U.S. DEPARTMENT OF ENERGY

SAND2018-12539R

Sandia National Laboratories

Addressing Food Insecurity on the Navajo Reservation Through Sustainable Greenhouses

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Albuquerque, NM
August 2018

Abstract

Navajo (Diné) tribal members experience alarming rates of diabetes and food insecurity on the reservation. Increasing involvement with food production through gardening is a crucial step to rebuilding Diné food systems and improving the health of Navajos. The main challenges are drought, lack of available land, limited food production knowledge, and large up-front costs. However, implementing community-based gardens would help alleviate land space issues, leverage community knowledge, and shift financial responsibility to local community level or chapter level. Greenhouses are advantageous because they reduce water consumption and allow for year-round production, but require energy intensive heating, ventilation, and air conditioning (HVAC) systems.

Therefore, the purpose of this paper is to compare a propane heating and evaporative cooling HVAC system to a ground source heat pump (GSHP). Using EnergyPlus to simulate annual energy loads, this paper compares the financial feasibility and environmental impact of each system. The operating cost of GSHPs was found to be 57% – 72% less than traditional HVAC systems based on location and fuel prices. Additionally, GSHPs required 72% – 90% less water and emitted 35% – 69% less carbon dioxide annually. Given the large up-front cost of GSHPs, conservative estimates showed payback periods from 5.2 – 10.8 years when using renewable energy grants. A life cycle cost analysis over 20 years showed greenhouses with GSHPs could cost $1,272 – $1,605 per year or 27% – 44% less than traditional HVAC systems. Tax revenue for chapters showed that funding is available to carry out such projects. Food produced using GSHP systems was found to cost $2.26 – $2.30 per daily serving of fruit and vegetables, which is competitive with grocery store prices. More importantly, greenhouses equipped with GSHPs present a compelling case because they cost less to operate and are more environmentally friendly than traditional HVAC systems. Future work should focus on adding a photovoltaic (PV) and battery storage system, which would completely eliminate HVAC water consumption and carbon dioxide emissions.

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[1] Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

1. Introduction & Background

The Navajo Nation currently has 332,129 enrolled members, of which 47% reside on the reservation. (*Navajo Population Profile 2010 U.S. Census*, 2013) Amongst the many challenges that Navajos face on the reservation, one of the most pressing issues is the on-going health crisis. Navajos experience rates of diabetes and obesity far greater than the average American. In fact, 21.2% of Navajo adults on and near the reservation have diabetes, which is 2.5 times greater than the national average. (Mihesuah, 2003; Will et al., 1997) As of 2014, a third of Navajos had type-II diabetes or were pre-diabetic. (Eldridge et al., 2014) In general, adult onset diabetes is most prevalent; however, type-II diabetes has become increasingly more common in Navajo young people (Dabelea et al., 2009) Nevertheless, diabetes has not always impacted Navajo communities as it does today. A 1937 survey of the Ganado AZ hospital showed only 1 in 6,000 Navajos had type-II diabetes. (Eldridge et al., 2014; Lombard, Forster-Cox, Smeal, & O'Neill, 2006) But from 1972 to 1986, the diabetes rate increased to 10% and 12% across different communities. (Sugarman & Percy, 1989; Will et al., 1997) From 1990 to 1997, diabetes across all Native Americans rose by 29%. (Lombard et al., 2006) Clearly, the prevalence of diabetes in Navajo communities has developed over the past 80 years and can be linked to significant dietary and lifestyle changes over time. (Colberg et al., 2010; Nelson, Reiber, & Boyko, 2002; Tuomilehto et al., 2001) However, these dietary changes stem from the impacts of U.S. colonization on Diné food systems.

Before European contact, Navajos had pre-existing food systems, which made various forms of corn, squash, melon, beans, apricots, yucca fruit, sumac berries, celery, oats, acorns, herbs, pinons, and wild game available. (Eldridge et al., 2014; Frisbie, 2018; Mihesuah, 2003) Spanish contact introduced apples, peaches, wheat, and sheep. However, in 1851, a U.S. scorched-earth policy against the Navajos caused significant food shortages. Over 4,000 thousand peach trees were destroyed in Canyon de Chelly, fields were burned, and livestock were killed by the U.S. military. (Eldridge et al., 2014) By 1863, most Navajos were forcefully relocated to Fort Sumner NM at Bosque Redondo through the Long Walk. Poor soil conditions and hunting restrictions prevented Navajos from consuming traditional foods during their imprisonment. Navajos were given rations which consisted of pork, flour, salt, sugar, lard, and coffee beans; foods far different from their traditional diet. These rations were often spoiled and many Navajos suffered from diarrhea and dysentery. Approximately 2,000 of the 10,000 Navajos at Fort Sumner died from starvation. (Eldridge et al., 2014; Frisbie, 2018)

After the Treaty of 1868, Navajos were moved onto the reservation. By 1900, Navajo peoples' diet included (but not limited to) mutton, goat, milk, coffee, flour, corn, squash, beans, potatoes, canned vegetables, wild plants, and wild game. (Eldridge et al., 2014; Frisbie, 2018) Most important, Navajos still incorporated pre-colonial foods and regularly grew their own food. Sheep became more prevalent in Navajo peoples' diet because the U.S. sought to increase wool production and encouraged large herds on the reservation. However, from 1933 to 1945, herds were reduced by 56% through the 1933 Emergency Conservation Work Act, which severely impacted the Navajo Nation's economy and food supply. (Eldridge et al., 2014; Frisbie, 2018) Forced to adapt to reduced livestock, Navajos began to embrace a wage-based economy focused on cash crops. Ultimately, this shift in values prioritized farming for income versus self-sustenance, and therefore reduced community and household sources of food for Navajos.

Article 6 of the Navajo Treaty of 1868, required Navajo children from 6 to 16 to attend school. (Kappler, 1904) Eventually, this evolved into sending children to boarding schools, which discouraged all forms of traditional knowledge. In attempts to westernize Native children, traditional foods were not served. In addition, World War II and relocation programs placed many Navajos in urban cities. The lack of access to traditional foods contributed to changes in food preference and diet over time. (Eldridge et al., 2014)

From the 1950s through the 1970s, food assistance programs distributed "commodity food" on the reservation, which often consisted of flour, cornmeal, rice, dry milk, sugar, syrup, lard, peanut butter, dried beans, rolled wheat, butter, cheese, canned fruit, chicken, vegetables, macaroni, cereals, and dehydrated products. (Eldridge et al., 2014; Frisbie, 2018) Despite 75% of Native Americans being lactose intolerant, Navajos were consuming more forms of dairy products. (Mihesuah, 2003) More importantly, these programs introduced foods high in carbohydrates and fat. (Mihesuah, 2003) By the 1980s, Navajos were consuming more soda, sweetened drinks, sugar, store bought bread, milk, tortillas, potatoes, mutton, and coffee and less vegetables and fruits. Household gardens were becoming less prevalent and "traditional" foods most commonly consisted of frybread, tortillas, and mutton.

Ultimately, the culmination of these events has led to what Navajos are experiencing today, which is food insecurity. The U.S. Department of Agriculture (USDA) defines food insecurity as the increased consumption of cheaper food alternatives due to lack of access to healthy foods. (Seligman, Bindman, Vittinghoff, Kanaya, & Kushel, 2007) In 2016, 12.3% of Americans were food insecure, with rates of 15% in rural environments. (Coleman-Jensen, Rabbitt, Gregory, & Singh, 2017) However, a 2007 study showed 76.7% of Navajos (from 10 communities) on the reservation expressed some level of food insecurity. (Pardilla, Prasad, Suratkar, & Gittelsohn, 2014) Currently, the Navajo Nation has 13 grocery stores to cover 27,000 square miles and the average resident drives 3 hours for groceries. ("Eating Well: Grocery Program Takes Off in the Navajo Nation | Partners In Health," 2018) Based off a separate study of five towns on the reservation, 51% preferred to purchase groceries off the reservation due to lower prices and a greater variety of foods. (Eldridge et al., 2014) From these five towns, the shortest roundtrip distance to an off-reservation grocery store was 155 miles. (Eldridge et al., 2014) Some respondents indicated they travel farther to Albuquerque or Flagstaff, which could be more than 400 miles roundtrip. (Eldridge et al., 2014) Clearly, the rural environment of the reservation enhances the effects of food insecurity and prioritizes vehicle availability. Considering the poverty and unemployment rates on the reservation are 43% and 44.25%, transportation costs can severely limit one's access to healthy foods. (Donovan, 2017; *Navajo Nation Community Profile*, 2016)

According to the USDA Food Access Research Atlas, nearly the entire Navajo Nation is classified as a "food desert," meaning it has severely limited access to healthy foods. As a result, many Navajos are left to substitute trips to the grocery store with fast food restaurants or gas stations. Building more grocery stores seems like a simple solution to address food insecurity, however, conducting business on the Navajo Nation is complex. The main factors limiting new business on the reservation are "a complicated business license application, a lack of private property, and limited access to lending opportunities." (Hoffer, 2017) For pre-existing businesses, they risk site leases not being renewed because lease agreements are not "indefinite rights to a parcel of land." (Hoffer, 2017) Furthermore, dealing with the dual bureaucracy of the federal government and the tribal government can discourage businesses from operating on the reservation. Unfortunately, building more grocery stores is not as easy as it might appear; it is important to recognize that food insecurity is a complex issue dependent not only on food access, but education, employment, infrastructure, and economic development.

2. Addressing Food Insecurity on the Navajo Reservation

The Diné Policy Institute (DPI) is a center that conducts public research pertaining to social and political issues on the Navajo Nation. In 2014, they completed a study focused on Diné food sovereignty. The major takeaway from this report was that issues of food insecurity stem from the impacts of U.S. colonization. The destruction or erasure of Diné food systems, that have sustained previous generations, has severely altered the diet of Navajo people today. By rebuilding these systems and increasing Navajo food production, it would allow Navajos to reconnect with "traditional foods and revitalize knowledge and practices around those foods." (Eldridge et al., 2014) Additional benefits include greater food access, improved health and wellness, re-establishing relationships between food, family, and community (K'é), being less reliant on the U.S. government, and being more informed about the quality of one's food. (Eldridge et al., 2014; Mihesuah, 2003) Overall, growing food offers many benefits; however, there are clear challenges that limit Navajo peoples' ability to carry out such projects.

One of the main challenges to growing food on the Navajo reservation is water availability. Annual rainfall on the Navajo Nation ranges from 159 to 482 millimeters (mm) with an average of 278 mm. (Tulley-Cordova, Strong, Brady, Bekis, & Bowen, 2018) As of February 2018, the Navajo Nation issued an emergency drought declaration. (The Associated Press, 2018) In addition, the Navajo Nation has experienced water contamination that has affected agricultural operations. In 2015, the San Juan river was contaminated by the Gold King Mine through the Colorado Animas River. (Duara, 2015) Some chapters diverted water from their fields for up to a year to avoid soil contamination. (Duara, 2015) Monitoring shows that contaminations levels have returned to pre-spill levels and is safe for agricultural use; however, this has not restored trust between farmers and the water utility. (U.S. Environmental Protection Agency, 2017) Overall, water sources on the reservation are already scarce and events like the Gold King Mine spill continue to put them at further risk. Therefore, attention to water usage is a crucial factor when considering growing food.

Challenges related to land are also prevalent throughout the reservation. Residents may not have the available land space for gardening or soil conditions may be poor due to overgrazing. Windy conditions may also limit the growing season and increase water consumption due to evapotranspiration. (O'Connor & Mehta, 2016) Open-air growing also makes plants more susceptible to animals and pests; and as outlined by the DPI, pesticides should be avoided.

Costs associated with gardening are another barrier to growing food. Depending on the scale, capital equipment such as tractors may be needed. If equipment is being used consistently, then there are added fuel and electricity costs. Furthermore, gardening is time consuming, and can take time away from one's job if they are employed.

Finally, residents may be interested in gardening, but might not know how to grow traditional foods. Or, they may not know how to prepare meals using the food they produce. Therefore, education related to food production can limit one from growing their own food.

3. Community Based Approach

It is clear there are many challenges to growing food on the reservation; however, implementing a community based approach involving the 110 chapter houses (community centers) on the reservation could help alleviate some of these issues. By creating community gardens at chapter houses, it would directly address challenges related to land space requirements. Chapter houses could designate a portion of the land they reside on to community gardens; and given that chapter houses are connected to the grid and water lines, infrastructure is already in place. Utilizing a community based approach would also distribute responsibility amongst community members, meaning less time is taken away from one's job and knowledge can be shared. Finally, a community based approach would shift the financial burden to the local government. The Diné Healthy Nation Act, a 2% sales tax on "junk food" sold on the reservation, allocates revenue to local chapters for health and wellness related projects, including community gardens. (Nation, 2014; Navajo Nation, 2016) The revenue is allocated for chapters using the 50/50 formula. Based off 2016 revenue and using census data as a proxy for registered voters, about \$7,000 – \$45,900 is available for chapters annually. (*Navajo Population Profile 2010 U.S. Census*, 2013; Smith, 2016) Clearly there is funding available and investing in community gardens could provide residents with the knowledge and skillset to begin growing their own food.

4. Introduction to Greenhouses

As discussed before, one of most pressing challenges is water availability. Unfortunately, the low cost of water makes it less of a factor when analyzing financial costs. However, considering its importance to Navajo people, it must be seriously evaluated. Therefore, climate controlled greenhouses should be considered because they consume less water than traditional open-air growing methods. Greenhouses consume less water because heating, ventilation, and air conditioning (HVAC) systems maintain moderate temperatures and increase relative humidity. As a result, less water is lost to evapotranspiration. (O'Connor & Mehta, 2016) In combination with irrigation systems, even greater water savings can be achieved. In some cases, greenhouses can even reduce the growing season of fruits and vegetables, which not only cuts down on water requirements, but also increases food production. (O'Connor & Mehta, 2016) Additional advantages include year-round operation and isolation from the surrounding environment, which limits the need for GMO/GE seeds and pesticides. Despite the many benefits of greenhouses, they are generally not used in commercial growing because they require expensive and energy intensive HVAC systems. However, HVAC systems utilizing renewables energy could potentially make greenhouse systems cost effective.

5. Greenhouse Heating and Cooling Technologies

In order to maintain an optimal temperature range, greenhouses must utilize HVAC systems. These systems must contain an energy source/supply, a heating/cooling unit, and a distribution system (fan, ductwork, pipes, pumps). Air and water are mediums through which heat can either be added or removed from a designated space. Systems that supply air, require fans or blowers and are generally known as forced-air heating/cooling. For buildings with multiple rooms or a large volume, ductwork is needed to distribute the hot and cold air through the space. Ductwork is often labor intensive and can add a significant amount to the initial cost of an HVAC system.

However, considering our greenhouse is not commercial-scale, options that require little to no ductwork will only be considered. For systems that utilize water as a heat transfer medium, they require a network of pipes below the surface of the space with pumps. Once again, to reduce installation and capital costs, options that use water heating/cooling will not be considered.

5.1 Heating

Four available forms of heating for greenhouses are gas furnaces, propane furnaces, electric resistant heaters, and ground source heat pumps (GHSPs).

5.1.1 Gas Furnace

Gas furnaces combust natural gas in order to heat distributed air. Natural gas is supplied through gas lines and is a relatively cheap fuel source. Gas furnaces usually operate at 90% – 97% efficiency. (Propane Clean American Energy, 2015) Wall gas furnaces are commercially available products that do not require ductwork. Some units use fans/blowers, while others use natural air circulation due to differences in room and inlet air temperatures. Considering most residents and chapters on the Navajo reservation do not have access to residential gas lines, it will not be considered in further analysis.

5.1.2 Propane Furnace

Propane furnaces function similar to gas furnaces; however, they use liquid propane as a fuel source. Propane is generally delivered to the place of residence/business by delivery truck and is stored in a tank for later use. Propane must be delivered in liquid form in order to increase its energy density and save space. However, despite its high efficiency, propane is generally a more expensive form of heating due to the cost of compression and transportation. In addition, propane tanks must be rented or purchased by the owner. As a result, propane is most common in rural environments where natural gas lines are unavailable. Propane furnaces usually have a low capital cost and wall furnaces will also be considered because they do not require ductwork.

5.1.3 Electric Resistance

Electric heaters use electric resistance coils in order to convert electricity into heat. They are 100% efficient; however, the price of electricity makes them an expensive option for heating. (Department of Energy, n.d.-b) In addition, they are commonly used for heating small spaces and come with included fans. Most units do not have a large heating capacity, therefore multiple units must be purchased. Individual units are generally inexpensive, however, because multiple units are needed, the capital cost can easily increase. These units will not be considered because they are expensive to operate and there are cheaper alternatives that also use electricity.

5.1.4 Ground Source Heat Pump (GSHP)

GSHPs use electricity and relatively constant subsurface temperatures to efficiently heat/cool circulated air. They consist of two systems, a ground loop of water and a heat pump that circulates a working fluid. (Banks, 2012; Rosen & Koohi-Fayegh, 2016) For this project, we will consider a water-to-air heat pump, which warms/cools inlet air.

The ground loop portion of a GSHP acts as a heat exchanger because it experiences less temperature change throughout the year. Figure 1 demonstrates up to a depth of 30 ft, the ground experiences seasonal variations in temperature throughout the year. (McQuay Air Conditioning, 2002) Therefore, the configuration of the ground loop will impact the performance of a GSHP, which will be discussed later. More importantly, when a GSHP is used for heating, the ground loop exchanges heat in order to vaporize the working fluid. In the heat pump, the vapor can then be compressed, which gives off heat to the incoming air. Once the working fluid is condensed and expanded, the process is repeated as shown in Figure 2. GSHPs can also have a cooling effect by simply reversing the cycle described. (Banks, 2012; Rosen & Koohi-Fayegh, 2016)

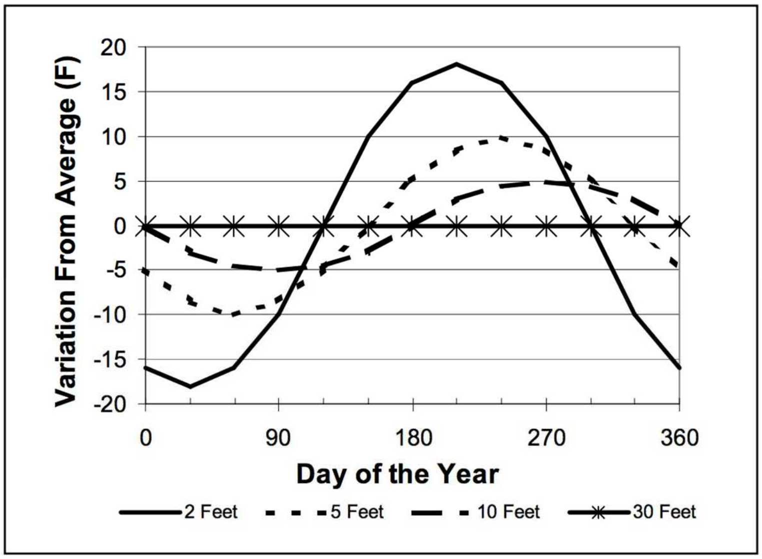

Figure 1. Variation from Average Ground Temperature as Function of Depth. This figure shows the deviation from the average ground temperature at varying depths over the course of the year. At 30 feet and below, the temperature should remain constant. (McQuay Air Conditioning, 2002)

By making use of the ground loop, GSHPs have a heating efficiency greater than 100%, meaning they use less electricity and become cost competitive with natural gas and propane. (Banks, 2012) The efficiency can fluctuate throughout operation because it is dependent on the ground loop temperature and the incoming air temperature. Ultimately, GSHPs are not as common because of the high capital cost associated with installing the ground loop. Figure 2 shows different configurations for the ground loop and the length of piping is dictated by the heating/cooling capacity. Horizontal closed loops are usually less expensive, but require a large area because they are exposed to a wider range in ground temperatures. (Banks, 2012; McQuay Air Conditioning, 2002; Rosen & Koohi-Fayegh, 2016) Vertical closed loops require less space and experience a smaller range in ground temperatures, but are more expensive. (Banks, 2012; McQuay Air Conditioning, 2002; Rosen & Koohi-Fayegh, 2016) Open loop systems can be installed; however, they require a natural water source such as a pond or an underground water reservoir. (Banks, 2012; McQuay Air Conditioning, 2002) Despite the higher efficiency of open loop systems, they will not be considered because natural water sources are already scarce and it would limit the location of the greenhouse.

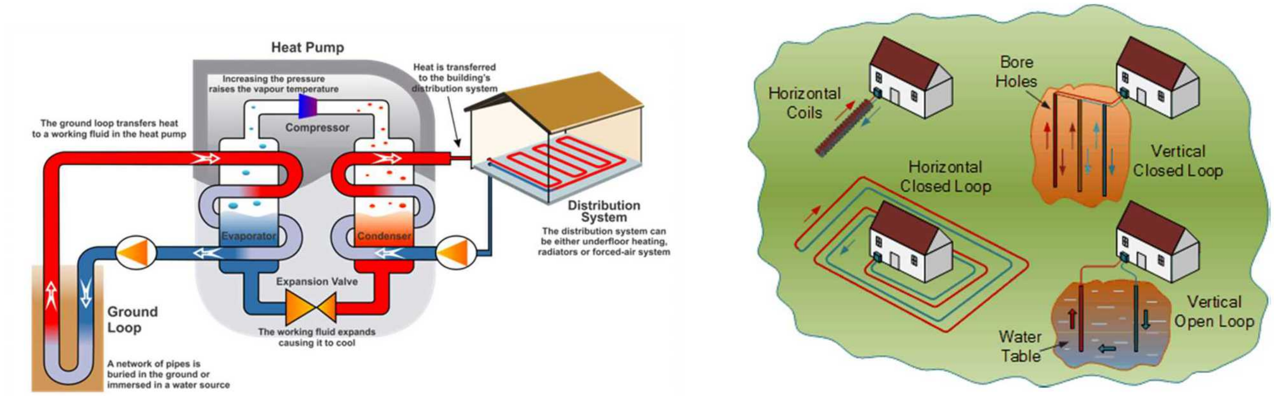

Figure 2. Ground Source Heat Pump Diagram (Left) and Ground-Loop Configuration for GSHPs (Right). On the left is a diagram of a GSHP showing the ground loop, heat pump, and distribution system. On the right, is a figure showing the different available forms of ground-loops for GSHPs.

5.2 Cooling

5.2.1 Direct Evaporative Cooler

Direct evaporative coolers rely on the evaporation of water to remove heat from incoming air. (Hackel et al., 2014) About 1,061 British thermal units (Btu) of heat is removed through the evaporation of 1 pound (lbs) of water. (Kinney, 2004) The cooled air (supplied from outside) displaces the hot air inside the greenhouse through an electric fan. To maintain steady ventilation, a fan at the opposite end of the evaporative cooler must also be installed to draw out the hot air. The limit at which the outside air can be cooled is based on the dry and wet bulb temperatures. Most evaporative coolers operate at 80% effectiveness, meaning they can lower the dry bulb temperature by 80% of the difference between the dry and wet bulb temperature. (Hackel et al., 2014; Kinney, 2004) Therefore, evaporative coolers are more efficient in locations with low wet bulb temperatures and low relative humidity. Arid climates like the Navajo reservation are optimal locations for evaporative coolers. Two types of units are available, wall-covering units and single fixed-size units. Because the greenhouse is not on the scale of a commercial indoor farm, only fixed-sized units, also known as swamp coolers will be considered. The main disadvantage of evaporative coolers is the water usage. Despite low water prices, sustainable options must be considered which limit water consumption. Overall, evaporative coolers consume little electricity, which is why they are an industry standard for greenhouses.

5.2.2 Ground Source Heat Pump

As mentioned earlier, GHSPs can run opposite of the cycle shown in Figure 2 to have a cooling effect. When GSHPs are used for cooling purposes, it also operates at efficiencies greater than 100%. The main advantage of using GSHPs with a closed ground loop is that it does not constantly consume water. The water used stays in the ground loop and rarely has to be replaced.

6. Greenhouse and HVAC Equipment Specifications

For energy load calculations, the greenhouse was modeled off the GrowSpan Estate Pro Large Greenhouse shown in Figure 3. The greenhouse features twin-wall polycarbonate glazing material, a fairly common building material for greenhouses. (FarmTek, n.d.) The type of fiberglass was not specified; however, it appears to be polycarbonate with an opaque finish.

Therefore, the solar gain heat coefficient (SGHC) and light transmittance values were based off opaque polycarbonate. Newly constructed fiberglass greenhouses generally have an air leakage rate between 0.75 – 1.0 air volume exchanges per hour. (Texas A&M AgriLife Extension, n.d.; Worley, 2014) To be on the conservative side, 1.0 air volume exchanges per hour was assumed. All relevant specifications can be found in Table 1.

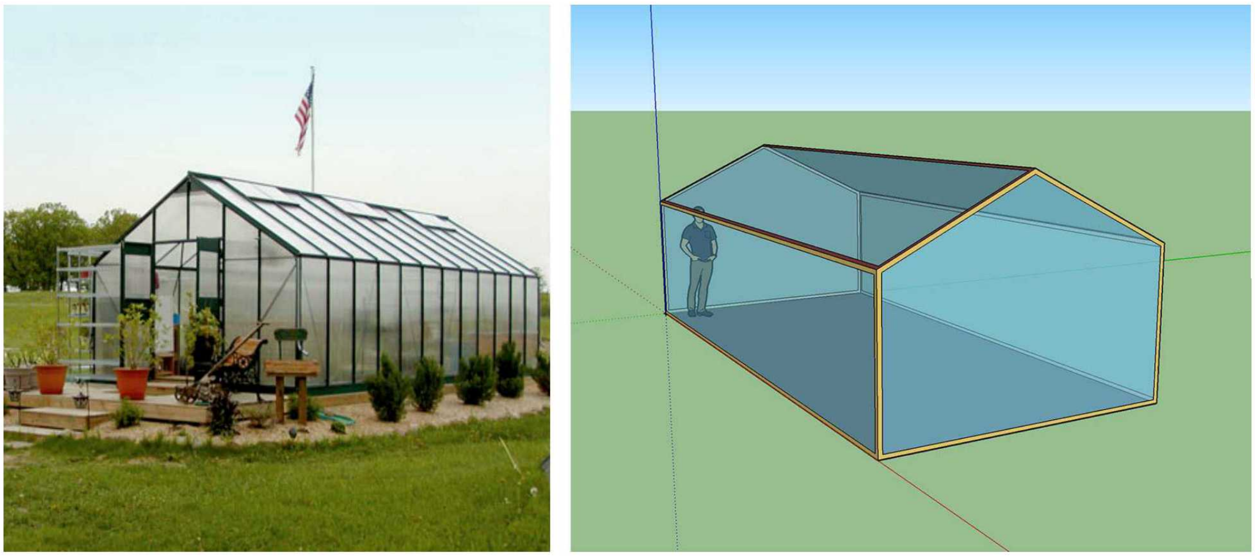

Figure 3. GrowSpan Greenhouse and SketchUp Model. On the left is the GrowSpan Estate Pro Large Greenhouse. On the right is a SketchUp model of the greenhouse previously mentioned. The 3D model will be used to calculate the energy load of the greenhouse.

Table 1. Greenhouse Specifications	
Dimensions (FarmTek, n.d.)	W = 11ft 8 in, H = 8 ft 10 in, L = 24 ft 8 in
Floor Area	288 ft^2
Volume	2,280 ft^3
Glazing Material (FarmTek, n.d.)	6 mm twin-wall polycarbonate
Frame Material (FarmTek, n.d.)	Aluminum
Air Exchanges Per Hour (Texas A&M AgriLife Extension, n.d.; Worley, 2014)	1.0
Glazing Material Properties	
U-Value (AmeriLux International, 2013)	0.625
Solar Gain Heat Coefficient (SGHC) (Palram Americas, n.d.)	0.24
Light Transmittance (AmeriLux International, 2013)	0.40

Frame Material Properties	
Thickness	0.125 in
Density (The Engineering ToolBox, n.d.-b)	170 lbs./ft^3
Thermal Conductivity (The Engineering ToolBox, n.d.-d)	118 Btu-in/hr-ft^2-R
Specific Heat (The Engineering ToolBox, n.d.-c)	0.22 Btu/lbs.-R
Solar Absorbance (The Engineering ToolBox, n.d.-a)	0.7

For the HVAC comparison, two systems will be considered: a propane furnace with evaporative cooling and a GSHP. The propane furnace was based off a wall furnace, ideal for easy installation. The Rinnai EX38CTP was also chosen because it can operate at high elevations in the high desert. Furnace specifications can be found below in Table 2.

Table 2. Propane Furnace Specifications	
Unit	Rinnai EX38CTP
Heating Capacity (Alpine Home Air Products, n.d.)	36,500 Btu/h
Efficiency (Alpine Home Air Products, n.d.)	82%
Air Flow Rate (Alpine Home Air Products, n.d.)	162.7 cfm
Power (Alpine Home Air Products, n.d.)	117 W

It is recommended that the air flow rate of the evaporative cooler be twice the volume of the space to be cooled. (Bartok, Jr., 2013) Therefore, a 5,000 cubic feet per minute (cfm) cooler was found on a reputable greenhouse supply store. Relevant evaporative cooler specifications can be found below in Table 3.

Table 3. Evaporative Cooler Specifications	
Air Flow Rate (Growerssupply, n.d.)	5,000 cfm
Cooling Capacity (Breezair, n.d.)	27,600 Btu/h
Type (Growerssupply, n.d.)	Two-Speed
Power Requirement (Growerssupply, n.d.)	372.85 kW
Cooler Effectiveness (Hackel et al., 2014; Kinney, 2004)	80%

The GSHP system was designed off the Bosch BP015 unit. Relevant input data was found in Bosch literature, which is shown below in Table 4. The undisturbed ground temperature on the Navajo Nation is approximately between 57ºF (in northern regions) and 64ºF (in southern regions). (*2011 ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Applications (SI Edition) - Knovel*, 2011) For comparison, Albuquerque, NM has an undisturbed ground temperature of 59ºF and Phoenix, AZ 73ºF. (McQuay Air Conditioning, 2002) More importantly, it is suggested to set the ground loop temperature 10ºF – 20ºF lower than the undisturbed ground temperature for heating, and 20ºF – 30ºF higher for cooling. (McQuay Air Conditioning, 2002) Because vertical loops experience less temperature deviations, a 10ºF decrease was used for heating and a 20ºF increase for cooling. Also, a vertical loop configuration will produce a more conservative cost estimate. Because the temperature data from Bosch is based on 10ºF and 5ºF increments, ground loop temperatures of 50ºF for heating and 85ºF for cooling will be used.

Table 4A. GSHP Ground Loop Specifications	
Pump	Single-Speed
Water Flow Rate (Bosch, 2012)	6 gpm
Undisturbed Ground Temperature Range (*2011 ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Applications (SI Edition) - Knovel*, 2011)	57.2ºF – 64.4ºF
Heating Loop Design Temperature (Bosch, 2012; McQuay Air Conditioning, 2002)	50ºF

Cooling Loop Design Temperature (Bosch, 2012; McQuay Air Conditioning, 2002)	85ºF

Table 4B. GSHP Water-to-Air Heat Pump Specifications	
Water Flow Rate (Bosch, 2012)	6 gpm
Air Flowrate (Bosch, 2012)	500 cfm
Heating COP (Bosch, 2012)	5.28
Heating Total Capacity (Bosch, 2012)	15,980 Btu/h
Cooling EER (Bosch, 2012)	19.99
Cooling Total Capacity (Bosch, 2012)	16,950 Btu/h
Cooling Sensible Capacity (Bosch, 2012)	12,870 Btu/h

7. Energy Load Calculations

In order to assess the various heating and cooling systems, annual energy simulations must be run. EnergyPlus is a simulation engine developed by the National Renewable Energy Lab (NREL) and is commonly used for energy load analysis. In order to make use of EnergyPlus, the design space must be 3D modeled in SketchUp. SketchUp files can then be interpreted by the graphical user interface (GUI), called OpenStudio, which allows one to input building materials, load conditions, weather data, and HVAC systems. From there, OpenStudio can run the EnergyPlus simulation engine to carry out annual calculations.

Location can dramatically affect energy load calculations because of the unique weather conditions at each site. Using the EnergyPlus weather data search tool, Farmington, NM, Gallup, NM, and Page, AZ were the only available locations near or on the Navajo reservation. Therefore, calculations were carried out for these three locations to show a range of costs more representative of the entire Navajo reservation.

In addition to weather, operating temperatures directly influence the annual energy load. Without HVAC systems, greenhouses are prone to extreme temperature ranges because the building materials generally have low insulation and let in large amounts of solar radiation. At the three designated locations, internal temperatures ranged from 38ºF – 124ºF in summer months and 8ºF – 94ºF in winter months without HVAC systems. (Appendix A) These temperature ranges are not uncommon because greenhouses can easily reach up to 150ºF in the summer. For optimal growing, narrower temperature ranges are required and were based off various fruits and vegetables. By researching optimal growing conditions for various fruits and vegetables, operating temperatures must be between 50ºF – 90ºF depending on the season. (Sanchez, 2002) A month by month day and night schedule can be found in Appendix B.

More importantly, after running the EnergyPlus simulation for the propane heating and evaporative cooling system, 186 – 392 gallons (gal) of propane and 1,626 – 2,009 kilowatt-hour (kWh) of electricity were consumed (Table 5). The GSHP only uses electricity and consumed 2,089 – 2,267 kWh per year (Table 6).

Table 5. Summary of Annual Liquid Propane (gal) and Electricity Consumption (kWh) for Propane Heating and Evaporative Cooling System			
	Farmington, NM	Gallup, NM	Page, AZ
Propane (gal)	325	391	186
Electricity (kWh)	1,689	1,626	2,009

Table 6. Summary of Annual Electricity Consumption (kWh) for GSHP System			
	Farmington, NM	Gallup, NM	Page, AZ
Heating (kWh)	1,229	1,500	698
Cooling (kWh)	1,015	767	1,391
Total (kWh)	**2,244**	**2,267**	**2,089**

8. Annual Operating Costs

Greenhouse operating costs generally include, labor, heating/cooling, water, electricity, and nutrients/fertilizers. Labor and heating/cooling make up a majority of the operating costs for greenhouses. However, labor costs will not be accounted for because the intention of this project is for the greenhouse to be maintained by members of the community. Additionally, the greenhouse will not be using artificial lighting because of the glazing material; therefore, electricity costs (excluding electricity used for heating/cooling) will also not be included. Finally, the cost of nutrients and fertilizers is rather insignificant in comparison to the energy costs, therefore it will also not be included. Overall, water and heating/cooling will only be considered for annual operating costs.

7.1 Water

Daily water needs for crops are influenced by the climate zone and mean daily temperature. The water requirement for crops is generally measured in mm of water over the growing area. Daily water requirements for grass is generally used as a standard and can be adjusted -30% to +20% depending on the crop. (Brouwer & Heibloem, 1986) Appendix C shows the daily water requirement based on climate zone and daily mean temperature, which has been provided by the Food and Agricultural Organization of the United Nations (FOA). An additional 20% water requirement will be assumed for a more conservative estimate. Because the greenhouse will be climate controlled, a daily mean temperature between 59ºF and 77ºF will be used. Additionally, greenhouses generally increase the internal relative humidity, therefore, a semi-arid climate will be assumed instead of arid climate. Given this information, the annual water requirement for the greenhouse is 20,107 gal/yr. The Navajo Tribal Utility Authority (NTUA) provides water on the Navajo reservation for $3.91 per 1,000 gal for the first 3,000 gal each month. (NTUA, n.d.) In addition, they charge a $9.89 service fee for water meters each month. (NTUA, n.d.) Therefore, the annual cost of water for crops is $197.30. In addition, water consumed by evaporative coolers is between 4,711 – 6,532 gal per year. As a result, the annual cost of water used by evaporative coolers is between $18.42 – $25.54.

7.2 Heating and Cooling

Annual operating costs for heating and cooling include fuel, electricity, and maintenance costs. For propane heating, the average residential price of propane is $2.55/gal (U.S. EIA, n.d.-c)

However, on the Navajo reservation, prices can range from $1.92 – $2.82/gal of propane. (Allaround Propane, n.d.) In general, one can expect to spend roughly $100.00 on maintenance for a propane furnace. (improvenet, n.d.) For this analysis, it will be assumed that a propane tank will be rented for $100 per year. The advantage of renting a propane tank is that maintenance costs are covered by the propane company. (Fixr, n.d.-a) For evaporative coolers, it relies on electricity and water, refer to Table 5 and 10 for specific water and electricity usage. Appendix D provides a table of the average residential price of electricity for the states the Navajo reservation resides on. An average value of 12.08 cents per kilowatt-hour (¢/kWh) will be used for all further analysis. Replacement of aspen pads each season totals to $135.00 per year. (Greenhouse Megastore, n.d.; hvac.com, n.d.) As a result, the combined operating cost of the propane heating and evaporating cooling system ranges between $1156.78 - $1,850.59 based on location and propane price (Table 7).

Table 7. Annual Operating Cost of Propane Heating and Evaporative Cooling System

	Farmington, NM	Gallup, NM	Page, AZ
Propane Heating ($1.92/gal-propane)	$681.95	$809.10	$414.32
Propane Heating ($2.82/gal-propane)	$974.73	$1,161.55	$581.51
Propane Maintenance	$100.00	$100.00	$100.00
Propane Tank Rental	$100.00	$100.00	$100.00
Evaporative Cooling	$194.52	$138.32	$184.62
Evaporative Cooling Water	$20.69	$18.42	$25.54
Evaporative Cooling Maintenance	$135.00	$135.00	$135.00
Water for Crops	$78.62	$78.62	$78.62
NTUA Water Meter Service Fee	$118.68	$118.68	$118.68
Total Operating Cost ($1.92/gal-propane)	**$1,380.86**	**$1,498.13**	**$1,156.78**
Total Operating Cost ($2.82/gal-propane)	**$1,673.65**	**$1,850.59**	**$1,323.97**

For GSHPs, operating costs are based off electricity consumption; therefore, low electricity prices make them more advantageous. GSHPs are known for requiring very little maintenance. (Banks, 2012) A study of installed GSHPs estimated maintenance costs to be 17 ¢/ft^2-yr. (Martin, Durfee, & Hughes, 1999) Moreover, the annual operating cost of the GSHP is between $498.40 – $519.87, which is 57% - 72% less than the propane heating and evaporative cooling system (Table 8).

Table 8. Annual Operating Cost of GSHP System			
	Farmington, NM	Gallup, NM	Page, AZ
GSHP Heating	$148.48	$181.19	$84.32
GSHP Cooling	$122.65	$92.62	$168.02
GSHP Maintenance	$48.76	$48.76	$48.76
Water for Crops	$78.62	$78.62	$78.62
NTUA Water Meter Service Fee	$118.68	$118.68	$118.68
Total Operating Cost	**$517.19**	**$519.87**	**$498.40**

9. Annual Water Consumption

As stated earlier, the maximum annual water requirement for crops in a greenhouse can be estimated to be 20,100 gallons. If traditional open-air growing methods were used, the maximum annual water requirement for crops would be 29,400 gallons. However, given an average annual rainfall of 278 mm (1,960 gallons), open-air crops would only require 27,440 gallons per year. (Tulley-Cordova et al., 2018)

Additionally, when evaluating greenhouse water savings, it must account for other direct and indirect forms of water consumption as a result of the HVAC system. For example, in order to maintain cool temperatures, the evaporative cooler requires 4,700 – 6,500 gallons per year.

Electricity usage is also an indirect form of water consumption. Assuming fossil fuels are used for power generation, natural gas power plants consume 0.33 gal/kWh and coal power plants 0.67 gal/kWh. (Kinney, 2004) Therefore, electricity used by the propane and evaporative cooling systems consumes 400 – 500 gallons (natural gas) and 800 – 1,000 gallons (coal) (Table 10). GSHPs, on the other hand, consume 700 gallons (natural gas) and 1,400 – 1,500 gallons (coal) (Table 10).

Moreover, the propane and evaporative systems consumes a net total of 5,100 – 7,500 gallons of water annually, whereas, the GSHP systems consumes 800 – 1,500 gallons annually (Table 10). Clearly, GSHPs consume significantly less water, meaning greenhouse systems can potentially use between 20,900 – 21,600 gallons per year, including the crop water requirement (Table 9). Considering this analysis does not take into account drip irrigation systems or the impact of climate control on growing time, greater water savings can be expected.

Table 9. Summary of Net Annual Water Consumption (gal) for Open-Air and Greenhouse Growing Systems	
Traditional Open-Air Growing	27,440
Greenhouse with Evaporative Cooling	25,200 – 27,600
Greenhouse with GSHP	20,900 – 21,600

Table 10. Annual Water Consumption (gal) Propane Heating and Evaporative Cooling System

Electricity Source		Farmington, NM	Gallup, NM	Page, AZ
N/A	Water Required by Evaporative Cooler	5,291	4,711	6,532
Natural Gas	Water from Electricity Consumption	531	378	504
	Net Water Use	5,822	5,088	7,036
Coal	Water from Electricity Consumption	1,079	767	1,024
	Net Water Use	6,315	5,478	7,556

Table 11. Annual Water Consumption (gal) from GSHP

Electricity Source		Farmington, NM	Gallup, NM	Page, AZ
Natural Gas	Net Water Use	741	748	689
Coal	Net Water Use	1,504	1,519	1,400

10. Annual Carbon Dioxide Emissions

Carbon dioxide emissions are directly emitted from fossil fuel heating systems and indirectly through electricity consumption. Per gallon of propane, 5.76 kilograms (kg) of carbon dioxide is emitted. (U.S. EIA, n.d.-a) Assuming fossil fuels are used for power generation, 0.4 kg of carbon dioxide is emitted per kWh from natural gas and 0.9 kg from coal. (Banks, 2012) Based off the energy simulation results from Table 12, 1,873 – 3,392 kg of carbon dioxide is emitted annually from the propane heating and evaporative cooling system. Using Table 12, 836 – 2,040 kg of carbon dioxide is emitted from the GSHP. In comparison, the average passenger vehicle emits 4,600 kg of carbon dioxide each year. (U.S. EIA, n.d.-b) Overall, the GSHP emits 35% – 69% less carbon dioxide.

Table 12. Annual Carbon Dioxide Emissions (kg) from Propane Heating and Evaporative Cooling System and GSHP System				
Electricity Source	HVAC System	Farmington, NM	Gallup, NM	Page, AZ
Natural Gas	Propane Heating and Evaporative Cooling	2,548	2,904	1,873
	GSHP	898	907	836
Coal	Propane Heating and Evaporative Cooling	3,392	3,717	2,877
	GSHP	2,020	2,040	1,880

11. Capital Costs

11.1 Propane Heating and Evaporative Cooling System

The propane wall furnace for this system costs $1,959.00, and it is assumed a propane tank is rented from the propane delivery company. Given the furnace is a wall unit, installation should not be difficult and expensive. However, installation estimates are usually for residential furnaces, which are much larger than our unit and would result in an overestimation. Therefore, further research is necessary to find more accurate installation costs. For this analysis, a $1,000.00 installation cost will be assumed. (Fixr, n.d.-b) As for the evaporative cooler, it is $1,169.00. Overall, the total capital cost for the propane heating and evaporative cooling system is $4,128.00 (Table 13).

Table 13. Capital Cost of Propane Heating and Evaporative Cooling System			
	Farmington, NM	Gallup, NM	Page, AZ
Propane Furnace	$1,959.00		
Evaporative Cooler	$1,169.00		
Cost of Labor	$1,000.00		
Total Capital Cost	**$4,128.00**		

11.2 GSHP System

GSHPs generally have low operating costs, however, high capital costs have prevented them from becoming more prevalent in the U.S. The water-to-air heat pump by Bosch is $6,413.00. The vertical ground loop cost is dependent on the bore field size; typical boreholes are 150 – 450 feet in depth and vary based on ground thermal properties. (Department of Energy, n.d.-c; Montana Department of Environmental Quality, n.d.; National Institutes of Health, 2013; Rosen & Koohi-Fayegh, 2016) Using an American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Excel spreadsheet for borehole sizing along with thermal data for different soil types, calculated borehole depths ranged from 127 to 268 feet and can be found in Appendix E. (Bard Manufacturing Company, 2007; Philippe, Bernier, & Marchio, 2010) Cost per borehole depth averages $8.51 per foot. (Rafferty, 1994) Therefore, the ground loop can be expected to cost $1,084.17 – $2,277.28. Given this system must provide 0.64 – 0.88 tons of heating/cooling, the ground loop cost is close to other estimates, which assume $2,500.00 per ton. (Montana Department of Environmental Quality, n.d.) In addition, labor can be estimated to be between $4,208.82 – $4,342.35 based off a study of installed GSHPs.

(Kavanaugh, Gilbreath, Assistant, & Kilpatrick, 1995) Using the largest estimated borehole length per site, the total installed cost of ranges between $12,678.69 – $13,032.62 (Table 14).

Table 14. Capital Cost of Ground Source Heat Pump System			
	Farmington, NM	Gallup, NM	Page, AZ
Water to Air Heat Pump	$6,413.00	$6,413.00	$6,413.00
Ground Loop	$2,029.64	$2,277.28	$2,056.87
Installation Cost	$4,256.71	$4,342.35	$4,208.82
Total Capital Cost	**$12,699.34**	**$13,032.62**	**$12,678.69**

12. Payback Period

Assuming a 2% fixed annual interest rate and using a present work annual payment analysis, the payback period for the GSHP system is between 11.0 – 24.6 years (Table 15). Given that GSHPs are a form of renewable energy, there are opportunities for grants. If it is assumed half of the GSHP capital cost is covered by a grant, then the payback period becomes 5.2 – 10.8 years (Table 15).

Table 15. Ground Source Heat Pump System Payback Period (years) Based on Price of Propane				
	Propane Price	Farmington, NM	Gallup, NM	Page, AZ
GSHP Payback Period No Grant	$1.92/gal	17.6	15.6	24.6
	$2.82/gal	12.5	11.0	18.5
GSHP Payback Period with Grant	$1.92/gal	8.0	7.2	10.8
	$2.82/gal	5.9	5.2	8.4

13. Life Cycle Cost Analysis

GSHPs are long-term investments because they have a long service life. The ground loop can be expected to last 50 years, while the heat pump can last 20 – 25 years. (Department of Energy, n.d.-a) In order to complete a life cycle analysis, recurring costs (maintenance, water, electricity, and propane) must be adjusted to reflect inflation and escalation rates (Appendix F). The National Institute of Standards and Technology (NIST) releases an annual report of energy price indices and discount factors. However, these reports only extend 30 years into the future; therefore, a life cycle cost analysis cannot be completed for the service life of the GSHP system. Given that propane furnaces last between 16 - 27 years, a life cycle analysis can be completed over 20 years, which could also account for the service life of the water-to-air heat pump. (Navigant Consulting, 2018) Moreover, recurring costs will use values found in Appendix G. There are also non-recurring costs that must be adjusted, such as the replacement of the evaporative cooler and greenhouse every 10 years. (Davis Energy Group, 2004; Washington State University, n.d.) These costs equal the future value at the time of replacement and discounted to the present (Appendix F). Furthermore, to simplify this analysis, a coinciding study period and service period will be assumed. Moreover, the life cycle costs (Table 16) can be divided over 20 years to calculate the annual cost of total greenhouse system (Table 17). The annual cost of a greenhouse with a GSHP system ranges between $1,272.43 - $1,624.20, which is 9% - 44% less than a greenhouse with a propane heating and evaporative cooling system.

More importantly, the annual cost is well within the range of chapter house allocation from tax revenue and shows promise as a viable option.

Table 16. Life Cycle Cost Over 20 Years of Greenhouse with HVAC System			
	Farmington, NM	Gallup, NM	Page, AZ
Propane Heating + Evaporative Cooling ($1.92/gal-propane)	$38,582.97	$40,552.64	$34,799.59
Propane Heating + Evaporative Cooling ($2.82/gal-propane)	$43,478.33	$46,445.69	$37,595.04
GSHP System	$32,107.95	$32,484.00	$31,787.96
GSHP System with Grant	$25,758.28	$25,967.69	$25,448.61

Table 17. Annual Cost Over 20 Years of Greenhouse with HVAC System			
	Farmington, NM	Gallup, NM	Page, AZ
Propane Heating + Evaporative Cooling ($1.92/gal-propane)	$1,929.15	$2,027.63	$1,739.98
Propane Heating + Evaporative Cooling ($2.82/gal-propane)	$2,173.92	$2,322.28	$1,879.75
GSHP System	$1,605.40	$1,624.20	$1,589.40
GSHP System with Grant	$1,287.91	$1,298.38	$1,272.43

14. Fruit and Vegetable Yield

The greenhouse has a floor space of 288 square feet but, the entire floor space cannot be utilized for growing. In order to estimate the fruit and vegetable yield, it is assumed three layout configurations in which 59%, 69%, and 81% of the floor space is utilized. (Bartok, 2015) Based off data agricultural data from NC State, University of California Cooperative Extension, Texas A&M, UC Davis, University of Missouri, and the U.S. Department of Agriculture (USDA), the average yield of food per season is 243 grams (g) per square foot. Additionally, the World Health Organization (WHO) recommends a daily intake of 400 grams of fruits and vegetables. (*Diet, Nutrition and the Prevention of Chronic Diseases*, 2003) Assuming a 90-day growing season, the annual fruit and vegetables servings grown per year is 412 – 564. Using the life cycle annual cost data for the GSHP system with a grant, the cost per serving is $2.26 – $3.15 (Table 18). In comparison, the USDA estimates a daily serving of fruits and vegetables costs between $2.10 – $2.60 from the grocery store. (U.S. Department of Agriculture Economic

Research Service, n.d.) For a greenhouse utilizing the 81% layout configuration, the cost per generating serving is within the range of grocery store prices, making it a cost-effective option.

Table 18. Cost per Generated Serving of Fruits/Vegetables from GSHP System with Grant				
Greenhouse Layout Configuration	Servings of Fruits/Vegetables per Year	Farmington, NM	Gallup, NM	Page, AZ
59%	412	$3.13	$3.15	$3.09
69%	480	$2.68	$2.70	$2.65
81%	564	$2.28	$2.30	$2.26

15. Conclusion

The on-going health crisis and high rate of diabetes experienced by Navajo people are certainly linked to food insecurity on the reservation. In order to increase healthy food access, Navajo food systems that have historically been affected by U.S. colonialism must be rebuilt. Increasing direct involvement with food production offers many benefits; however, lack of water resources, available land, food production knowledge, and capital are major challenges to rebuilding these self-sufficient systems.

On the other hand, a community based approach, utilizing gardens at chapter houses, distributes responsibility and costs and leverages community knowledge. To address water sustainability, greenhouse systems should be considered because they consume 21% to 24% less water than traditional open-air growing methods. By incorporating drip irrigation and water collection systems, even greater water savings could be achieved. The main drawback to greenhouses is the significant energy requirement for HVAC systems, which is both a financial concern as well an environmental issue.

Greenhouse HVAC systems generally consume propane, water, and electricity. However, GSHPs are a promising technology that would eliminate the use of propane and would reduce HVAC water consumption by 72% – 90%. Because GSHPs are a form of renewable energy, they also consume less electricity. As a result, operating costs are 57% – 72% less than propane heating and evaporative cooling systems; and GSHPs emit 35% – 69% less carbon dioxide. Use of solar photovoltaics and battery storage would eliminate HVAC water consumption and carbon dioxide emissions completely. Despite the benefits of GSHPs, high capital costs are a major barrier. If grants are taken advantage of, then conservative estimates show GSHPs could have a payback period between 5.2 – 10.8 years. A life cycle cost analysis over 20 years shows that a greenhouse equipped with a GSHP could cost as low as $1,272 per year. Based off available Navajo Nation tax revenue, each chapter could afford a greenhouse with a GSHP.

More importantly, the greenhouse would yield 412 – 564 daily servings of fruits and vegetables per year at a price that is competitive with grocery store prices. By no means are greenhouses going to solve food insecurity and diabetes on the Navajo reservation; however, they are a step toward rebuilding traditional food systems, educating people on healthy eating, and encouraging involvement with food production.

Appendix

Appendix A. Greenhouse Temperature Statistics - No Heating of Cooling				
Annual Statistics				
	Average (ºF)	**Standard Deviation (ºF)**	**Low (ºF)**	**High (ºF)**
Farmington, NM	63	23	14	121
Gallup, NM	60	24	8	116
Page, AZ	69	23	25	124
Summer Months (June, July, Aug) Statistics				
	Average (ºF)	**Standard Deviation (ºF)**	**Low (ºF)**	**High (ºF)**
Farmington, NM	83	19	39	121
Gallup, NM	78	19	38	116
Page, AZ	88	18	49	124
Winter Months (Nov, Dec, Jan) Statistics				
	Average (ºF)	**Standard Deviation (ºF)**	**Low (ºF)**	**High (ºF)**
Farmington, NM	45	16	15	85
Gallup, NM	44	19	8	94
Page, AZ	50	14	25	88

This table shows statistics for internal greenhouse temperatures by year, summer, and winter at three design locations. All calculations were carried out using SketchUp, OpenStudio, and EnergyPlus.

Table B. Greenhouse Internal Operating Temperature Schedule		
Month	**Daytime Operating Temperature**	**Nighttime Operating Temperature**
January	70ºF - 60ºF	60ºF - 50ºF
February	70ºF - 60ºF	60ºF - 50ºF
March	80ºF - 70ºF	70ºF - 60ºF
April	80ºF - 70ºF	70ºF - 60ºF
May	80ºF - 70ºF	70ºF - 60ºF
June	90ºF - 70ºF	70ºF - 60ºF
July	90ºF - 70ºF	70ºF - 60ºF
August	90ºF - 70ºF	70ºF - 60ºF
September	80ºF - 70ºF	70ºF - 60ºF
October	80ºF - 70ºF	70ºF - 60ºF
November	80ºF - 70ºF	70ºF - 60ºF
December	70ºF - 60ºF	60ºF - 50ºF

All temperature ranges were based off optimal growing temperatures from various fruits and vegetables. (Sanchez, 2002)

Appendix C. Average Daily Water Requirement (gal/day) of Standard Grass for Area of 288 ft^2 (Brouwer & Heibloem, 1986)			
	Mean Daily Temperature		
Climate Zone	**Less than 59ºF**	**59ºF - 77ºF**	**Greater than 77ºF**
Desert/Arid	35	53	67
Semi-Arid	32	46	63
Sub-Humid	25	39	53
Humid	11	25	39

Appendix D. Average 2018 Residential Electricity Price (¢/kWh) by State (U.S. EIA, 2018)	
State	**Price (2018 USD)**
Arizona	13.30 ¢/kWh
New Mexico	12.14 ¢/kWh
Utah	10.79 ¢/kWh
Average	12.08 ¢/kWh

Appendix E. GSHP Ground Loop Borehole Depth (ft) Based on Soil Type			
Soil Type	Farmington, NM	Gallup, NM	Page, AZ
Sand	239	268	242
Clay	190	213	193
Loam	215	241	218
Sat. Sand	127	142	129
Sat. Clay	152	170	154

Borehole depths were calculated using the ASHRAE Excel borehole sizing spreadsheet. (Philippe et al., 2010) Soil thermal properties were obtained from a ground loop design manual. (Bard Manufacturing Company, 2007)

Appendix F. Present Value Formulas and Discount Factors for Life Cycle Cost Analysis	
One Time Amount	$P = C\frac{(1+e)^N}{(1+d)^N}$
Annually Recurring Uniform Amounts	$P = A \times \frac{(1+d)^N - 1}{d(1+d)^N} = A \times UPV_N$
Annually Recurring Non-Uniform Amounts	$P = A_O \times \left(\frac{1+e}{d-e}\right)\left[1 - \left(\frac{1+e}{d+e}\right)^N\right] = A \times UPV_N^*$
Annually Recurring Energy Costs	$P = A \times UPV_{N,FEMP}^*$
Variables	P = Present Value C = Current Future Single Cost e = Escalation Rate d = Discount Rate N = Time Period (years) A = Annually Recurring Uniform Cost A_O = Annually Recurring Cost at Base-Date Price UPV_N = Uniform Present Value Factor UPV_N^* = Modified Uniform Present Value Factor $UPV_{N,FEMP}^*$ = Energy Uniform Present Value Factor

Appendix G. Life Cycle Cost Analysis Factors	
Discount Rate (d)	3.00%
Average Water Escalation Rate (e) (U.S. DOE, 2017)	0.40%
Number of Discount Periods (N)	20 years
UPV_{20} (Lavappa, Kneifel, & O'Rear, 2017)	14.88
$UPV^*_{20\text{-Water}}$ (Lavappa et al., 2017)	15.46
$UPV^*_{20\text{-Propane}}$ (Lavappa et al., 2017)	16.72
$UPV^*_{20\text{-Electricity}}$ (Lavappa et al., 2017)	15.93

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