	38.3
230	3.0	4.2	10	25.8
135	1.8	2.0	6	12.0
70	0.9	0.7	3	4.2

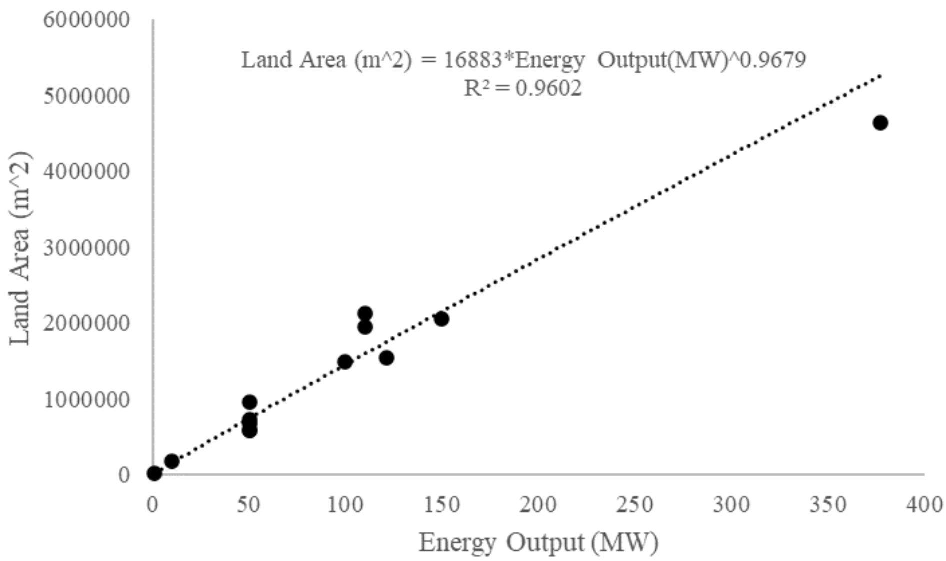


Figure B2: Power Tower Power Plant Land Area versus Megawatt Output

Table B9: Power Tower Power Plant Land Area Required for a Range of Locomotive Sizes for a Single Charge.

Locomotive Tank Capacity (Cubic Feet)	Energy Required For Single Charge(MW)	Land Area Required For Single Charge (Acres)	Energy Required For Multiple Charges (MW)	Land Area Required for Multiple Charges (Acres)
730	9	41	31	130
600	8	34	26	110
425	6	24	18	77
380	5	22	17	73
300	4	18	13	56
230	3	14	10	44
135	2	8	6	27
70	1	4	3	15

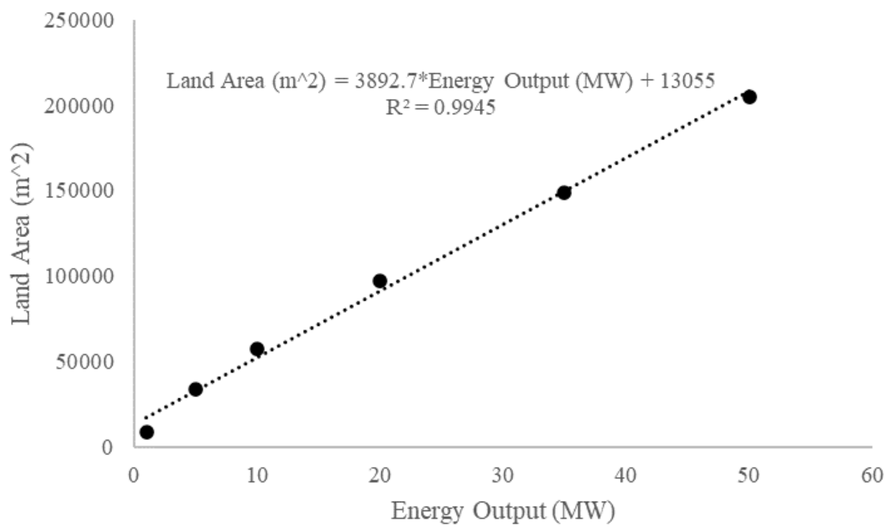


Figure B3: Parabolic Trough Power Plant Land Area versus Megawatt Output

Table B10: Parabolic Trough Power Plant Land Area Required for a Range of Locomotive Sizes for a Single Charge.

Locomotive Tank Capacity (Cubic Feet)	Power Required For Single Charge(MW)	Land Area Required For Single Charge (Acres)	Power Required For Multiple Charges (MW)	Land Area Required for Multiple Charges (Acres)
730	9	20	31	54
600	8	17	26	46
425	6	14	18	34
380	5	13	17	32
300	4	11	13	26
230	3	10	10	21
135	2	8	6	15
70	1	7	3	10

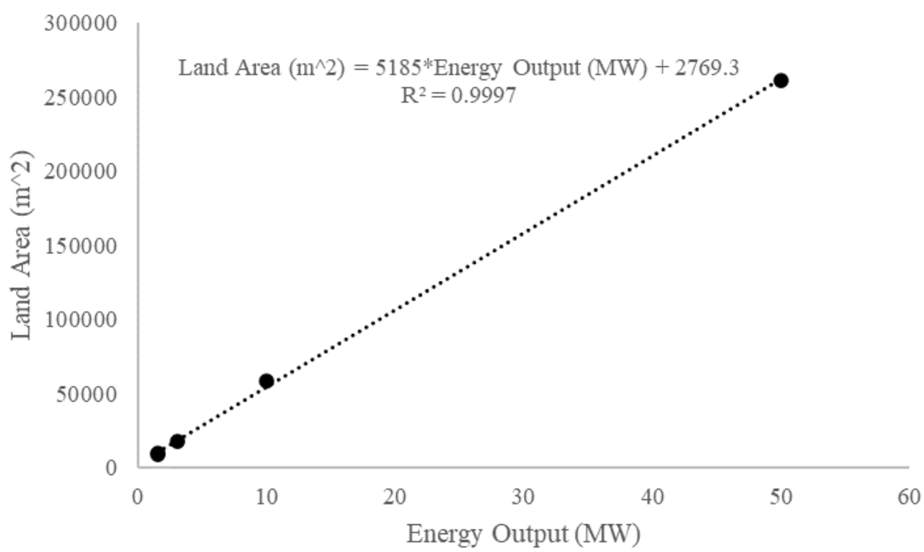


Figure B4: Parabolic Dish Power Plant Land Area versus Megawatt Output

Table B11: Parabolic Dish Power Plant Land Area Required for a Range of Locomotive Sizes for a Single Charge.

Locomotive Tank Capacity (Cubic Feet)	Energy Required For Single Charge(MW)	Land Area Required For Single Charge (Acres)	Energy Required For Multiple Charges (MW)	Land Area Required for Multiple Charges (Acres)
730	9	14	31	45
600	8	12	26	38
425	6	9	18	27
380	5	8	17	25
300	4	6	13	19
230	3	5	10	15
135	2	3	6	9
70	1	2	3	5

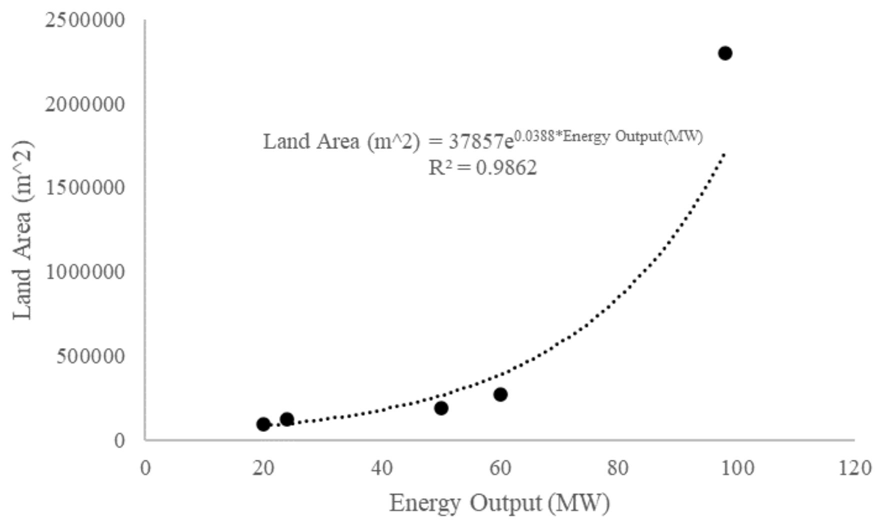


Figure B5: Photovoltaic Power Plant Land Area versus Megawatt Output

Table B12: Photovoltaic Power Plant Land Area Required for a Range of Locomotive Sizes for a Single Charge.

Locomotive Tank Capacity (Cubic Feet)	Energy Required For Single Charge(MW)	Land Area Required For Single Charge (Acres)	Energy Required For Multiple Charges (MW)	Land Area Required for Multiple Charges (Acres)
730	12	17	38	47
600	10	15	32	36
425	7	14	22	25
380	6	13	20	23
300	5	13	16	19
230	4	12	12	17
135	2	11	7	14
70	1	11	4	12

Appendix C: Top Five Concepts Engineering Analysis

The engineering analysis for the top five concepts started with a bottom up approach, by determining the energy requirements to power the heat exchanger and the electric steam generator.

Heat Exchanger

To determine the size and energy requirements of the heat exchanger we determined the mass of water within the range of locomotives and the amount of time between charges to determine the mass of water that needs to be heated per hour.

The energy required (Q) to generate the proper amount of steam can be calculated by the mass of the water (m), the specific heat of the water (C_p), and the difference between the starting temperature (T_1) and evaporation temperature (T_2), using equation C1.

$$Q = mC_p(T_2 - T_1) \quad \text{(Eq. C1)}$$

After determining the energy in J/h, this can be converted into the megawatt output needed. This calculated energy is used to calculate the area of heat exchange tubes needed. The area of the heat exchange tubes needed (A) is determined by the relationship between the energy per hour required (Q), the log mean temperature (deltaT), and the overall heat transfer coefficient (U), using equation C2. The log mean temperature is calculated with the Inlet tube side fluid temperature (T_1), the inlet shell fluid temperature (t_1), the outlet tube fluid temperature (T_2), and the outlet shell fluid temperature (t_2), using equation C3.

$$A = \frac{Q}{U * \Delta T} \quad \text{(Eq. C2)}$$

$$\Delta T = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln(\frac{(T_1 - t_2)}{(T_2 - t_1)}} \quad \text{(Eq. C3)}$$

A summary of the energy required, area of heat exchange tubes needed, and the volume of the heat exchanger can be found below in table C1.

Table C1: Heat Exchanger Volume, Energy, and Area of Heat Exchange Tube Requirements for Various Size Locomotives

Locomotive Tank Size (Cubic Feet)	Mass of Water to be charged (kg/h)	Heat Transfer Rate (J/h)	Power Requirement (kW)	Volume of tank (Cubic Feet)	Area of heat exchange (m^2)
730	3112	1025968666	285	3.53	8266
600	2558	843261918	234	2.90	6794
425	1812	597310525	166	2.05	4813
380	1620	534065881	148	1.84	4303
300	1279	421630959	117	1.45	3397
230	981	323250402	90	1.11	2604
135	576	189733932	53	0.65	1529
70	298	98380557	27	0.34	793

Electric Steam Generator

Sizing for the electric steam generators is based on the steam output required. To do this calculation we first determined the mass of steam (m_s) inside an individual locomotive using equation C4, based on the mass of the water inside the locomotive (m_w), the enthalpy of water at the locomotive operating pressure (h_1) and the enthalpy of water at the heat exchangers operating pressure (h_2). Then we determined the amount of steam that needs to be generated per hour. The energy required to power the electric steam generator is based on the relationship between steam output and energy requirements for current electric steam generators, which generated equation C5.

$$m_{steam}(kg) = \frac{m_w * (h_1 - h_2)}{h_2} \quad \text{(Eq. C4)}$$

$$Energy\ Required\ (kW) = (0.645 * m_s) + 0.21 \quad \text{(Eq. C5)}$$

Table C2: Electric Steam Generator Volume and Energy Requirements for Various Size Locomotives

Locomotive Tank Size (ft^3)	Mass of Steam (kg)	Steam output (kg/h)	Mass of Water Needed (kg)	Volume of Tank (ft^3)	Power Required (kW)
730	2617	596	7031	282	384
600	2151	490	5779	231	316
425	1524	347	4094	164	224
380	1362	310	3660	147	200
300	1076	245	2890	116	158
230	825	188	2215	89	121
135	484	110	1300	52	71
70	251	57	674	27	37

Steam Accumulator

To calculate the size of the exchanger we have to take into account the amount of flash steam that is generated from the pressure drop between the heat exchanger and the steam accumulator when steam is pulled from the accumulator into the locomotive. The proportion of flash steam generated (F_s) is calculated with equation C6, using the enthalpy of water at the steam accumulator pressure , the enthalpy of water at the discharge pressure which is the operating pressure of the locomotive, and the evaporation enthalpy of water at the steam accumulator pressure.

$$F_s = \frac{h_2 - h_1}{h_{fg}} \quad \text{(Eq. C6)}$$

This proportion of flash steam is then divided by the mass of steam storage required, equation C7, to get the mass of water needed. Since steam accumulator tanks are generally filled 90% full with water, the mass of water is divided by the percent it will be filled to get the mass of water of a 100% full tank. Using the density of water we can then determine the volume of a 100% full steam accumulation tank, which is equal to the total volume of the tank, equation C8.

$$Mass\ of\ Water\ Needed = \frac{Mass\ of\ Steam\ Required}{F_s} \quad \text{(Eq. C7)}$$

$$Volume\ (ft^3) = \left(\frac{Mass\ of\ Water\ Needed}{0.90}\right)/Density\ of\ Water \quad \text{(Eq. C8)}$$

Table C3: Proportion of Flash Steam Generated

Enthalpy at 20 bar	908.560
Enthalpy at 10 bar	762.790
Evaporation Enthalpy at 10 bar	2776.160
Proportion of flash steam	0.053

Table C4: Steam Mass Required For Single Fireless Locomotive Charge

Tank Capacity (Cubic Feet)	Tank capacity (liters)	Mass of water (kg)	Mass of water at 75% Capacity (kg)	Steam storage capacity (kg)
730	20671	18232	13674	2617
600	16990	14985	11239	2151
425	12035	10615	7961	1524
380	10760	9491	7118	1362
300	8495	7493	5620	1076
230	6513	5744	4308	825
135	3823	3372	2529	484
70	1982	1748	1311	251

Table C5: Steam Accumulator Sizing For Various Fireless Locomotive Sizes

Locomotive Tank Size (Cubic Feet)	Minimum steam storage (kg)	Amount of water needed (kg)	90% full of water	Minimum Volume (m^3)	Volume (Cubic Feet)
730	2617	49844	55382	63	2217
600	2151	40968	45520	52	1823
425	1524	29019	32243	37	1291
380	1362	25946	28829	33	1154
300	1076	20484	22760	26	911
230	825	15704	17449	20	699
135	484	9218	10242	12	410
70	251	4780	5311	6	213

Solar Power Plant Calculations

Using the equations generated from the graphs during our initial solar sizing calculations (Equations C9 - C13) and the energy required to power the heat exchanger and electric steam generator, we calculated the size of the solar fields needed.

Table C6: Summary of equations for determining necessary land area as function of energy output for five common solar power technologies

Power Plant	Equation	
Linear Fresnel	$\text{Land Area}=2938.4*\text{Energy Output}^{1.5024}$	(Eq. C9)
Power Tower	$\text{Land Area}=16883*\text{Energy Output}^{0.9679}$	(Eq. C10)
Parabolic Trough	$\text{Land Area}=3892.7*\text{Energy Output}+13055$	(Eq. C11)
Parabolic Dish	$\text{Land Area}=5185*\text{Energy Output}+2769.3$	(Eq. C12)
Photovoltaic	$\text{Land Area}=37857e^{0.0388*\text{Energy Output}}$	(Eq. C13)

Table C7: Linear Fresnel Solar Power Plant Land Area Required Based on Various Locomotive Sizes

Locomotive Tank Capacity (Cubic Feet)	Energy Required (MW)	Land Area Required (Acres)
730	0.284	0.1242
600	0.234	0.0926
425	0.165	0.0551
380	0.148	0.0468
300	0.117	0.0332
230	0.090	0.0226
135	0.053	0.0108
70	0.027	0.048

Table C8: Power Tower Power Plant Land Area Required Based on Various Locomotive Sizes

Locomotive Tank Capacity (Cubic Feet)	Energy Required (MW)	Land Area Required (Acres)
730	0.285	1.392
600	0.234	1.151
425	0.166	0.825
380	0.148	0.740
300	0.117	0.589
230	0.090	0.455
135	0.053	0.272
70	0.027	0.144

Table C9: Parabolic Trough Power Plant Land Area Required Based on Various Locomotive Sizes

Locomotive Tank Capacity (Cubic Feet)	Energy Required (MW)	Land Area Required (Acres)
730	0.285	5.7
600	0.234	5.6
425	0.166	5.5
380	0.148	5.5
300	0.117	5.5
230	0.090	5.4
135	0.053	5.4
70	0.027	5.3

Table C10: Parabolic Dish Power Plant Land Area Required Based on Various Locomotive Sizes

Locomotive Tank Capacity (Cubic Feet)	Energy Required (MW)	Land Area Required (Acres)
730	0.2850	1.2
600	0.2342	1.1
425	0.1659	1.0
380	0.1483	1.0
300	0.1171	0.9
230	0.0897	0.9
135	0.0527	0.8
70	0.0273	0.8

Table C11: Photovoltaic Power Plant Land Area Required Based on Various Locomotive Sizes

Locomotive Tank Capacity (Cubic Feet)	Energy Required (MW)	Land Area Required (Acres)
730	0.38	10.68
600	0.32	10.65
425	0.22	10.61
380	0.20	10.60
300	0.16	10.58
230	0.12	10.57
135	0.07	10.55
70	0.04	10.53

Appendix D: Alpha Concept Calculations

After conducting the original engineering analysis, we determined that the full scale application required mirror fields and panel fields that were too large to be feasible. Due to this, we did the same evaluations for a 1:8 Scale Locomotive.

Linear Fresnel Power Plant

Table D1: Linear Fresnel Power Plant Land Requirements for Various 1:8 Scale Fireless Locomotives

Locomotive Tank Capacity (Cubic Feet)	Energy Required (MW)	Land Area Required (Acres)
1.43	$5.57*10^{-4}$	$1.07*10^{-5}$
1.17	$4.57*10^{-4}$	$7.99*10^{-6}$
0.83	$3.24*10^{-4}$	$4.76*10^{-6}$
0.74	$2.90*10^{-4}$	$4.03*10^{-6}$
0.59	$2.29*10^{-4}$	$2.82*10^{-6}$
0.45	$1.75*10^{-4}$	$1.90*10^{-6}$
0.26	$1.03*10^{-4}$	$8.53*10^{-7}$
0.14	$5.34*10^{-5}$	$3.18*10^{-7}$

Steam Accumulator

To calculate the size of the exchanger we have to take into account the amount of flash steam that is generated from the pressure drop between the heat exchanger and the steam accumulator when steam is pulled from the accumulator into the locomotive. The proportion of flash steam generated (F_s) is calculated with equation D1, using the enthalpy of water at the steam accumulator pressure , the enthalpy of water at the discharge pressure which is the operating pressure of the locomotive, and the evaporation enthalpy of water at the steam accumulator pressure.

$$F_s = \frac{h_2 - h_1}{h_{fg}} \quad \text{(Eq. D1)}$$

This proportion of flash steam is then divided by the mass of steam storage required, equation D2, to get the mass of water needed. Since steam accumulator tanks are generally filled 90% full with water, the mass of water is divided by the percent it will be filled to get the mass of water of a 100% full tank. Using the density of water we can then determine the volume of a 100% full steam accumulation tank, which is equal to the total volume of the tank, equation D3.

$$Mass\ of\ Water\ Needed = \frac{Mass\ of\ Steam\ Required}{F_s} \quad \text{(Eq. D2)}$$

$$Volume\ (ft^3) = \left(\frac{Mass\ of\ Water\ Needed}{0.90}\right) / Density\ of\ Water \quad \text{(Eq. D3)}$$

Table D2: Flash Steam Proportion

Enthalpy at 6 bar	698
Enthalpy at 10 bar	762.790
Evaporation Enthalpy at 10 bar	2776.160
Proportion of Flash Steam	0.023

Table D3: Steam Mass Required for Various 1:8 Scale Fireless Locomotives

Tank Capacity (ft^3)	Tank capacity (liters)	Mass of water (kg)	Mass of water at 75% Capacity (kg)	Steam storage capacity (kg)
1.4	40	36	23	2.2
1.2	33	29	22	1.9
0.8	24	21	16	1.3
0.7	21	19	14	1.2
0.6	17	15	11	0.9
0.5	13	11	8	0.7
0.3	8	7	5	0.4
0.1	4	3	3	0.2

Table D4: Steam Accumulator Size for Various 1:8 Scale Fireless Locomotives

Locomotive Tank Size (ft^3)	Minimum steam storage (kg)	Amount of water needed (kg)	90% full of water	Minimum Volume (m^3)	Volume (ft^3)
1.4	2.2	97	108	0.12	4.3
1.2	1.9	80	89	0.10	3.5
0.8	1.3	56	63	0.07	2.5
0.7	1.2	50	56	0.06	2.2
0.6	0.9	40	44	0.05	1.8
0.5	0.7	31	34	0.04	1.4
0.3	0.4	18	20	0.02	0.8
0.1	0.2	9	10	0.01	0.4

Heat Exchanger

To determine the size and energy requirements of the heat exchanger we determined the mass of water within the range of locomotives and the amount of time between charges to determine the mass of water that needs to be heated per hour.

The energy required (Q) to generate the proper amount of steam can be calculated by the mass of the water (m), the specific heat of the water (C_p), and the difference between the starting temperature (T_1) and evaporation temperature (T_2), using equation D4.

$$Q = mC_p(T_2 - T_1) \quad \text{(Eq. D4)}$$

After determining the energy in J/h, this can be converted into the megawatt output needed. This calculated energy is used to calculate the area of heat exchange tubes needed. The area of the heat exchange tubes needed (A) is determined by the relationship between the energy per hour required (Q), the log mean temperature (deltaT), and the overall heat transfer coefficient (U), using equation D5. The log mean temperature is calculated with the Inlet tube side fluid temperature (T_1), the inlet shell fluid temperature (t_1), the outlet tube fluid temperature (T_2), and the outlet shell fluid temperature (t_2), using equation D6.

$$A = \frac{Q}{U^*\Delta T} \quad \text{(Eq. D5)}$$

$$\Delta T = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln(\frac{(T_1 - t_2)}{(T_2 - t_1)})} \quad \text{(Eq. D6)}$$

A summary of the energy required, area of heat exchange tubes needed, and the volume of the heat exchanger can be found below in table D5.

Table D5: Heat Exchanger Volume, Heat Exchange Tube Area, and Energy Requirements for Various 1:8 Scale Fireless Locomotives

Locomotive Tank Size (ft^3)	Mass of Water to be charged (kg/h)	Heat Transfer Rate (J/h)	Power Required (kW)	Volume of tank (Cubic Feet)	Area of heat exchange Tubes (m2)
1.4	6	2003845	0.6	16	0.24
1.2	5	1646996	0.5	13	0.20
0.8	4	1166622	0.3	9	0.14
0.7	3	1043097	0.3	8	0.13
0.6	2	823498	0.2	7	0.10
0.4	2	631348	0.2	5	0.08
0.3	1	370574	0.1	3	0.05
0.1	1	192150	0.1	2	0.02

1:8 Scale Fireless Locomotive

For every foot of measurement on a full scale locomotive, the 1:8 scale is 1.25 inches. Using this relationship we converted the range of standard switching locomotives to a 1:8 scale. And performed the tractive effort and horsepower calculations.

Table D6: Engineering Specifications, Tractive Effort, and Horsepower for Various 1:8 Scale Fireless Locomotives

Locomotive Tank Size (Cubic Feet)	Cylinder Bore Diameter (in)	Stroke Of Piston (in)	Driving Wheel Diameter (in)	Maximum Tractive Effort (lb)	Horsepower
1.4	3.125	2.5	4.75	10136	184
1.2	2.75	2.25	4.25	7895	144
0.8	2.5	2.25	4.25	6525	119
0.7	2.3125	2	3.75	5624	102
0.6	2.125	2	3.75	4749	86
0.4	1.875	1.75	3.375	3595	65
0.3	1.5	1.25	2.875	1929	35
0.1	1.25	1.25	2.5	1541	28

Appendix E: Final Design Engineering Analysis

Steam Generation and Power Consumption

Each locomotive has a certain amount of steam required to power the piston and cylinder to drive the locomotive forward. The amount of steam required is based on the working pressure of the steam tank on board the locomotive, overall tank volume, and the amount of water within the tank. A standard 1:8 scale Fireless locomotive has an overall tank volume of 1.4 cubic feet and is 75% full of water operating at 87 psi. To determine the mass of steam (m_s) needed to power the locomotive we need the mass of the water (m_w), the enthalpy of water at the locomotive operating pressure(h_1) and the enthalpy of water at the electric steam generators operating pressure (h_2). Using equation E1 we are able to determine the mass of steam needed to power the train [23].

$$m_{steam}\,(kg) = \frac{m_w * (h_1 - h_2)}{h_2} \quad \text{(Eq. E1)}$$

To determine the power requirements of the electric steam generator, we took a baseline of electric steam generators that are currently on the market. Graphing these generators based on the mass of the steam generated and the power required, we generated the following equation (equation E2) to determine the power needed for the 1:8 scale Fireless locomotive. The graph of the baseline electric steam generators is in figure E1 below

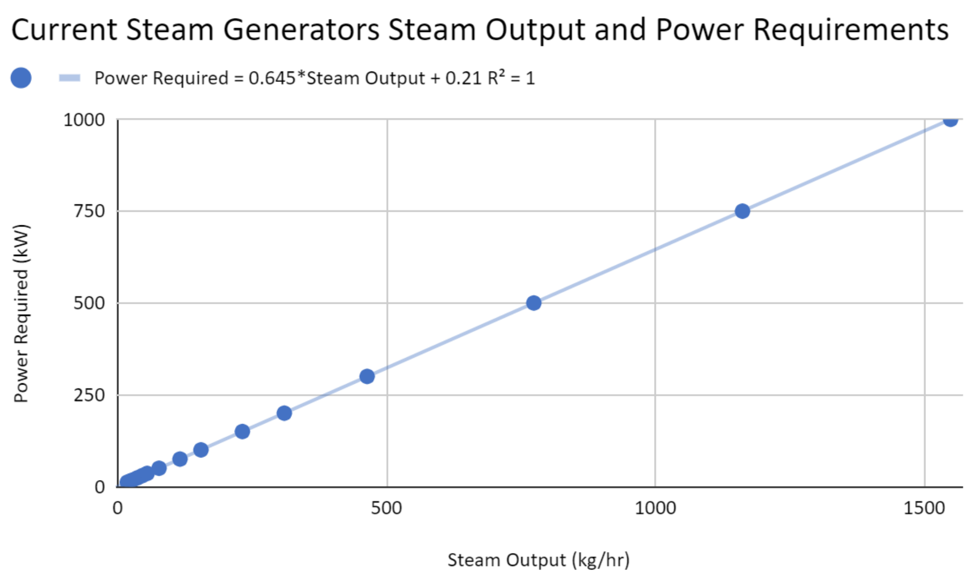


Figure E1: Baseline of Current Fireless Steam Locomotives Steam Output and Power Requirements

$$Power\ Required\ (kW) = 0.6454 * m_{steam} + 0.212 \quad \text{(Eq. E2)}$$

To account for losses that can occur during recharging from escaped steam and heat loss through the recharging hose, we determined the steam generator should produce 25% more steam than the locomotive actually requires. The mass of steam and power required can be found in Table E1 below.

Table E1: Mass of Steam Required to Power 1:8 Scale Locomotive

Locomotive Tank Size (Cubic Feet)	Mass of Water in Tank (kg)	Mass of Steam (kg)
1.4	26.79	2.27
1.2	21.92	1.86
0.8	15.55	1.32
0.7	13.86	1.17
0.6	11.05	0.94
0.5	8.43	0.71
0.3	4.87	0.41
0.1	2.62	0.22

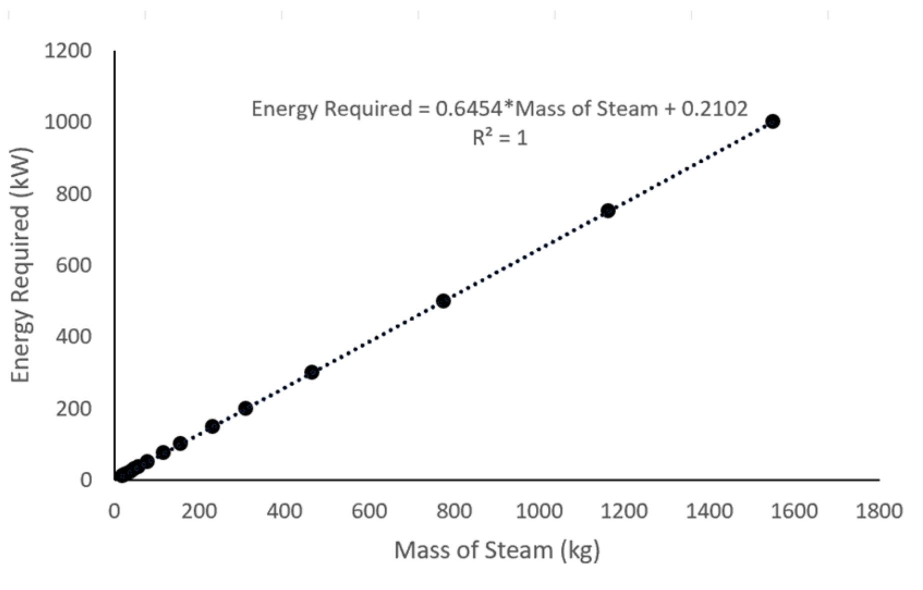


Figure E2: Baseline for Current Electric Steam Generators

Table E2: Mass of Steam To Be Generated and Power Requirements

Locomotive Tank Size (Cubic Feet)	Mass of Steam output kg/h	Power Requirements (kW)
1.4	2.84	2.04
1.2	2.32	1.71
0.8	1.65	1.27
0.7	1.47	1.16
0.6	1.17	0.96
0.5	0.89	0.79
0.3	0.52	0.54
0.1	0.28	0.39

Heat loss and Steam Retention

To determine the heat loss we first need to determine the overall resistance of the shell and insulation. The resistance (R_1) of the electric steam generator is determined by the cross sectional area of the tank initial temperature (T_1) and heat transfer coefficient of the water (h_w), the thickness (L_1, L_2) and thermal conductivity (k_1, k_2) of the shell and insulation, and the temperature (T_2) and heat transfer coefficient (h_a) of the air surrounding the system, Equation E3. Since the locomotive does not have insulation, resistance (R_2) is calculated with the cross-sectional area of the tank, the initial temperature of the steam and the heat transfer coefficient, the thickness of the shell and the thermal conductivity, and the ambient temperature of the air and its heat transfer coefficient, Equation E4[55].

$$R_1 = \frac{1}{\pi(D/2)^2}\left(\frac{1}{h_w} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{1}{h_a}\right) \quad \text{(Eq. E3)}$$

$$R_2 = \frac{1}{\pi(D/2)^2}\left(\frac{1}{h_w} + \frac{L_1}{k_1} + \frac{1}{h_a}\right) \quad \text{(Eq. E4)}$$

After calculating the resistance of each system we can calculate the rate of heat loss, equation E5. This heat loss is determined by the difference in the steam temperature and the ambient temperature outside the tank. This heat loss will change depending on the location the tank is held and the time of year. For this project we are assuming the electric steam generator and the locomotive are outside or within an unheated garage.

$$Heat\ Loss = \frac{T_1 - T_2}{R} \quad \text{(Eq. E5)}$$

Table E3: Heat Loss in Electric Steam Generator

Locomotive Tank Size (Cubic Feet)	Cross Sectional Area of Steam Generator (m^2)	Resistance	Heat Loss (J/s)
1.43	0.65	3.74	31.3
1.17	0.57	4.26	27.5
0.83	0.45	5.36	21.8
0.74	0.42	5.78	20.3
0.59	0.36	6.77	17.3
0.45	0.30	8.08	14.5
0.26	0.21	11.52	10.2
0.14	0.14	17.85	6.6

Table E4: Locomotive Tank Heat Loss

Locomotive Tank Size (Cubic Feet)	Cross Sectional Area of Locomotive Tank (m^2)	Resistance	Heat Loss (J/s)
1.43	0.56	0.35	334.09
1.17	0.49	0.40	293.14
0.83	0.39	0.50	232.94
0.74	0.36	0.54	216.19
0.59	0.31	0.63	184.67
0.45	0.26	0.76	154.69
0.26	0.18	1.08	108.44
0.14	0.12	1.67	69.99

To determine the time it takes for steam to condense, we need to determine the amount of energy that the steam needs to lose before it condenses back into water. This happens in two stages, first the cooling stage where the temperature drops to just above the saturation temperature. The energy to cool the steam (q_1) is calculated using the mass of the steam, the difference in temperature, and the heat capacity of steam (C_p), equation E6 [56]. The second stage is when the steam condenses back into water. The energy to condense (q_2) is calculated using the specific enthalpy of saturated steam and the mass of the steam, equation E7. Totaling both these values together and dividing by the heat loss rate, we can determine the amount of time it takes for the steam to condense [56].

$$q_1 = m_s * C_p * (T_2 - T_1) \quad \text{(Eq. E6)}$$

$$q_2 = m_s * h_g \quad \text{(Eq. E7)}$$

Table E5: Energy Loss and Time to Condense For Electric Steam Generator

Locomotive Tank Size (Cubic Feet)	Mass of Steam (kg)	Energy Loss to Cool (J)	Energy Loss to Condense (J)	Time for Steam to Condense (hr)
1.43	2.8	987291	7796	8.8
1.17	2.3	811472	6408	8.3
0.83	1.6	574793	4539	7.4
0.74	1.5	513932	4058	7.1
0.59	1.2	405736	3204	6.6
0.45	0.9	311064	2456	6.0
0.26	0.5	182581	1442	5.0
0.14	0.3	94672	748	4.0

Table E6: Energy Loss and Time to Condense for Locomotive Tank

Locomotive Tank Size (Cubic Feet)	Mass of Steam (kg)	Energy Loss to Cool (J)	Energy Loss to Condense (J)	Time for Steam to Condense (hr)
1.43	2.3	873851	6237	0.7
1.17	1.9	718233	5126	0.7
0.83	1.3	508749	3631	0.6
0.74	1.2	454881	3247	0.6
0.59	0.9	359117	2563	0.5
0.45	0.7	275323	1965	0.5
0.26	0.4	161603	1153	0.4
0.14	0.2	83794	598	0.3

Solar Power Generation

Table E7: Solar Panel Spec Sheet Values

Nominal Operating Cell Temp (C)	Standard Current (A)	Standard Voltage (V)	Voltage Temp Coefficient (mV/C)	Current Temp Coefficient (mA/C)
25	6.58	75.6	-176.8	2.9

Fill Factor	Solar Radiation Test Conditions (kW/m^2)	Panel Length (m)	Panel Width (m)	Panel Area (m^2)
0.76	1	1.69	1.046	1.76774

The performance of photovoltaic solar panels is greatly affected by the solar radiation and temperature of the cells within each panel. Since solar radiation and temperature are driving factors for the performance of solar panels no system will perform the same as another. This variability comes from the solar radiation of the area, the ambient temperature that changes due to humidity and wind speed, cloud coverage, and shade. To properly size a solar field for this project we needed to understand how solar radiation and temperature affects the panels power output. Since the analysis for a photovoltaic power system changes based on the location, we chose to do our initial engineering analysis for a system in Michigan operating Year-Round. We chose this location due to the fact that our stakeholders and primary customer would be building this system in Michigan.

To begin our analysis we needed to determine how solar irradiance is impacted by cloud coverage. A common weather indicator for cloud coverage is the clearness index. The clearness index $[C]$ is the fraction of solar radiation $[Q_o]$ that is transmitted through the atmosphere that comes into contact with the earth's surface [homer]. Using this relationship seen in equation E3, we can calculate the 'actual' solar radiation for the area for a specified month of the year [homer].

$$Q = (1 - C) * Q_o \qquad \text{(Eq. E3)}$$

After calculating the 'actual' solar radiation, we then calculated the ambient temperature $[T_a]$. The ambient temperature can sometimes also be referred to as the feels like temperature. This is the temperature of a certain area due to the humidity $[H]$ and wind speed $[W]$. Depending on the humidity and wind speed this ambient temperature can be higher or lower than the measured dry bulb temperature $[T_M]$. This relationship is seen below in equation E4 [apparent temp calc].

$$T_a = T_M + 0.348 * H - 0.7 * W * \left(\frac{Q}{W+10}\right) - 4.25 \qquad \text{(Eq. E4)}$$

Once we have determined the ambient temperature we can now determine the photovoltaic cell temperature $[T_C]$, using equation E5.

$$T_c = T_a + \frac{NOCT-20}{0.8} + Q \qquad \text{(Eq. E5)}$$

This change in cell temperature will change the indicated operating current $[I]$ and indicated operating voltage $[V]$ as given by the solar panel spec sheets. As current $[I_a]$ and voltage $[V_a]$ change the actual power generated $[P_a]$ will change [design]. The actual current is calculated using the operating current, the ratio of the actual solar radiation and testing solar radiation $[Q, Q_t]$, the current temperature coefficient, and the cell temperature$[T_c]$, using equation E6 below.

$$I_a = I * \left(\frac{Q}{Q_t}\right) + \left(\frac{ITC}{1000}\right) * \left(T_c - 25\right) \qquad \text{(Eq. E6)}$$

The actual current is calculated using the operating voltage, voltage temperature coefficient $[VTC]$, cell temperature, boltzmann constant $[k]$, electron charge $[q]$, and the ratio of actual solar radiation and testing solar radiation, seen below in equation E7.

$$V_a = I - \left(\frac{VTC}{1000}\right) * \left(T_c - 25\right) + \frac{k*(T_c+273)}{q} * ln\left(\frac{Q}{Q_t}\right) \quad \text{(Eq. E7)}$$

The actual power generated by the panels is also impacted by the Fill Factor $[FF]$ given by the spec sheet, and the Derating Factor $[DF]$. The derating factor takes into account losses generated by dirt and matter covering the panel (soiling), reduction in solar radiation caused by shadows (shading), Snow coverage, electrical losses from manufacturing imperfections (mismatch), resistive losses from DC and AC wiring (wiring), resistive losses from electrical connections (connections), reduced efficiency from degradation after the first few months of use (Light-Induced Degradation), losses as determined by the specific manufacturer (Nameplate Rating), Age of the panels, and losses incurred by system down time from power outages, maintenance or other unscheduled outages (Availability) [61]. The standard Derating Factor is 14% and for simplicity was used in these calculations. Equation E8 shows how the actual power generated was calculated.

$$P_a = FF * I_a * V_a * DF \quad \text{(Eq. E8)}$$

Table E8: Calculated Solar Panel Performance

Solar Radiation (kW/m2)	Ambient Temp (C)	Cell Temp (C)	Actual Current (A)	Actual Voltage (V)	Actual Power Generated (kW)
1.901	15	27	12.5	76.0	0.13

The number of panels $[N]$ required to power a given load is determined by equation E9. The number of panels needed to generate enough power to power an electric steam generator and home Year-Round in Michigan can be found in table XX below. This table shows the power and panel requirements for a range of possible 1:8 scale fireless locomotives.

$$N = \frac{P_s + P_h}{P_a} \quad \text{(Eq. E9)}$$

Table E9: Hourly Power (kW) Requirements and Number of Solar Panels Needed to Power Both a Home and Electric Steam Generator

Locomotive Sizes	Total Power Needed (kW)	Panels Needed	Array Total Area (m2)
1.4	2.7	21	37
1.2	2.4	19	34
0.8	2.0	15	27
0.7	1.8	14	25
0.6	1.6	13	23
0.4	1.5	12	21
0.3	1.2	10	18
0.1	1.1	9	16

Cost Analysis

Solar PV cost data in the units of Cost ($) per Rated Power Capacity (kW) for all fifty states was used to approximate the installation costs [57], while lifetime maintenance costs were based on annual panel cleaning/maintenance costs [71]. Table E10 below shows the $/kW data that was used to calculate these installation costs. However, it is important to note that these costs may vary by proximity to panel distribution centers and qualified installers as well, not just by state.

Table E10: Various $/kW data for all fifty states and Washington DC that were used to calculate installation costs

Photovoltaic Solar System Cost By State

State	Average Cost of Solar Per Watt	Average Cost of a 5kW System After Tax Credit
Alabama	$2.45	$9,065
Alaska	$2.41	$8,917
Arizona	$2.61	$9,657
Arkansas	$2.54	$9,386
California	$2.73	$10,101
Colorado	$2.69	$9,965
Connecticut	$2.80	$10,360
Delaware	$2.58	$9,546
Washington, D.C.	$3.16	$11,704
Florida	$2.53	$9,361
Georgia	$2.55	$9,423
Hawaii	$2.67	$9,879
Idaho	$2.60	$9,608
Illinois	$2.73	$10,113
Indiana	$2.68	$9,916
Iowa	$2.77	$10,237
Kansas	$2.59	$9,571
Kentucky	$2.34	$8,658
Louisiana	$2.57	$9,521
Maine	$2.83	$10,483
Maryland	$2.77	$10,261
Massachusetts	$2.94	$10,878
Michigan	$2.81	$10,409
Minnesota	$2.84	$10,508
Mississippi	$2.64	$9,768
Missouri	$2.59	$9,583
Montana	$2.54	$9,386
Nebraska	$2.83	$10,471
Nevada	$2.52	$9,324
New Hampshire	$2.91	$10,767
New Jersey	$2.77	$10,249
New Mexico	$2.68	$9,904
New York	$2.95	$10,927
North Carolina	$2.54	$9,398
North Dakota	$2.42	$8,954
Ohio	$2.56	$9,460
Oklahoma	$2.62	$9,694
Oregon	$2.60	$9,632
Pennsylvania	$2.55	$9,447
Rhode Island	$2.84	$10,508
South Carolina	$2.72	$10,076
South Dakota	$2.39	$8,843
Tennessee	$2.49	$9,213
Texas	$2.69	$9,953
Utah	$2.68	$9,904
Vermont	$2.87	$10,619
Virginia	$2.75	$10,163
Washington	$2.69	$9,965
West Virginia	$2.64	$9,768
Wisconsin	$2.60	$9,620
Wyoming	$2.57	$9,509

Furthermore, the tool's steam generation analysis was used to determine the steam generation necessary for subsystem 2. From there, the electric steam generator costs were approximated by gathering publicly available cost data from Amerec electric steam generators available on the market [69]. However, a future iteration of this calculator would use the Reimers Electra Steam, Inc. AR4 electric steam generator for most applications; cost data was simply not readily available and so an assumption was made that product costs would be similar. The fittings costs were fixed values based on McMaster-Carr prices [58] and the hose cost was variable depending on the length needed from McMaster-Carr.

Table E11: Cost verification for Amerec electric steam generators that were used to approximate Reimers Electra Steam AR4 electric steam generator costs

Cost Verification for Electric Steam Generation

	Power Rating (kW)	Steam Generation (lbs/hr)	Steam Generation (kg/hr)	Price	Cubic Feet Low	Cubic Feet Max
Residential	4.5		6.649	$1,512	60	90
	7.5		11.299	$1,720	100	200
	11.2		17.034	$1,997	175	375
	14.1		21.529	$2,162	350	550
Commercial	12	36	16.33	$6,432		500
	18	54	24.49	$6,900		900
	24	73	33.11	$7,684		1200
	30	91	41.28	$8,640		1500
	36	109	49.44	$9,108		1800
	42	127	57.61	$9,568		2100
	48	145	65.77	$10,028		2400

With regards to subsystem 3, it was assumed that the hobbyist would construct a 1/16 mile track which requires 330 feet of track. It was also assumed that the hobbyist implements four switches into their track. Train costs were used from Backyard Train Co [59] while track and switch costs were used from RMI Railworks [65]. Table E12 below depicts Backyard Train Co's pricing model for trains and their various features such as adding paint and sound to the locomotive.

Table E12: Various train prices from Backyard Train Co's website as well as their respective prices for adding paint or sound to the locomotive option

Train Costs

Train	Price	Yes - Add paint & lettering (up to 3 colors)	No - Do not add paint & lettering	Yes - Add Large Scale Phoenix Sound system including enclosed subwoofer and 100 watt amp	No - Do Not Add Large Scale Phoenix Sound system
GP20 basic detailed all steel engine with controller & batteries ready-to-run	$14,000	$750	$0	$550	$0
GP7/9 Basic detailed engine with controller & batteries ready-to-run	$14,000	$850	$0	$550	$0
SW1 Switcher Base	$13,000	$800	$0	$550	$0
SW1200 Switcher ready-to-run with batteries and controller	$13,000	$800	$0	$550	$0
NW2 Switcher ready-to-run with batteries and controller	$13,000	$800	$0	$550	$0
GP35 Base	$16,000	$750	$0	$550	$0
Hustler Switcher Base R-T-R with batteries and controller	$5,750	$450	$0	$550	$0
Boxcab R-T-R with batteries and controller	$4,500	$600	$0	$550	$0
No Locomotive Needed	$0	$0	$0	$0	$0

Appendix F: Concept Generation Variations

Table F1: Summary of twenty possible concepts. The top five choices are colored in blue.

Concept #	Subsystem			
	Energy Generation	**Steam Generation**	**Recharging Station**	**Fireless Locomotive**
1)	Concentrated Solar Power (CSP) - Linear Fresnel	Synthetic Oil Heat Exchanger (HE)	Hose	Traditional Fireless Locomotive
2)	CSP - Power Tower	Synthetic Oil HE	Hose	Traditional Fireless Locomotive
3)	CSP - Parabolic Trough	Synthetic Oil HE	Hose	Traditional Fireless Locomotive
4)	CSP - Parabolic Dish	Synthetic Oil HE	Hose	Traditional Fireless Locomotive
5)	Solar Photovoltaic	Electric Steam Generator	Hose	Traditional Fireless Locomotive

6)	CSP	Molten Salt HE	Hose	Traditional Fireless Locomotive
7)	Solar Photovoltaic	Molten Salt HE	Hose	Traditional Fireless Locomotive
8)	CSP	Molten Salt HE	Automated	Traditional Fireless Locomotive
9)	CSP	Boiler	Automated	Traditional Fireless Locomotive
10)	CSP	Direct Solar to Steam	Automated	Tank Changing
11)	CSP	Direct Solar to Steam	Automated	Compressed Cartridge
12)	Solar Photovoltaic	Synthetic Oil HE	Track Recharging	Supplementary Steam
13)	CSP	Synthetic Oil HE	Automated	Compressed Cartridge
14)	Solar Photovoltaic	Synthetic Oil HE	Automated	Compressed Cartridge
15)	CSP	Resistive Heating	Automated	Traditional Fireless Locomotive
16)	Hydrogen	Resistive Heating	Hose	Supplementary Steam
17)	Hydrogen	Resistive Heating	Automated	Compressed Cartridge
18)	CSP	Direct Solar to Steam	N/A	Onboard CSP
19)	Nuclear	Direct Nuclear to Steam	N/A	Onboard Nuclear To Steam
20)	Nuclear	Direct Nuclear to Electricity	N/A	Onboard Nuclear To Electricity

Twenty Possible Concept Descriptions

1) A linear Fresnel solar collector uses long reflecting mirrors at the base of the system to focus sunlight into an absorber located at the focal line of the mirrors to concentrate energy into it. Representing approximately 1% of the world installed capacity of CSP, the technology is largely unproven, but has proven effective in its limited projects. With respect to our project, linear

Fresnel CSP becomes a better choice the smaller the application is, thus a 1:8 scale locomotive is ideal for this technology.

2) The power tower CSP has become far more popular in recent years as it offers higher temperature operation than competing CSP technologies such as parabolic troughs, thus achieving higher efficiencies. Furthermore, this technology is much more commonplace worldwide with several notable projects in California, Spain, and China. The technology features a receiver atop a central tower which absorbs reflected sunlight from dual-axis tracking reflectors that are also known as heliostats. The central tower receiver contains a heat-transfer fluid such as molten salt or oil that is used as a heat transfer fluid to exchange heat in a heat exchanger. Most current applications are used in large plants since 2010 (over 50 MW).
3) The least common of the four mainstream CSP technologies, the parabolic dish represents less than 1% of the world's installed capacity. Featuring a parabolic mirror (or multiple mirrors) arranged in a shell that reflects light onto a central receiver unit, parabolic dishes are most effective when pointing directly at the sun. Thus, they are often mounted on single or dual axis trackers to ensure optimal alignment throughout the day. Because of their point focus, this concept allows heat transfer fluids to reach upwards of 1500°C. Given its ability to produce high temperatures with only a single shell, the parabolic dish concept offers a lot of potential in the scope of our 1:8 model.
4) The most common CSP technology in practice, parabolic trough CSP makes up 87% of the world's installed capacity. This concept features a parabolic trough that uses a set of concave mirrors that concentrate sunlight onto a central receiver tube. The receiver tube contains a heat transfer fluid that absorbs the thermal energy from the reflected rays and is pumped through a heat exchanger where water is turned into steam to power a steam turbine to generate electricity. The introduction of heat transfer fluids such as synthetic oils or molten salts allow for a maximum attainable temperature of 600°C. With respect to a fireless locomotive, the steam turbine would be eliminated and replaced with the hose refueling and steam accumulator
5) The least common of the four mainstream CSP technologies, the parabolic dish represents less than 1% of the world's installed capacity. Featuring a parabolic mirror (or multiple mirrors) arranged in a shell that reflects light onto a central receiver unit, parabolic dishes are most effective when pointing directly at the sun. Thus, they are often mounted on single or dual axis trackers to ensure optimal alignment throughout the day. Because of their point focus, this concept allows heat transfer fluids to reach upwards of 1500°C. Given its ability to produce high temperatures with only a single shell, the parabolic dish concept offers a lot of potential in the scope of our 1:8 model.
6) This concept uses concentrated solar power to heat a molten salt heat exchanger. This heat exchanger generates steam which is then pumped via a hose into a fireless locomotive.
7) This concept uses photovoltaic panels to electrically heat a molten salt heat exchanger. This heat exchanger generates steam which is then pumped via a hose into a fireless locomotive.
8) This concept uses concentrated solar power to heat a molten salt heat exchanger. This heat exchanger generates steam which is then pumped via an automated refueling apparatus into a fireless locomotive.
9) This concept uses concentrated solar power to generate supplementary steam for a traditional steam locomotive that is primarily powered by a boiler. This steam is automatically injected into the accumulator whenever it is available and the traditional boiler can be disabled, saving fuel.

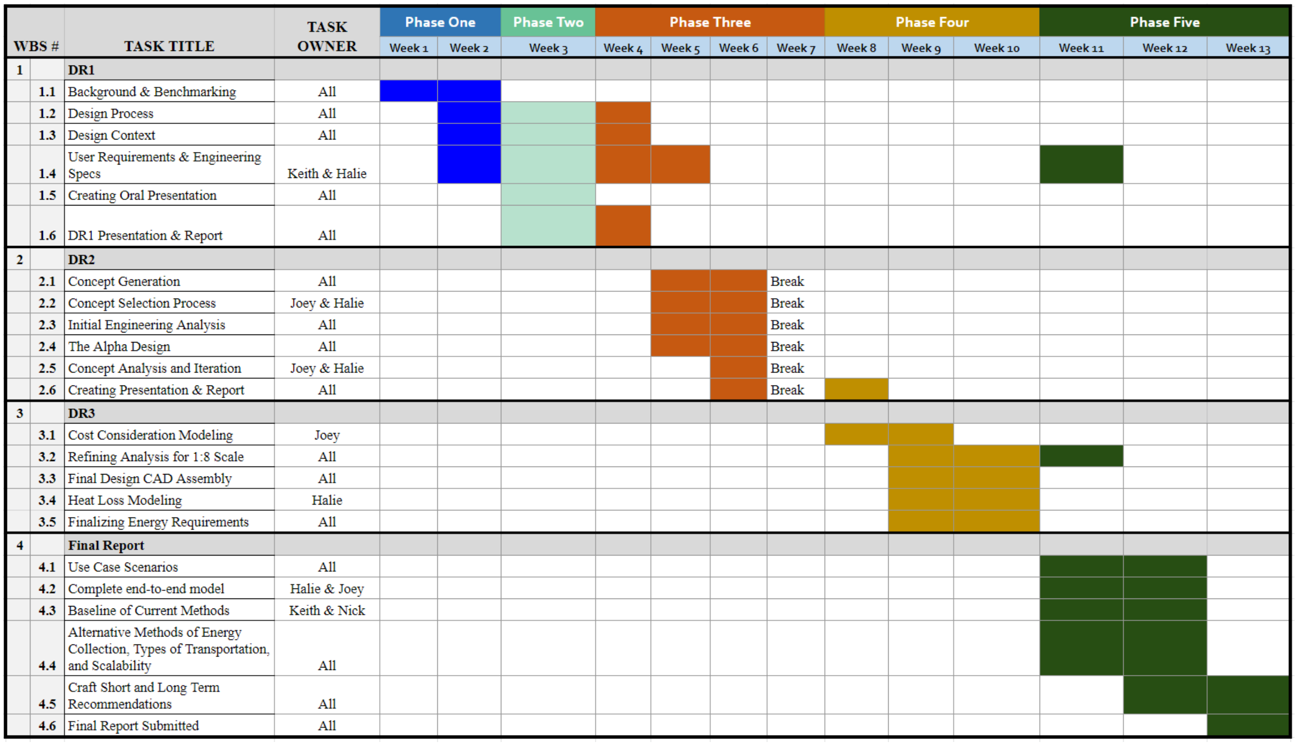
10) This concept uses concentrated solar power to directly generate steam which is then stored in removable tanks that can be attached to the back of the fireless locomotive to refuel it.
11) This concept uses concentrated solar power to directly generate steam which is then stored in removable cartridges that can be swapped in and out of the fireless locomotive to refuel it.
12) This concept uses photovoltaic panels to electrically heat a synthetic oil heat exchanger. This heat exchanger generates steam which is then pumped via a hose into a fireless locomotive.
13) This concept uses concentrated solar power to heat a synthetic oil heat exchanger. This heat exchanger generates steam which is then stored in removable cartridges that can be swapped in and out of the fireless locomotive to refuel it.
14) This concept uses photovoltaic power to electrically heat a synthetic oil heat exchanger. This heat exchanger generates steam which is then stored in removable cartridges that can be swapped in and out of the fireless locomotive to refuel it.
15) This concept uses photovoltaic panels to resitively heat water into steam which is then pumped via an automated refueling apparatus into a fireless locomotive.
16) This concept uses hydrogen fuel cells to power a resistive heater to turn water into steam which is then pumped via a hose into a fireless locomotive.
17) This concept uses hydrogen fuel cells to power a resistive heater to turn water into steam which is then pumped via an automated refueling apparatus into a fireless locomotive.
18) This concept uses an on board concentrated solar power system to directly heat water into steam for use in the locomotive's engine.
19) This concept uses an on board nuclear power system to directly heat water into steam for use in the locomotive's engine.
20) This concept uses an on board nuclear power system to generate electricity for use in an AC locomotive.

Concept Selection

Fifteen of the above concepts were not selected from our initial list. Concepts 6 through 8, while theoretically viable, made use of a molten salt heat exchanger. Molten salts are something that we as a team were not initially familiar with and so we eliminated these three options for being outside the scope of our project. Concept 9 used a boiler as its primary steam generation method while using CSP for supplementary power. This option was eliminated because such a system would be both highly expensive as well as awkward to use given that two different energy sources would have to be managed. Concepts 10, 11, 13, and all featured some sort of steam vessel that could be swapped two and from the train to provide immediate recharging. These options were eliminated due to the high cost incurred by the infrastructure necessary to make such designs practical. Concept 12 used electric track recharging while in operation to generate steam on board the train and was eliminated based on the overall complexity of the systems required. Concept 15 used concentrated solar power to generate electricity which was then used to power a resistive heating element. It was eliminated on account of the multiple unnecessary points of energy loss introduced between energy generation and the locomotive itself. Concepts 16, 17, 19, and 20 all used an alternative energy source, either nuclear or hydrogen, to power the system. While there are strong arguments to be made for both options, neither fits into our sponsor's vision for a solar powered locomotive. Concept 18 proposes installing a CSP generator directly atop of the train but this is impractical as such systems require much more surface area to generate sufficient power.

Appendix G: Compressed Gantt Chart

This appendix shows how the team followed its design process for the semester by splitting the project into five phases spanning Design Reviews 1-3 as well as the completion of the Final Report. A notable edit that was made to this plan at the beginning of Phase Five was revisiting the user requirements and engineering specifications to specifically define how our modeling tool could be used by train hobbyists.



Appendix H: Reference Charts

Table H1: Weather Data broken down by State, month, season, and yearly averages.

State	Month	DNI	Average Low Temp (C)	Average High Temp (C)	Average Temp (C)	Average Humidity (%)	Average Humidity (hPA)	Average Wind Speed (m/s)	Average Clearness Index
Michigan	January	1.55	-8	0	-4	74	3	4.1	0.45
Michigan	February	2.51	-7	1	-3	84	3	4.1	0.51
Michigan	March	3.7	-2	7	3	59	3	4.3	0.51
Michigan	April	4.35	4	14	9	70	6	3.8	0.51
Michigan	May	5.27	10	21	15	66	9	3.4	0.53
Michigan	June	5.46	15	26	21	68	12	3.5	0.54
Michigan	July	5.83	18	29	23	73	15	3.1	0.54
Michigan	August	5.14	17	27	22	67	13	2.7	0.53
Michigan	September	4.98	12	23	18	64	10	3.5	0.50

Michigan	October	3.01	6	16	11	73	7	3.6	0.46
Michigan	November	1.76	1	9	5	63	4	3.9	0.41
Michigan	December	1.26	-5	2	-1	73	3	3.8	0.40
Michigan	Year-round	3.74	5	15	10	70	7	3.7	0.49
Michigan	Spring	4.44	4	14	9	65	6	3.8	0.52
Michigan	Summer	5.48	16	27	22	69	13	3.1	0.54
Michigan	Fall	3.25	6	16	11	67	7	3.7	0.46
Michigan	Winter	1.77	-6	1	-3	77	3	4.0	0.45
Alaska	January	1.11	-12	-5	-8	91	2	2.4	0.43
Alaska	February	1.9	-10	-3	-6	94	3	2.1	0.47
Alaska	March	4	-7	1	-3	89	3	1.9	0.52
Alaska	April	5.18	-2	7	3	81	5	2.1	0.53
Alaska	May	6.16	4	13	9	71	6	1.7	0.47
Alaska	June	6.21	9	17	13	75	9	1.6	0.44
Alaska	July	5.68	11	18	15	79	10	1.6	0.42
Alaska	August	4.92	10	18	14	78	9	1.6	0.41
Alaska	September	3.58	6	13	9	74	7	2.4	0.42
Alaska	October	2.22	-2	4	1	78	4	2.6	0.42
Alaska	November	1.36	-8	-2	-5	85	3	2.9	0.44
Alaska	December	1.45	-11	-4	-7	91	3	1.6	0.48
Alaska	Year-round	3.65	-1	6	3	82	5	2.0	0.45
Alaska	Spring	5.11	-1	7	3	80	5	1.9	0.51
Alaska	Summer	5.60	10	18	14	77	9	1.6	0.42
Alaska	Fall	2.39	-1	5	2	79	5	2.6	0.43
Alaska	Winter	1.49	-11	-4	-7	92	3	2.0	0.46
Alabama	January	4.3	1	12	7	72	5	3.4	0.47
Alabama	February	4.99	3	14	9	69	6	3.3	0.51
Alabama	March	5.35	7	19	13	75	9	3.2	0.53
Alabama	April	5.88	11	23	17	71	10	2.8	0.55
Alabama	May	5.77	16	28	22	66	13	2.8	0.54
Alabama	June	5.6	20	31	26	72	17	2.7	0.54
Alabama	July	5.55	22	33	27	71	19	2.0	0.53
Alabama	August	5.62	22	33	27	73	19	2.5	0.54
Alabama	September	5.89	18	29	24	72	15	2.2	0.54
Alabama	October	5.66	12	24	18	71	11	2.5	0.57
Alabama	November	5.1	7	18	13	60	7	2.5	0.51
Alabama	December	3.96	2	13	8	79	6	2.9	0.48
Alabama	Year-round	5.31	12	23	17	71	11	2.7	0.52
Alabama	Spring	5.67	11	24	17	71	10	2.9	0.54
Alabama	Summer	5.59	21	32	27	72	18	2.4	0.54
Alabama	Fall	5.55	12	24	18	68	11	2.4	0.54

Alabama	Winter	4.42	2	13	8	73	6	3.2	0.49
Arizona	January	5.84	8	19	14	27	3	1.7	0.62
Arizona	February	6.31	9	22	16	22	3	2.5	0.64
Arizona	March	7.02	12	25	18	24	4	3.2	0.64
Arizona	April	7.3	16	29	23	17	3	3.3	0.68
Arizona	May	7.13	21	35	28	13	3	3.1	0.69
Arizona	June	6.96	26	40	33	15	5	3.5	0.70
Arizona	July	6.51	28	41	35	34	13	3.1	0.63
Arizona	August	6.65	28	40	34	29	11	3.1	0.63
Arizona	September	7.02	25	38	31	27	9	2.5	0.67
Arizona	October	6.92	18	32	25	22	5	2.4	0.68
Arizona	November	5.99	12	24	18	19	3	1.7	0.65
Arizona	December	5.26	7	19	13	36	4	2.0	0.61
Arizona	Year-round	6.58	17	30	24	24	6	2.7	0.65
Arizona	Spring	7.15	16	30	23	18	4	3.2	0.67
Arizona	Summer	6.71	27	40	34	26	10	3.2	0.65
Arizona	Fall	6.64	18	31	25	23	6	2.2	0.67
Arizona	Winter	5.80	8	20	14	28	3	2.1	0.62
Arkansas	January	4.35	0	11	5	62	4	3.2	0.50
Arkansas	February	4.74	2	13	7	71	6	3.6	0.53
Arkansas	March	5.15	6	18	12	71	8	3.6	0.54
Arkansas	April	5.68	11	23	17	70	10	3.4	0.55
Arkansas	May	5.29	16	27	22	75	14	3.1	0.56
Arkansas	June	5.97	21	32	26	75	18	2.8	0.57
Arkansas	July	5.83	23	33	28	70	19	2.4	0.57
Arkansas	August	6.04	22	34	28	66	18	2.6	0.59
Arkansas	September	6.07	18	30	24	61	13	2.6	0.55
Arkansas	October	5.51	12	24	18	66	10	3.1	0.57
Arkansas	November	4.82	6	17	11	58	6	3.1	0.51
Arkansas	December	4.02	1	11	6	73	5	3.5	0.48
Arkansas	Year-round	5.29	11	23	17	68	11	3.1	0.54
Arkansas	Spring	5.37	11	23	17	72	11	3.4	0.55
Arkansas	Summer	5.95	22	33	27	70	19	2.6	0.58
Arkansas	Fall	5.47	12	24	18	62	10	2.9	0.54
Arkansas	Winter	4.37	1	11	6	69	5	3.4	0.50
California	January	5.35	4	12	8	72	6	1.9	0.51
California	February	5.65	5	16	10	58	6	2.3	0.55
California	March	6.51	7	18	13	67	7	2.6	0.58
California	April	6.6	8	22	15	51	6	2.9	0.62
California	May	6.5	11	27	19	39	6	3.7	0.62
California	June	6.08	13	31	22	41	8	3.8	0.63

California	July	6.63	14	33	24	38	8	3.7	0.66
California	August	7.09	14	33	24	38	8	3.4	0.66
California	September	6.94	13	31	22	34	7	2.9	0.64
California	October	6.37	10	26	18	51	8	2.9	0.62
California	November	5.97	6	18	12	65	7	2.2	0.56
California	December	4.95	3	12	8	73	6	3.1	0.52
California	Year-round	6.22	9	23	16	52	7	3.0	0.60
California	Spring	6.54	8	22	15	52	7	3.1	0.61
California	Summer	6.60	14	32	23	39	8	3.6	0.65
California	Fall	6.43	10	25	17	50	7	2.7	0.61
California	Winter	5.32	4	13	9	68	6	2.4	0.53
Colorado	January	4.97	-8	7	0	64	3	2.1	0.59
Colorado	February	5.57	-7	8	0	66	3	2.2	0.59
Colorado	March	6.27	-3	12	5	56	4	2.3	0.60
Colorado	April	6.2	1	16	9	53	5	2.5	0.61
Colorado	May	6.21	6	22	14	55	7	2.6	0.61
Colorado	June	6.5	11	28	19	41	7	2.7	0.64
Colorado	July	6.53	15	32	24	41	9	2.6	0.62
Colorado	August	6.4	14	31	23	32	6	2.5	0.62
Colorado	September	6.48	9	26	18	27	4	2.3	0.63
Colorado	October	5.85	3	19	11	33	3	2.2	0.65
Colorado	November	5.46	-4	11	4	34	2	2.0	0.61
Colorado	December	4.78	-8	7	0	33	2	2.4	0.58
Colorado	Year-round	5.94	2	18	10	45	5	2.4	0.61
Colorado	Spring	6.23	1	17	9	55	5	2.5	0.61
Colorado	Summer	6.48	13	30	22	38	7	2.6	0.62
Colorado	Fall	5.93	3	19	11	31	3	2.2	0.63
Colorado	Winter	5.11	-8	7	0	54	3	2.2	0.59
Connecticut	January	3.39	-5	3	-1	65	3	3.4	0.48
Connecticut	February	4.24	-4	4	0	73	4	3.2	0.51
Connecticut	March	4.83	-1	8	4	59	4	3.4	0.48
Connecticut	April	5.41	5	14	10	68	6	3.1	0.51
Connecticut	May	5.43	11	20	15	68	9	2.8	0.49
Connecticut	June	5.59	16	25	20	70	12	2.6	0.51
Connecticut	July	5.94	19	28	23	81	17	2.0	0.51
Connecticut	August	5.68	19	27	23	72	15	2.0	0.51
Connecticut	September	5.64	14	23	19	76	12	2.3	0.50
Connecticut	October	4.35	8	17	13	76	8	2.4	0.50
Connecticut	November	3.8	3	12	8	64	5	2.6	0.45
Connecticut	December	2.97	-2	6	2	70	4	2.7	0.45
Connecticut	Year-round	4.77	7	16	11	70	8	2.7	0.49

Connecticut	Spring	5.22	5	14	10	65	6	3.1	0.49
Connecticut	Summer	5.74	18	27	22	74	15	2.2	0.51
Connecticut	Fall	4.60	9	17	13	72	9	2.4	0.48
Connecticut	Winter	3.53	-4	4	0	69	3	3.1	0.48
Delaware	January	3.94	-3	6	2	72	4	5.3	0.48
Delaware	February	4.69	-2	8	3	70	4	5.0	0.53
Delaware	March	5.25	2	13	8	65	5	4.9	0.51
Delaware	April	5.72	7	19	13	70	8	4.7	0.51
Delaware	May	5.65	12	24	18	69	11	4.4	0.51
Delaware	June	5.74	17	28	23	74	15	3.9	0.55
Delaware	July	5.91	20	31	25	73	17	3.2	0.54
Delaware	August	5.89	19	29	24	74	17	3.0	0.55
Delaware	September	5.43	16	26	21	72	13	4.1	0.52
Delaware	October	4.97	9	21	15	73	9	4.3	0.54
Delaware	November	4.22	4	14	9	63	6	4.5	0.48
Delaware	December	3.62	-1	8	4	70	4	4.3	0.43
Delaware	Year-round	5.09	9	19	14	70	9	4.3	0.51
Delaware	Spring	5.54	7	19	13	68	8	4.7	0.51
Delaware	Summer	5.85	19	29	24	74	16	3.4	0.55
Delaware	Fall	4.87	10	20	15	69	9	4.3	0.51
Delaware	Winter	4.08	-2	8	3	71	4	4.9	0.48
Florida	January	5.59	4	18	11	71	7	2.8	0.52
Florida	February	6.22	6	19	13	67	7	2.5	0.54
Florida	March	6.36	8	23	16	71	10	2.8	0.55
Florida	April	6.19	11	27	19	66	11	2.5	0.59
Florida	May	5.52	17	31	24	63	13	2.5	0.56
Florida	June	4.77	21	33	27	71	18	2.1	0.53
Florida	July	5.16	22	33	28	76	20	1.7	0.53
Florida	August	5.42	22	33	28	79	21	1.9	0.54
Florida	September	5.34	20	31	26	72	17	1.6	0.53
Florida	October	5.83	14	27	21	68	12	1.9	0.54
Florida	November	5.82	8	23	16	61	8	2.2	0.54
Florida	December	5.55	5	18	12	77	8	2.2	0.51
Florida	Year-round	5.65	13	26	20	70	13	2.2	0.54
Florida	Spring	6.02	12	27	19	67	11	2.6	0.57
Florida	Summer	5.12	22	33	27	75	20	1.9	0.53
Florida	Fall	5.66	14	27	21	67	12	1.9	0.54
Florida	Winter	5.79	5	19	12	72	7	2.5	0.53
Georgia	January	4.54	1	11	6	62	5	3.6	0.48
Georgia	February	4.76	3	14	8	62	5	3.4	0.53
Georgia	March	5.36	7	18	13	61	7	3.4	0.54

Georgia	April	5.78	11	22	17	58	8	3.2	0.57
Georgia	May	5.77	16	27	22	59	11	2.9	0.56
Georgia	June	5.69	20	30	25	63	15	2.7	0.54
Georgia	July	5.39	22	32	27	66	17	2.2	0.55
Georgia	August	5.64	22	31	27	66	17	2.4	0.55
Georgia	September	5.74	18	28	23	64	13	2.2	0.53
Georgia	October	5.73	12	23	18	67	10	2.6	0.58
Georgia	November	4.99	6	18	12	49	5	2.9	0.54
Georgia	December	4.13	2	12	7	71	6	2.8	0.49
Georgia	Year-round	5.29	12	22	17	62	10	2.9	0.54
Georgia	Spring	5.64	11	22	17	59	9	3.2	0.56
Georgia	Summer	5.57	21	31	26	65	16	2.4	0.55
Georgia	Fall	5.49	12	23	17	60	9	2.6	0.55
Georgia	Winter	4.48	2	12	7	65	5	3.3	0.50
Hawaii	January	4.12	19	27	23	75	15	2.6	0.53
Hawaii	February	3.93	19	27	23	73	15	4.8	0.55
Hawaii	March	3.77	20	27	24	76	16	6.5	0.53
Hawaii	April	3.67	21	28	24	70	16	5.2	0.52
Hawaii	May	3.69	22	29	26	72	17	5.6	0.54
Hawaii	June	3.72	23	31	27	70	18	5.9	0.57
Hawaii	July	3.8	23	31	27	73	19	7.6	0.56
Hawaii	August	3.85	24	32	28	72	19	5.8	0.58
Hawaii	September	4.12	23	32	28	72	19	6.4	0.59
Hawaii	October	3.54	23	31	27	74	19	6.6	0.56
Hawaii	November	3.5	22	29	25	73	17	4.3	0.52
Hawaii	December	3.57	20	27	24	77	16	6.7	0.53
Hawaii	Year-round	3.77	21	29	25	73	17	5.7	0.55
Hawaii	Spring	3.71	21	28	25	73	16	5.8	0.53
Hawaii	Summer	3.79	23	31	27	72	19	6.4	0.57
Hawaii	Fall	3.72	23	30	26	73	18	5.8	0.55
Hawaii	Winter	3.87	19	27	23	75	15	4.7	0.54
Idaho	January	2.67	-4	3	0	93	4	2.0	0.46
Idaho	February	3.89	-2	7	3	93	5	1.7	0.50
Idaho	March	4.79	1	13	7	73	6	2.9	0.54
Idaho	April	6.16	4	17	10	50	5	4.3	0.56
Idaho	May	6.53	8	22	15	54	7	3.7	0.59
Idaho	June	6.99	12	27	20	39	7	3.7	0.61
Idaho	July	7.41	16	33	24	30	7	3.1	0.67
Idaho	August	7.18	16	32	24	31	7	3.4	0.67
Idaho	September	6.76	11	26	18	26	4	3.6	0.64
Idaho	October	5.59	5	18	12	60	6	3.7	0.62

Idaho	November	3.49	0	9	4	64	4	3.6	0.49
Idaho	December	2.53	-4	3	-1	80	4	4.0	0.45
Idaho	Year-round	5.33	5	18	11	58	5	3.3	0.56
Idaho	Spring	5.83	4	17	11	59	6	3.6	0.56
Idaho	Summer	7.19	14	31	23	33	7	3.4	0.65
Idaho	Fall	5.28	5	18	11	50	5	3.6	0.58
Idaho	Winter	3.03	-4	5	1	89	5	2.6	0.47
Illinois	January	2.96	-8	0	-4	69	3	4.8	0.48
Illinois	February	3.87	-6	2	-2	81	3	4.8	0.51
Illinois	March	4.79	-1	8	3	71	4	5.1	0.49
Illinois	April	5.38	5	15	10	74	7	4.7	0.51
Illinois	May	5.41	11	21	16	75	10	4.2	0.53
Illinois	June	5.94	17	27	22	80	16	3.5	0.55
Illinois	July	6.06	20	29	24	87	19	3.0	0.56
Illinois	August	5.91	19	28	23	82	17	3.3	0.54
Illinois	September	5.47	14	24	19	67	11	4.1	0.54
Illinois	October	4.32	8	17	13	74	8	4.2	0.54
Illinois	November	3.3	1	9	5	61	4	4.3	0.46
Illinois	December	2.52	-5	2	-1	66	3	4.7	0.43
Illinois	Year-round	4.66	6	15	11	74	9	4.2	0.51
Illinois	Spring	5.19	5	15	10	73	7	4.7	0.51
Illinois	Summer	5.97	19	28	23	83	17	3.3	0.55
Illinois	Fall	4.36	8	17	12	67	8	4.2	0.51
Illinois	Winter	3.12	-6	1	-2	72	3	4.8	0.47
Indiana	January	3.47	-7	2	-3	61	2	3.9	0.45
Indiana	February	4.22	-6	4	-1	79	4	3.9	0.48
Indiana	March	5.1	-1	11	5	64	4	4.1	0.48
Indiana	April	5.25	4	17	11	69	7	3.9	0.50
Indiana	May	5.53	10	23	16	72	10	3.3	0.53
Indiana	June	5.85	15	28	21	75	14	3.1	0.55
Indiana	July	5.72	17	29	23	79	17	2.7	0.55
Indiana	August	5.88	16	28	22	75	15	2.5	0.55
Indiana	September	5.77	12	25	18	68	11	3.2	0.53
Indiana	October	4.73	6	18	12	75	8	3.4	0.52
Indiana	November	3.66	1	11	6	59	4	3.4	0.44
Indiana	December	2.78	-5	4	-1	70	3	3.7	0.40
Indiana	Year-round	4.83	5	17	11	71	8	3.4	0.50
Indiana	Spring	5.29	4	17	11	68	7	3.8	0.51
Indiana	Summer	5.82	16	29	22	76	15	2.8	0.55
Indiana	Fall	4.72	6	18	12	67	8	3.3	0.50
Indiana	Winter	3.49	-6	3	-1	70	3	3.8	0.44

Iowa	January	3.45	-10	-1	-5	80	3	4.5	0.52
Iowa	February	4.11	-7	2	-3	69	3	5.0	0.53
Iowa	March	5.33	-1	9	4	74	5	4.9	0.52
Iowa	April	5.19	5	17	11	69	7	4.6	0.51
Iowa	May	5.57	11	22	17	79	11	4.3	0.54
Iowa	June	5.63	17	28	22	77	15	3.6	0.56
Iowa	July	6.03	19	30	25	81	18	3.5	0.57
Iowa	August	5.9	18	29	24	69	15	4.3	0.56
Iowa	September	5.94	13	24	19	56	9	4.4	0.55
Iowa	October	4.67	6	17	12	66	7	4.1	0.55
Iowa	November	3.87	-1	9	4	62	4	4.4	0.47
Iowa	December	2.97	-8	1	-3	61	2	4.7	0.48
Iowa	Year-round	4.89	5	16	10	70	8	4.4	0.53
Iowa	Spring	5.36	5	16	11	74	8	4.6	0.52
Iowa	Summer	5.85	18	29	24	76	16	3.8	0.56
Iowa	Fall	4.83	6	17	11	61	7	4.3	0.52
Iowa	Winter	3.51	-8	1	-4	70	3	4.7	0.51
Kansas	January	4.28	-7	4	-1	62	3	4.8	0.56
Kansas	February	4.81	-4	7	1	62	3	5.5	0.57
Kansas	March	5.45	1	13	7	71	5	5.9	0.58
Kansas	April	5.66	7	19	13	72	8	5.7	0.57
Kansas	May	5.55	12	24	18	83	13	4.9	0.55
Kansas	June	5.92	18	29	24	77	16	4.2	0.60
Kansas	July	6.21	20	32	26	75	18	4.2	0.61
Kansas	August	6.05	19	32	25	60	14	5.3	0.61
Kansas	September	5.84	13	27	20	54	9	5.2	0.59
Kansas	October	5.21	7	20	14	62	7	5.3	0.60
Kansas	November	4.38	1	13	7	58	4	4.9	0.56
Kansas	December	3.57	-6	6	0	51	2	5.2	0.55
Kansas	Year-round	5.24	7	19	13	66	9	5.1	0.58
Kansas	Spring	5.55	6	19	13	75	9	5.5	0.56
Kansas	Summer	6.06	19	31	25	71	16	4.6	0.61
Kansas	Fall	5.14	7	20	13	58	7	5.1	0.58
Kansas	Winter	4.22	-6	6	0	58	3	5.2	0.56
Kentucky	January	3.62	-6	4	-1	75	3	3.7	0.45
Kentucky	February	4.09	-5	7	1	80	4	3.9	0.47
Kentucky	March	4.68	-1	13	6	76	6	3.8	0.49
Kentucky	April	5.41	4	19	11	78	8	3.6	0.51
Kentucky	May	5.51	9	24	17	80	11	3.1	0.53
Kentucky	June	5.77	15	28	22	81	15	2.9	0.55
Kentucky	July	5.64	17	31	24	81	18	2.7	0.53

Kentucky	August	5.88	17	30	23	75	16	2.4	0.54
Kentucky	September	5.64	13	26	19	76	13	2.8	0.53
Kentucky	October	5.09	6	20	13	81	9	3.3	0.54
Kentucky	November	4.04	1	13	7	70	5	3.4	0.46
Kentucky	December	3.33	-3	7	2	80	4	4.1	0.41
Kentucky	Year-round	4.89	6	18	12	78	9	3.3	0.50
Kentucky	Spring	5.20	4	19	11	78	8	3.5	0.51
Kentucky	Summer	5.76	16	30	23	79	16	2.7	0.54
Kentucky	Fall	4.92	6	20	13	76	9	3.2	0.51
Kentucky	Winter	3.68	-5	6	1	78	4	3.9	0.44
Louisiana	January	4.89	7	17	12	69	7	3.3	0.46
Louisiana	February	5.11	9	18	14	71	8	3.3	0.51
Louisiana	March	5.57	12	22	17	78	11	3.6	0.52
Louisiana	April	5.77	16	26	21	78	14	3.2	0.53
Louisiana	May	5.75	20	29	25	80	18	3.2	0.54
Louisiana	June	5.37	23	32	28	82	22	2.5	0.55
Louisiana	July	5.21	24	33	28	81	22	1.9	0.54
Louisiana	August	5.58	24	33	28	78	22	2.5	0.55
Louisiana	September	5.7	22	31	26	78	19	2.3	0.53
Louisiana	October	6.19	17	27	22	75	15	2.6	0.59
Louisiana	November	5.37	12	22	17	67	10	2.3	0.52
Louisiana	December	4.43	8	18	13	80	9	2.9	0.48
Louisiana	Year-round	5.41	16	26	21	76	15	2.8	0.53
Louisiana	Spring	5.70	16	26	21	79	14	3.3	0.53
Louisiana	Summer	5.39	24	32	28	80	22	2.3	0.54
Louisiana	Fall	5.75	17	26	22	73	15	2.4	0.55
Louisiana	Winter	4.81	8	18	13	73	8	3.2	0.48
Maine	January	3.64	-12	-2	-7	75	2	3.2	0.54
Maine	February	4.79	-9	0	-5	77	3	3.4	0.58
Maine	March	5.66	-5	4	0	69	3	3.6	0.57
Maine	April	5.62	2	11	6	74	6	3.2	0.54
Maine	May	5.27	7	18	13	71	8	2.8	0.50
Maine	June	5.35	12	23	18	73	11	2.5	0.51
Maine	July	5.95	16	26	21	80	15	2.2	0.52
Maine	August	5.6	14	26	20	75	13	2.2	0.52
Maine	September	5.5	11	21	16	76	10	2.5	0.51
Maine	October	4.12	4	14	9	81	7	2.4	0.50
Maine	November	3.38	-1	7	3	72	4	2.6	0.46
Maine	December	2.96	-7	1	-3	78	3	2.6	0.49
Maine	Year-round	4.82	3	12	8	75	7	2.8	0.52
Maine	Spring	5.52	1	11	6	71	6	3.2	0.53

Maine	Summer	5.63	14	25	20	76	13	2.3	0.52
Maine	Fall	4.33	5	14	9	76	7	2.5	0.49
Maine	Winter	3.80	-9	-1	-5	77	3	3.1	0.54
Maryland	January	3.91	-2	6	2	69	4	5.3	0.47
Maryland	February	4.73	-1	8	4	69	4	4.7	0.52
Maryland	March	5.03	4	12	8	66	5	4.5	0.51
Maryland	April	5.49	9	18	14	71	8	4.1	0.51
Maryland	May	5.51	14	24	19	71	11	3.9	0.50
Maryland	June	5.61	19	29	24	77	17	3.6	0.54
Maryland	July	5.77	23	32	27	72	19	3.0	0.54
Maryland	August	5.57	22	31	26	73	18	3.0	0.52
Maryland	September	5.32	18	27	22	70	14	4.1	0.51
Maryland	October	4.98	11	20	16	72	10	4.1	0.55
Maryland	November	4.11	6	14	10	62	6	4.5	0.48
Maryland	December	3.64	1	8	4	69	4	4.0	0.43
Maryland	Year-round	4.97	10	19	15	70	10	4.1	0.51
Maryland	Spring	5.34	9	18	14	69	8	4.2	0.51
Maryland	Summer	5.65	21	31	26	74	18	3.2	0.53
Maryland	Fall	4.80	12	20	16	68	10	4.2	0.51
Maryland	Winter	4.09	-1	7	3	69	4	4.7	0.47
Massachusetts	January	3.92	-6	2	-2	62	3	4.5	0.48
Massachusetts	February	4.66	-4	4	0	74	4	4.2	0.54
Massachusetts	March	5.01	-1	7	3	56	3	4.5	0.52
Massachusetts	April	5.42	5	13	9	66	6	3.7	0.49
Massachusetts	May	5.54	10	19	14	65	8	3.6	0.51
Massachusetts	June	5.64	16	24	20	66	11	3.4	0.52
Massachusetts	July	6.01	18	27	23	80	16	2.8	0.54
Massachusetts	August	5.77	18	27	23	69	14	2.9	0.54
Massachusetts	September	5.51	14	22	18	73	11	3.1	0.53
Massachusetts	October	4.56	8	16	12	75	8	3.4	0.53
Massachusetts	November	3.57	3	11	7	60	5	3.7	0.47
Massachusetts	December	3.28	-2	5	1	68	4	3.6	0.46
Massachusetts	Year-round	4.91	7	15	11	68	8	3.6	0.51
Massachusetts	Spring	5.32	5	13	9	62	6	3.9	0.51
Massachusetts	Summer	5.81	17	26	22	72	14	3.0	0.53
Massachusetts	Fall	4.55	9	16	12	69	8	3.4	0.51
Massachusetts	Winter	3.95	-4	4	0	68	3	4.1	0.49
Minnesota	January	3.67	-14	-3	-9	90	2	3.5	0.53
Minnesota	February	4.48	-11	-1	-6	86	3	4.1	0.58
Minnesota	March	5.43	-4	6	1	70	4	3.8	0.57
Minnesota	April	5.62	3	14	9	68	6	3.5	0.51

Minnesota	May	5.62	10	22	16	68	9	3.3	0.52
Minnesota	June	5.73	15	27	21	65	12	3.2	0.54
Minnesota	July	6.28	18	29	24	61	13	3.1	0.55
Minnesota	August	5.98	17	28	22	55	11	3.7	0.54
Minnesota	September	5.41	12	23	17	60	9	3.5	0.51
Minnesota	October	4.11	5	15	10	62	6	3.4	0.50
Minnesota	November	3.55	-3	6	1	62	3	3.7	0.46
Minnesota	December	2.99	-11	-2	-6	77	2	3.7	0.47
Minnesota	Year-round	4.91	3	14	8	69	7	3.5	0.52
Minnesota	Spring	5.56	3	14	9	69	6	3.5	0.53
Minnesota	Summer	6.00	16	28	22	60	12	3.3	0.54
Minnesota	Fall	4.36	5	14	10	61	6	3.5	0.49
Minnesota	Winter	3.71	-12	-2	-7	84	3	3.8	0.53
Mississippi	January	4.58	2	13	8	70	6	3.3	0.46
Mississippi	February	4.71	3	16	9	73	7	3.5	0.53
Mississippi	March	5.42	7	21	14	78	9	3.4	0.52
Mississippi	April	5.68	11	24	18	75	11	3.0	0.55
Mississippi	May	5.62	17	28	23	77	15	2.9	0.56
Mississippi	June	5.61	21	32	26	80	20	2.5	0.56
Mississippi	July	5.47	22	33	28	78	21	2.0	0.55
Mississippi	August	5.87	22	33	28	74	20	2.3	0.54
Mississippi	September	5.96	18	31	24	74	17	2.3	0.53
Mississippi	October	6.15	12	25	18	71	11	2.6	0.58
Mississippi	November	5.09	7	19	13	65	7	2.5	0.52
Mississippi	December	4.15	3	14	9	80	7	3.2	0.49
Mississippi	Year-round	5.36	12	24	18	75	13	2.8	0.53
Mississippi	Spring	5.57	12	24	18	77	12	3.1	0.54
Mississippi	Summer	5.65	21	33	27	77	20	2.3	0.55
Mississippi	Fall	5.73	12	25	19	70	12	2.5	0.54
Mississippi	Winter	4.48	3	14	9	74	6	3.3	0.49
Missouri	January	3.97	-6	4	-1	69	3	3.9	0.50
Missouri	February	4.43	-4	7	2	76	4	4.2	0.52
Missouri	March	4.98	1	13	7	75	6	4.5	0.53
Missouri	April	5.38	7	19	13	77	9	4.1	0.54
Missouri	May	5.47	12	24	18	82	13	3.5	0.54
Missouri	June	5.9	18	28	23	80	16	2.8	0.57
Missouri	July	5.98	20	31	26	81	19	2.5	0.57
Missouri	August	5.85	19	31	25	70	16	3.1	0.57
Missouri	September	5.92	14	27	20	59	10	3.6	0.55
Missouri	October	5.13	7	21	14	73	9	3.8	0.56
Missouri	November	4.21	2	13	8	61	5	3.7	0.49

Missouri	December	3.48	-4	6	1	64	3	4.2	0.46
Missouri	Year-round	5.06	7	19	13	72	9	3.7	0.53
Missouri	Spring	5.28	6	19	13	78	9	4.0	0.54
Missouri	Summer	5.91	19	30	25	77	17	2.8	0.57
Missouri	Fall	5.09	8	20	14	64	8	3.7	0.53
Missouri	Winter	3.96	-5	6	1	70	4	4.1	0.49
Montana	January	2.4	-11	1	-5	82	3	1.8	0.49
Montana	February	3.82	-8	4	-2	73	3	2.5	0.52
Montana	March	5.08	-4	9	2	64	4	2.4	0.54
Montana	April	5.99	0	14	7	62	5	2.9	0.51
Montana	May	5.51	5	19	12	63	7	2.4	0.54
Montana	June	6.06	9	24	17	45	6	2.6	0.57
Montana	July	6.82	12	30	21	35	6	2.3	0.63
Montana	August	6.57	11	29	20	45	8	2.4	0.61
Montana	September	5.82	6	23	14	37	5	2.5	0.58
Montana	October	4.41	1	15	8	57	5	2.5	0.55
Montana	November	3.36	-6	6	0	56	3	2.5	0.49
Montana	December	2.32	-11	0	-6	76	2	2.3	0.46
Montana	Year-round	4.85	0	15	7	58	5	2.4	0.54
Montana	Spring	5.53	0	14	7	63	5	2.6	0.53
Montana	Summer	6.48	11	28	19	42	7	2.4	0.60
Montana	Fall	4.53	0	15	8	50	4	2.5	0.54
Montana	Winter	2.85	-10	1	-4	77	3	2.2	0.49
Nebraska	January	3.84	-11	0	-6	61	2	4.7	0.55
Nebraska	February	4.9	-8	3	-3	50	2	5.2	0.55
Nebraska	March	5.14	-2	10	4	74	5	5.0	0.56
Nebraska	April	5.49	4	17	11	69	7	5.0	0.55
Nebraska	May	5.63	10	23	16	79	11	4.7	0.56
Nebraska	June	6.05	16	29	23	70	14	4.2	0.60
Nebraska	July	5.95	19	31	25	66	15	4.2	0.60
Nebraska	August	5.92	18	30	24	53	11	5.1	0.59
Nebraska	September	6.07	12	25	19	52	8	4.5	0.58
Nebraska	October	4.87	5	18	11	56	6	4.6	0.59
Nebraska	November	4.24	-2	9	3	56	3	4.4	0.53
Nebraska	December	3.53	-9	2	-3	52	2	4.8	0.52
Nebraska	Year-round	5.14	4	16	10	62	7	4.7	0.57
Nebraska	Spring	5.42	4	17	10	74	7	4.9	0.56
Nebraska	Summer	5.97	18	30	24	63	14	4.5	0.60
Nebraska	Fall	5.06	5	17	11	55	6	4.5	0.57
Nebraska	Winter	4.09	-9	2	-4	54	2	4.9	0.54
Nevada	January	5.51	-6	7	1	57	3	1.7	0.56

Nevada	February	5.91	-4	10	3	49	3	1.9	0.57
Nevada	March	7.02	-1	14	6	50	4	2.7	0.60
Nevada	April	7.17	1	17	9	37	3	3.3	0.61
Nevada	May	7.22	5	22	13	37	4	3.3	0.62
Nevada	June	7.18	8	27	18	28	4	3.6	0.66
Nevada	July	6.52	11	32	22	29	6	3.2	0.68
Nevada	August	7	11	31	21	27	5	3.5	0.68
Nevada	September	7.41	6	27	16	29	4	3.3	0.70
Nevada	October	6.94	2	20	11	51	5	2.6	0.67
Nevada	November	5.87	-3	12	5	51	3	2.0	0.59
Nevada	December	5.12	-6	7	1	72	4	3.1	0.56
Nevada	Year-round	6.57	2	19	10	43	4	2.9	0.63
Nevada	Spring	7.14	2	18	10	41	4	3.1	0.61
Nevada	Summer	6.90	10	30	20	28	5	3.4	0.67
Nevada	Fall	6.74	2	20	11	44	4	2.6	0.65
Nevada	Winter	5.51	-5	8	2	59	3	2.2	0.56
New Hampshire	January	3.72	-12	-1	-6	74	2	3.3	0.53
New Hampshire	February	4.69	-10	2	-4	78	3	3.2	0.55
New Hampshire	March	4.97	-6	7	1	67	3	3.6	0.53
New Hampshire	April	5.41	1	14	7	74	6	3.1	0.52
New Hampshire	May	5.35	6	21	13	69	8	2.8	0.52
New Hampshire	June	5.35	12	25	18	69	11	2.4	0.53
New Hampshire	July	5.79	14	28	21	81	15	2.0	0.53
New Hampshire	August	5.81	13	27	20	74	13	1.9	0.54
New Hampshire	September	5.35	8	23	16	78	10	2.2	0.52
New Hampshire	October	4.21	2	16	9	81	7	2.3	0.49
New Hampshire	November	3.62	-2	9	3	70	4	2.8	0.47
New Hampshire	December	3.26	-8	2	-3	80	3	2.7	0.47
New Hampshire	Year-round	4.79	2	14	8	75	7	2.7	0.52
New Hampshire	Spring	5.24	0	14	7	70	6	3.2	0.52

New Hampshire	Summer	5.65	13	27	20	75	13	2.1	0.53
New Hampshire	Fall	4.39	3	16	9	76	7	2.4	0.49
New Hampshire	Winter	3.89	-10	1	-5	77	3	3.1	0.52
New Jersey	January	3.5	-4	4	0	66	3	3.8	0.48
New Jersey	February	4.48	-3	6	1	66	4	3.8	0.50
New Jersey	March	5.21	1	11	6	58	4	3.7	0.50
New Jersey	April	5.39	7	17	12	66	7	3.7	0.50
New Jersey	May	5.44	12	22	17	66	10	3.2	0.52
New Jersey	June	5.76	17	82	50	68	56	3.1	0.52
New Jersey	July	5.92	21	30	25	72	17	2.4	0.52
New Jersey	August	5.7	19	29	24	71	16	2.3	0.52
New Jersey	September	5.62	16	25	20	73	13	3.0	0.53
New Jersey	October	4.67	9	18	14	72	8	3.1	0.53
New Jersey	November	3.89	4	13	8	61	5	3.3	0.47
New Jersey	December	3.29	-1	7	3	67	4	3.1	0.45
New Jersey	Year-round	4.91	8	22	15	67	12	3.2	0.50
New Jersey	Spring	5.35	6	16	11	63	7	3.5	0.50
New Jersey	Summer	5.79	19	47	33	70	29	2.6	0.52
New Jersey	Fall	4.73	9	19	14	69	9	3.1	0.51
New Jersey	Winter	3.76	-3	5	1	66	4	3.6	0.47
New Mexico	January	5.78	-8	7	-1	44	2	2.6	0.62
New Mexico	February	6.19	-6	9	2	42	2	3.2	0.63
New Mexico	March	6.65	-3	13	5	36	2	4.7	0.64
New Mexico	April	6.99	0	18	9	27	2	4.4	0.67
New Mexico	May	6.86	5	23	14	27	3	4.1	0.67
New Mexico	June	6.83	9	28	19	32	5	3.4	0.69
New Mexico	July	6.48	12	30	21	46	8	2.9	0.67
New Mexico	August	6.66	12	28	20	41	7	2.8	0.65
New Mexico	September	6.95	14	26	20	34	6	2.8	0.64
New Mexico	October	6.63	2	19	11	31	3	3.6	0.67
New Mexico	November	6.18	-4	12	4	35	2	2.3	0.64
New Mexico	December	5.49	-8	6	-1	43	2	3.2	0.62
New Mexico	Year-round	6.47	2	18	10	37	4	3.3	0.65
New Mexico	Spring	6.83	1	18	9	30	3	4.4	0.66
New Mexico	Summer	6.66	11	29	20	40	7	3.0	0.67
New Mexico	Fall	6.59	4	19	11	33	4	2.9	0.65
New Mexico	Winter	5.82	-7	7	0	43	2	3.0	0.62
New York	January	3.53	-3	4	0	72	4	3.4	0.45
New York	February	4.53	-2	6	2	75	4	3.4	0.50

New York	March	4.85	2	10	6	63	5	3.8	0.49
New York	April	5.33	7	16	11	72	7	2.7	0.50
New York	May	5.03	13	22	17	71	10	2.6	0.51
New York	June	5.4	18	26	22	72	14	2.6	0.52
New York	July	5.68	21	29	25	82	19	1.9	0.53
New York	August	5.69	21	28	24	76	17	1.8	0.53
New York	September	5.38	16	24	20	77	14	2.4	0.50
New York	October	4.59	10	18	14	78	10	2.2	0.48
New York	November	3.68	5	12	9	70	6	2.6	0.40
New York	December	2.99	0	7	3	75	5	2.9	0.42
New York	Year-round	4.72	9	17	13	74	9	2.7	0.49
New York	Spring	5.07	7	16	11	69	7	3.0	0.50
New York	Summer	5.59	20	28	24	77	17	2.1	0.53
New York	Fall	4.55	10	18	14	75	10	2.4	0.46
New York	Winter	3.68	-2	5	2	74	4	3.2	0.46
North Carolina	January	4.53	-1	11	5	69	5	3.7	0.51
North Carolina	February	4.82	1	13	7	69	5	3.6	0.51
North Carolina	March	5.47	4	17	11	65	6	3.6	0.55
North Carolina	April	5.7	8	22	15	61	8	3.6	0.56
North Carolina	May	5.74	13	26	20	64	11	3.3	0.54
North Carolina	June	5.92	18	30	24	73	16	3.2	0.55
North Carolina	July	5.71	20	32	26	71	17	3.1	0.53
North Carolina	August	5.43	19	31	25	72	17	2.5	0.54
North Carolina	September	5.22	16	27	21	63	12	3.0	0.53
North Carolina	October	5.61	9	22	16	67	9	3.3	0.56
North Carolina	November	4.89	4	17	10	55	5	3.5	0.53
North Carolina	December	4.09	0	12	6	68	5	3.5	0.49
North Carolina	Year-round	5.26	9	22	15	66	10	3.3	0.53
North Carolina	Spring	5.64	9	22	15	63	8	3.5	0.55
North Carolina	Summer	5.69	19	31	25	72	17	2.9	0.54

North Carolina	Fall	5.24	10	22	16	62	9	3.3	0.54
North Carolina	Winter	4.48	0	12	6	69	5	3.6	0.50
North Dakota	January	2.98	-17	-5	-11	90	2	3.6	0.55
North Dakota	February	3.74	-13	-2	-8	77	2	4.6	0.60
North Dakota	March	4.92	-7	4	-1	59	3	4.3	0.56
North Dakota	April	4.8	-1	14	7	57	4	4.0	0.54
North Dakota	May	5.67	6	20	13	63	7	4.2	0.55
North Dakota	June	5.75	11	25	18	53	8	4.0	0.56
North Dakota	July	6.41	14	29	22	45	9	3.6	0.58
North Dakota	August	6.18	13	28	21	43	8	4.3	0.58
North Dakota	September	5.55	7	22	15	42	5	3.9	0.56
North Dakota	October	3.89	0	14	7	58	5	4.4	0.54
North Dakota	November	3.09	-7	4	-1	62	3	4.0	0.49
North Dakota	December	2.74	-14	-3	-9	81	2	3.5	0.50
North Dakota	Year-round	4.64	-1	13	6	61	5	4.0	0.55
North Dakota	Spring	5.13	-1	13	6	60	5	4.2	0.55
North Dakota	Summer	6.11	13	28	20	47	8	4.0	0.57
North Dakota	Fall	4.18	0	14	7	54	4	4.1	0.53
North Dakota	Winter	3.15	-15	-4	-9	83	2	3.9	0.55
Ohio	January	3.17	-7	2	-2	70	3	3.6	0.41
Ohio	February	4.12	-4	4	0	77	4	3.8	0.45
Ohio	March	4.3	0	11	6	62	4	3.8	0.46
Ohio	April	5.24	5	17	11	68	7	3.8	0.49
Ohio	May	5.45	11	23	17	71	10	3.0	0.51
Ohio	June	5.67	16	28	22	74	14	2.9	0.53
Ohio	July	5.74	29	29	29	74	22	2.6	0.53
Ohio	August	5.8	29	29	29	75	21	2.2	0.53
Ohio	September	5.58	25	25	25	69	16	3.0	0.52
Ohio	October	4.32	18	18	18	73	11	3.1	0.50
Ohio	November	3.62	11	11	11	60	6	3.4	0.40
Ohio	December	2.76	5	5	5	71	5	3.4	0.38
Ohio	Year-round	4.6475	12	17	14	70	10	3.2	0.48
Ohio	Spring	5.00	5	17	11	67	7	3.5	0.49
Ohio	Summer	5.74	25	29	27	74	19	2.6	0.53
Ohio	Fall	4.51	18	18	18	67	11	3.2	0.47
Ohio	Winter	3.35	-2	4	1	73	4	3.6	0.41
Oklahoma	January	4.85	-2	10	4	48	3	5.1	0.53
Oklahoma	February	5.46	1	13	7	60	5	6.1	0.54
Oklahoma	March	5.51	5	17	11	65	7	6.6	0.56

Oklahoma	April	5.99	10	22	16	65	9	6.2	0.58
Oklahoma	May	5.45	16	27	21	82	15	5.8	0.55
Oklahoma	June	5.98	20	31	26	74	18	5.0	0.57
Oklahoma	July	6.25	22	34	28	65	18	4.5	0.60
Oklahoma	August	6.43	22	34	28	56	15	5.2	0.60
Oklahoma	September	6.21	17	29	23	44	9	5.4	0.55
Oklahoma	October	5.69	11	23	17	51	7	5.9	0.60
Oklahoma	November	5.10	4	17	11	54	5	5.6	0.53
Oklahoma	December	4.51	-1	11	5	46	3	5.7	0.53
Oklahoma	Year-round	5.62	10	22	16	59	9	5.6	0.56
Oklahoma	Spring	5.65	10	22	16	71	10	6.2	0.56
Oklahoma	Summer	6.22	21	33	27	65	17	4.9	0.59
Oklahoma	Fall	5.67	11	23	17	50	7	5.6	0.56
Oklahoma	Winter	4.94	-1	11	5	51	4	5.6	0.53
Oregon	January	1.85	2	9	5	88	6	2.0	0.41
Oregon	February	3.38	2	11	6	83	6	1.9	0.44
Oregon	March	3.63	3	13	8	83	7	2.2	0.49
Oregon	April	4.64	4	13	9	73	6	1.9	0.50
Oregon	May	5.2	7	16	12	73	8	2.1	0.54
Oregon	June	5.49	9	20	15	67	8	2.1	0.56
Oregon	July	6.47	12	23	18	57	8	2.3	0.62
Oregon	August	6.35	12	28	20	57	10	2.2	0.61
Oregon	September	5.59	9	28	18	63	10	2.2	0.59
Oregon	October	3.64	6	25	15	77	10	2.4	0.53
Oregon	November	2.35	3	18	11	87	8	2.5	0.42
Oregon	December	1.85	1	12	6	90	7	3.0	0.40
Oregon	Year-round	4.20	6	8	12	75	8	2.2	0.51
Oregon	Spring	4.49	5	14	10	76	7	2.1	0.51
Oregon	Summer	6.10	11	24	17	60	9	2.2	0.60
Oregon	Fall	3.86	6	24	15	76	9	2.4	0.52
Oregon	Winter	2.36	1	11	6	87	6	2.3	0.41
Pennsylvania	January	4.02	-3	4	1	75	4	3.6	0.44
Pennsylvania	February	4.81	-2	7	2	73	4	3.7	0.48
Pennsylvania	March	4.94	1	12	6	66	5	3.6	0.48
Pennsylvania	April	5.57	7	18	12	73	8	3.5	0.50
Pennsylvania	May	5.29	12	23	18	75	11	2.8	0.51
Pennsylvania	June	5.59	18	28	23	78	16	2.3	0.52
Pennsylvania	July	5.75	21	31	26	77	18	2.0	0.53
Pennsylvania	August	5.59	20	29	25	76	17	1.7	0.52
Pennsylvania	September	5.43	16	26	21	78	14	2.5	0.51
Pennsylvania	October	4.62	9	19	14	81	10	2.6	0.50

Pennsylvania	November	4.16	4	13	9	69	6	3.0	0.42
Pennsylvania	December	3.44	-1	7	3	75	4	2.9	0.41
Pennsylvania	Year-round	4.93	8	18	13	75	10	2.9	0.48
Pennsylvania	Spring	5.27	7	18	12	71	8	3.3	0.50
Pennsylvania	Summer	5.64	19	29	24	77	17	2.0	0.52
Pennsylvania	Fall	4.74	9	19	14	76	10	2.7	0.47
Pennsylvania	Winter	4.09	-2	6	2	74	4	3.4	0.44
Rhode Island	January	3.81	-6	3	-2	65	3	4.0	0.48
Rhode Island	February	4.54	-4	4	0	77	4	3.8	0.52
Rhode Island	March	5.09	-1	9	4	60	4	3.9	0.52
Rhode Island	April	5.55	4	15	10	70	6	3.6	0.52
Rhode Island	May	5.38	9	20	15	69	9	3.3	0.51
Rhode Island	June	5.78	14	26	20	71	12	3.3	0.53
Rhode Island	July	5.84	18	28	23	79	16	2.6	0.56
Rhode Island	August	5.68	17	27	22	73	14	2.6	0.55
Rhode Island	September	5.72	13	23	18	76	12	3.0	0.50
Rhode Island	October	4.6	7	17	12	77	8	3.1	0.52
Rhode Island	November	3.79	2	12	7	65	5	3.2	0.47
Rhode Island	December	3.33	-3	6	1	72	4	3.3	0.45
Rhode Island	Year-round	4.93	6	16	11	71	8	3.3	0.51
Rhode Island	Spring	5.34	4	15	9	66	6	3.6	0.52
Rhode Island	Summer	5.77	16	27	22	74	14	2.8	0.55
Rhode Island	Fall	4.70	7	17	12	73	8	3.1	0.50
Rhode Island	Winter	3.89	-5	4	0	71	3	3.7	0.48
South Carolina	January	4.86	3	15	9	64	6	3.4	0.50
South Carolina	February	5.12	5	17	11	64	6	3.1	0.52
South Carolina	March	5.54	8	21	15	64	8	3.2	0.54
South Carolina	April	6.19	12	24	18	59	9	3.1	0.58
South Carolina	May	5.9	17	28	23	58	12	2.9	0.54
South Carolina	June	5.59	21	31	26	68	17	2.9	0.54
South Carolina	July	5.58	23	33	28	65	17	2.7	0.55
South Carolina	August	5.52	22	32	27	68	17	2.3	0.53
South Carolina	September	5.45	19	29	24	62	14	2.4	0.53

South Carolina	October	5.58	14	25	19	61	10	2.6	0.59
South Carolina	November	5.13	8	21	15	50	6	2.9	0.54
South Carolina	December	4.47	4	17	11	66	6	3.0	0.49
South Carolina	Year-round	5.41	13	24	19	62	11	2.9	0.54
South Carolina	Spring	5.88	12	25	18	60	10	3.1	0.56
South Carolina	Summer	5.56	22	32	27	67	17	2.6	0.54
South Carolina	Fall	5.39	14	25	20	58	10	2.6	0.55
South Carolina	Winter	4.82	4	16	10	65	6	3.2	0.50
South Dakota	January	3.44	-18	-6	-12	70	1	4.4	0.54
South Dakota	February	4.22	-15	-3	-9	63	2	5.0	0.55
South Dakota	March	5.35	-7	4	-2	62	3	5.1	0.55
South Dakota	April	5.68	0	14	7	55	4	5.0	0.55
South Dakota	May	5.87	7	21	14	66	8	4.8	0.55
South Dakota	June	5.93	13	26	19	49	8	4.3	0.58
South Dakota	July	6.35	16	29	22	48	9	4.4	0.61
South Dakota	August	6.02	14	28	21	40	7	4.9	0.60
South Dakota	September	5.73	8	22	15	44	6	4.6	0.58
South Dakota	October	4.77	1	14	8	53	4	5.2	0.58
South Dakota	November	4	-7	4	-2	50	2	4.8	0.52
South Dakota	December	3.14	-15	-4	-9	66	2	4.7	0.49
South Dakota	Year-round	5.04	0	12	6	56	5	4.8	0.56
South Dakota	Spring	5.63	0	13	6	61	5	5.0	0.55
South Dakota	Summer	6.10	14	27	21	46	8	4.5	0.59
South Dakota	Fall	4.83	0	14	7	49	4	4.9	0.56
South Dakota	Winter	3.60	-16	-4	-10	66	2	4.7	0.53
Tennessee	January	4.2	1	10	5	71	5	3.3	0.46
Tennessee	February	4.43	2	13	8	70	6	3.5	0.49
Tennessee	March	5.41	7	18	12	68	7	3.4	0.52
Tennessee	April	5.46	12	23	17	72	11	2.9	0.54
Tennessee	May	5.75	17	27	22	72	14	2.8	0.53
Tennessee	June	5.82	21	32	26	75	19	2.5	0.55
Tennessee	July	5.94	23	33	28	74	21	2.2	0.54
Tennessee	August	6.01	23	33	28	72	19	1.9	0.55
Tennessee	September	5.99	18	29	24	74	16	2.2	0.52
Tennessee	October	5.33	12	23	18	76	12	2.7	0.57

Tennessee	November	4.58	7	17	12	61	6	2.9	0.48
Tennessee	December	3.75	2	11	6	75	6	3.5	0.46
Tennessee	Year-round	5.22	12	22	17	72	12	2.8	0.52
Tennessee	Spring	5.54	12	23	17	71	11	3.0	0.53
Tennessee	Summer	5.92	22	33	28	74	20	2.2	0.55
Tennessee	Fall	5.30	12	23	18	70	11	2.6	0.52
Tennessee	Winter	4.13	1	11	6	72	5	3.4	0.47
Texas	January	4.29	6	17	11	50	5	3.7	0.55
Texas	February	4.93	7	18	13	66	7	3.9	0.56
Texas	March	5.24	11	22	16	62	9	4.5	0.56
Texas	April	5.54	15	27	21	66	12	4.3	0.57
Texas	May	5.37	19	31	25	82	19	4.0	0.60
Texas	June	5.45	22	33	28	73	20	3.5	0.60
Texas	July	5.43	23	36	29	68	20	3.3	0.59
Texas	August	5.67	24	36	30	60	18	3.5	0.58
Texas	September	5.93	21	33	27	53	13	3.2	0.61
Texas	October	5.85	16	28	22	58	11	3.6	0.56
Texas	November	5.01	11	22	16	63	9	3.6	0.52
Texas	December	4.56	6	17	11	72	7	3.6	
Texas	Year-round	5.27	15	27	21	64	13	3.7	0.57
Texas	Spring	5.38	15	26	21	70	13	4.3	0.57
Texas	Summer	5.52	23	35	29	67	19	3.4	0.59
Texas	Fall	5.60	16	27	22	58	11	3.5	0.56
Texas	Winter	4.59	6	17	12	63	7	3.7	0.55
Utah	January	3.56	-3	3	0	67	3	1.6	0.54
Utah	February	4.63	-1	7	3	55	3	2.0	0.57
Utah	March	5.72	3	12	8	55	4	2.4	0.57
Utah	April	5.96	6	16	11	44	4	2.4	0.59
Utah	May	6.43	11	22	16	43	6	2.5	0.63
Utah	June	6.69	16	28	22	27	5	3.2	0.66
Utah	July	6.72	21	32	26	31	8	2.9	0.66
Utah	August	6.74	19	32	26	28	7	3.0	0.66
Utah	September	6.46	14	26	20	28	5	2.9	0.65
Utah	October	5.47	8	18	13	52	6	2.8	0.65
Utah	November	4.37	2	10	6	51	4	1.8	0.57
Utah	December	3.35	-3	4	1	73	4	3.0	0.51
Utah	Year-round	5.51	8	17	13	46	5	2.5	0.60
Utah	Spring	6.04	7	16	12	47	5	2.4	0.60
Utah	Summer	6.72	19	31	25	29	7	3.0	0.66
Utah	Fall	5.43	8	18	13	44	5	2.5	0.62
Utah	Winter	3.85	-2	5	1	65	3	2.2	0.54

Vermont	January	3.01	-12	-3	-8	86	2	2.4	0.50
Vermont	February	4.29	-11	-1	-6	84	3	2.7	0.54
Vermont	March	4.95	-6	4	-1	78	4	2.9	0.52
Vermont	April	5.49	2	13	7	83	7	2.3	0.51
Vermont	May	5.46	7	19	13	76	9	2.1	0.53
Vermont	June	5.57	13	24	19	74	12	2.2	0.52
Vermont	July	5.86	16	27	21	82	15	1.7	0.53
Vermont	August	5.73	14	26	20	77	14	1.8	0.54
Vermont	September	5.27	11	21	16	79	11	2.2	0.51
Vermont	October	3.79	4	14	9	86	8	1.7	0.48
Vermont	November	2.85	-1	8	4	79	5	2.3	0.42
Vermont	December	2.3	-7	1	-3	83	3	2.5	0.42
Vermont	Year-round	4.55	3	13	8	81	8	2.2	0.50
Vermont	Spring	5.30	1	12	7	79	6	2.4	0.52
Vermont	Summer	5.72	14	26	20	78	14	1.9	0.53
Vermont	Fall	3.97	5	14	9	81	8	2.1	0.47
Vermont	Winter	3.20	-10	-1	-5	84	3	2.5	0.49
Virginia	January	3.97	-2	8	3	69	4	3.2	0.50
Virginia	February	4.8	-1	11	5	67	5	3.1	0.52
Virginia	March	5.4	3	16	9	61	5	2.9	0.52
Virginia	April	5.72	8	21	14	62	8	3.1	0.53
Virginia	May	5.63	13	26	19	64	11	2.7	0.52
Virginia	June	5.77	18	30	24	69	15	2.6	0.54
Virginia	July	5.72	21	32	26	67	17	2.4	0.54
Virginia	August	5.66	19	31	25	73	17	2.0	0.53
Virginia	September	5.51	16	27	21	67	13	2.4	0.53
Virginia	October	5.38	9	22	15	68	9	2.6	0.54
Virginia	November	4.67	4	16	10	56	5	2.8	0.51
Virginia	December	3.95	-1	11	5	64	4	2.8	0.47
Virginia	Year-round	5.18	9	21	15	66	9	2.7	0.52
Virginia	Spring	5.58	8	21	14	62	8	2.9	0.52
Virginia	Summer	5.72	19	31	25	70	16	2.3	0.54
Virginia	Fall	5.19	9	22	16	64	9	2.6	0.53
Virginia	Winter	4.24	-1	10	4	67	4	3.0	0.50
Washington	January	1.9	3	8	6	90	6	2.0	0.37
Washington	February	3	3	10	6	83	6	1.7	0.41
Washington	March	3.65	4	12	8	81	7	2.0	0.45
Washington	April	5.13	6	14	10	71	7	2.0	0.46
Washington	May	5.17	8	18	13	72	8	2.1	0.51
Washington	June	5.72	11	21	16	68	9	2.0	0.52
Washington	July	6.22	13	24	19	65	11	1.9	0.58

Washington	August	6.08	13	24	19	67	11	2.0	0.56
Washington	September	5.15	11	22	16	73	10	1.8	0.54
Washington	October	3.32	8	16	12	81	8	2.0	0.49
Washington	November	2.33	4	11	8	90	7	2.4	0.38
Washington	December	1.78	2	8	5	92	6	2.4	0.37
Washington	Year-round	4.12	7	16	11	78	8	2.0	0.47
Washington	Spring	4.65	6	15	10	75	7	2.0	0.48
Washington	Summer	6.01	13	23	18	67	10	2.0	0.55
Washington	Fall	3.60	8	16	12	81	9	2.1	0.47
Washington	Winter	2.23	3	9	6	88	6	2.0	0.39
West Virginia	January	3.04	-3	6	1	83	4	2.4	0.45
West Virginia	February	3.86	-2	8	3	78	5	2.6	0.45
West Virginia	March	4.44	2	13	8	69	6	2.5	0.47
West Virginia	April	5.2	7	20	13	73	8	2.7	0.49
West Virginia	May	5.44	12	24	18	74	11	2.1	0.50
West Virginia	June	5.47	17	28	22	74	15	1.9	0.50
West Virginia	July	5.6	19	29	24	74	16	1.7	0.51
West Virginia	August	5.67	18	29	24	74	16	1.4	0.51
West Virginia	September	5.37	14	26	20	72	12	2.0	0.50
West Virginia	October	4.33	7	20	14	79	9	2.1	0.51
West Virginia	November	3.54	3	14	8	66	6	2.3	0.45
West Virginia	December	2.8	-2	8	3	76	5	2.6	0.40
West Virginia	Year-round	4.56	8	19	13	74	9	2.2	0.48
West Virginia	Spring	5.03	7	19	13	72	8	2.4	0.49
West Virginia	Summer	5.58	18	29	23	74	16	1.7	0.51
West Virginia	Fall	4.41	8	20	14	72	9	2.1	0.49
West Virginia	Winter	3.23	-2	7	3	79	5	2.5	0.43
Wisconsin	January	3.19	-9	-2	-5	89	3	4.6	0.51
Wisconsin	February	4.06	-7	1	-3	83	3	5.3	0.54
Wisconsin	March	5.08	-2	6	2	76	4	4.9	0.52
Wisconsin	April	5.09	3	12	8	75	6	4.5	0.50
Wisconsin	May	5.48	8	18	13	79	9	4.2	0.54
Wisconsin	June	5.76	14	24	19	80	13	3.6	0.54
Wisconsin	July	6.18	18	27	22	83	16	3.5	0.55
Wisconsin	August	5.75	17	26	21	77	14	3.7	0.54
Wisconsin	September	5.5	13	22	17	66	10	4.1	0.51
Wisconsin	October	4.16	6	15	11	74	7	4.1	0.51
Wisconsin	November	3.52	0	8	4	65	4	4.5	0.43
Wisconsin	December	3.07	-7	1	-3	72	3	4.6	0.45
Wisconsin	Year-round	4.74	4	13	9	77	8	4.3	0.51
Wisconsin	Spring	5.22	3	12	8	77	6	4.5	0.52

Wisconsin	Summer	5.90	16	25	21	80	15	3.6	0.54
Wisconsin	Fall	4.39	6	15	11	68	7	4.2	0.48
Wisconsin	Winter	3.44	-8	0	-4	81	3	4.8	0.50
Wyoming	January	4.49	-8	4	-2	54	2	7.2	0.55
Wyoming	February	5.29	-7	4	-1	56	2	6.6	0.57
Wyoming	March	6.18	-4	8	2	62	3	5.1	0.58
Wyoming	April	6.1	-1	13	6	56	4	5.7	0.58
Wyoming	May	6.18	4	18	11	65	7	4.8	0.57
Wyoming	June	6.51	9	24	17	46	7	4.7	0.61
Wyoming	July	6.35	13	28	21	47	9	4.2	0.61
Wyoming	August	6.27	12	27	20	34	6	4.4	0.63
Wyoming	September	6.45	7	22	15	31	4	4.6	0.63
Wyoming	October	5.55	1	15	8	41	3	5.9	0.61
Wyoming	November	4.79	-4	8	2	39	2	6.6	0.56
Wyoming	December	4.35	-8	3	-3	42	2	7.2	0.53
Wyoming	Year-round	5.71	1	15	8	48	4	5.6	0.58
Wyoming	Spring	6.15	0	13	6	61	5	5.2	0.57
Wyoming	Summer	6.38	12	26	19	42	7	4.4	0.62
Wyoming	Fall	5.60	1	15	8	37	3	5.7	0.60
Wyoming	Winter	4.71	-8	4	-2	51	2	7.0	0.55

Table H2: Enthalpy Table

Temperature C	Temperature F	Saturated Liquid Enthalpy	Evaporation Enthalpy
0.01	32.018	0	2500.9
5	41	21.02	2489.1
10	50	42.02	2477.2
15	59	62.98	2465.3
20	68	83.91	2453.5
25	77	104.83	2441.7
30	86	125.73	2429.8
35	95	146.63	2417.9
40	104	167.53	2406
45	113	188.43	2394
50	122	209.34	2382
55	131	230.26	2369.8
60	140	251.18	2357.6
65	149	272.12	2345.4
70	158	293.07	2333
75	167	314.03	2320.6
80	176	335.01	2308

85	185	356.01	2295.3
90	194	377.04	2282.5
95	203	398.09	2269.5
100	212	419.17	2256.4
110	230	461.42	2229.7
120	248	503.81	2202.1
130	266	546.38	2173.7
140	284	589.16	2144.2
150	302	632.18	2113.7
160	320	675.47	2081.9
170	338	719.08	2048.8
180	356	763.05	2014.2
190	374	807.43	1977.9
200	392	852.27	1939.7
210	410	897.63	1899.7
220	428	943.58	1857.3
230	446	990.19	1812.7
240	464	1037.6	1765.4
250	482	1085.8	1715.1
260	500	1135	1661.6
270	518	1185.3	1604.4
280	536	1236.9	1543
290	554	1290	1476.7
300	572	1345	1404.6
310	590	1402.2	1325.7
320	608	1462.2	1238.4
330	626	1525.9	1140.1
340	644	1594.5	1027.3
350	662	1670.9	892.7
360	680	1761.7	719.8
370	698	1890.7	443.8
373.95	705.11	2084.3	0

Appendix I: Bill of Materials

This appendix was used extensively to create our cost calculator for the solar to steam modeling tool. The 11 parts below were sourced from suppliers such as Grainger, SunPower, McMaster-Carr, and Backyard Trains. Several components were not able to have specific prices placed on them as solar panel installation depends on the state you live in and which suppliers are most readily available. References [59], [65], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], and [78] were used to find the information necessary to complete this bill of materials.

Part No.	Part Title	Material	Dimension(s)	Supplier	Catalog Number	Quantity	Price	Notes	Contributors *Design/CAD*	*Drawing/Plan*
1	Solar Panel Mounts	Aluminum - bolts, brackets, channels, mounting rail, support rails, washers, and nuts	30" x 7" x 4"	ex. Grainger	#26KH76	Depends on user input	$196.96	Quantity/price dependent on number of panels	ex. Grainger	ex. Grainger
2	Solar Panels	Solar Cells; High-transmission tempered anti-reflective glass; IP-68 junction box with MC4 connector inputs; Class 1 black anodized frame	~2 ft by ~2 ft (depending on local supplier)	ex. Grainger or SunPower	#60UR11	Depends on user input	$2.34 - $3.16 per Watt	Quantity/price dependent on targeted power capacity and state	ex. Grainger or SunPower	ex. Grainger or SunPower
3	MC4 Connectors and Wiring	Copper	20 Amps	Grainger	#26KH80	1	$12.59 per pair	Quantity/price dependent on number of panels	Grainger	Grainger
4	Solar Inverter (DC to AC Transformer)	Plastic Coating	2.8" x 5" x 8.2"; 3 outlets	McMaster-Carr	6987K29	1	$168.42	Prevent damage from overloads	McMaster-Carr	McMaster-Carr
5	Electric Steam Generator	Reimers AR Steam Boiler Series	2' by 3'	Reimers	AR4 Steam Boiler	1	>$1,300	Prices vary depending on user inputs	Amerec	Amerec
6	Installation Kit and Fittings for Steam Generator	Fittings are made from copper	1.5 NPT	SteamSpa	Model:STMKIT	1	$140.57	Ships within 1-2 days	SteamSpa	SteamSpa
7	EPDM Hose	EPDM rubber reinforced with steel wire	1.5 NPT, 20" bend radius	McMaster-Carr	5301K25	multiples of 50 ft	$963.67 per 50 ft	Smaller lengths are available if needed.	McMaster-Carr	McMaster-Carr
8	High-Pressure Ball Valve	Steel and PTFE Plastic	1.5 NPT; max steam pressure 150 psi at 365 F	McMaster-Carr	49355K87	2	$244.90	With lockable lever handle; rated for at least 3 times pressure of standard threaded valves	McMaster-Carr	McMaster-Carr
9	1.5/1.6 Locomotive	All steel engine with controller and batteries ready-to-run	1:8 of full-scale locomotive	Backyard Trains	GP20, GP7/9, SW1, etc.	1	$4,500 - $15,400	Can be purchased with additional features such as paint and sound	Backyard Trains	Backyard Trains
10	1.5/1.6 Tracks	Steel Rail	10' long	RMI Railworks	the Stamped Steel Tie	33	$230 per 10 ft	Can easily be purchased in bulk; shipped via crate	RMI Railworks	RMI Railworks
11	1.5/1.6 Train Track Switch	Steel Rail	4' long	RMI Railworks	the Stamped Steel Tie w/ Precision Frogs	4	$1,250	Can be purchased with tracks; shipped via crate	RMI Railworks	RMI Railworks

Appendix J: 1:8 Scale System Assembly Plan

Provided below are the steps to assemble the 1:8 scale fireless locomotive system.

1. Determine the optimal placement of the photovoltaic panels and then install them. This should be done first as the end user can reap the benefits of their passive power generation while building out the rest of the system.
2. Modify the accumulator to accept the resistive heating element by drilling a hole and tapping with appropriately sized threading. Ensure the air-tightness of this fitting either through the use of teflon tape around the threading or by welding around the perimeter of the heating element.
3. Install the accumulation tank outside of the house by connecting it to the house's utilities and insert the proper threaded fittings.
4. Install the high pressure ball valve followed by the threaded steam hose.
5. Power the resistive heating element and verify that steam generation is successful.
6. Install the railroad tracks.
7. Modify the 1:8 scale locomotive by exchanging its original engine for one capable of using steam charging for power.
8. Install the 1:8 scale locomotive onto the tracks.
9. Verify function of the locomotive by charging it with steam and operating it.