THESIS

INFORMED DECISION-MAKING ON PHOTOVOLTAIC ADOPTION FOR WESTERN COLORADO PEACH ORCHARDS

Submitted by

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ABSTRACT

INFORMED DECISION-MAKING ON PHOTOVOLTAIC ADOPTION FOR WESTERN COLORADO PEACH ORCHARDS

The Solar Orchard Analysis and Recommendation Tool (SOAR) is an interactive decision-support tool curated for Western Colorado's peach growers to characterize photovoltaic adoption on their farms. Peach orchards use a substantial amount of energy that has the potential to be offset by photovoltaic arrays, allowing the farmer to reduce their operational costs as well as contribute to renewable energy initiatives. In addition, the benefits of solar energy can be enhanced as producers electrify their equipment where appropriate. Each farmer has their own unique energy supply and demand needs that can change over time as tools and vehicles become electrified and as photovoltaic technology evolves. In response, SOAR was created with engineers and local orchard growers to help farmers manage their energy needs. Furthermore, this tool allows farmers to evaluate the effects of different financing options on payback period, return on investment and initial investment cost of a PV array. The use of this decision support tool is exemplified with the use of a case study farm to demonstrate various supply and demand scenarios.

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1. Introduction

1.1 Background

Agricultural operations represent a multifaceted challenge that involves many unique considerations. Notably, the rapid emergence and evolution of technology presents both opportunities and challenges for farmers. While technological innovations have the potential to streamline operations, their accessibility and comprehensibility can pose significant hurdles. For example, it has been shown that as of 2023, only 27 percent of farmers use precision agriculture technology, despite its technological emergence having been available since the 1990s (U.S. Government Accountability Office, 2024). One way to try and bridge the gap between implementing new technology into farming operations is through the creation of decision support tools (DSTs). DSTs can help farmers facilitate different management practices by giving them access to evidence-driven insights, actionable recommendations, and comprehensive analyses tailored to their specific operational needs and challenges (Iakovidis et al., 2024). Farmers navigating the ever-changing terrain of modern agriculture stand to benefit from the continual development of DTSs to assist them in improving efficiency and innovation in their operations.

Economists and extension collaborate directly with farmers to create such decision support tools. This engagement and collaboration are suggested by researchers alike in order for DSTs to be used, as commonly, there is not a large uptake of such tools by farmers (Iakovidis et al., 2024). One area where DTSs could prove invaluable is in guiding farmers on the feasibility and implementation of photovoltaic (PV) systems on their land. With the rising costs of traditional energy sources and the need for more sustainable practices, solar power presents an attractive opportunity for farms to reduce their carbon footprint and reduce their operational costs (USDA, n.d.).

The peach industry provides an ideal study area to apply this decision support tool. Peach orchards face significant operational costs due to the energy-intensive process of cooling and storing the fruit after harvest. Maintaining precisely controlled low temperatures in storage sheds is crucial to preserve the quality and shelf life of peaches, thus this practice cannot be easily substituted for something less energy intensive (Farcuh & Tripu, 2021). Cooling also reduces food waste by preventing peaches from rotting quicky. By implementing PV systems, orchards may be able to offset a considerable part of these energy costs, improving profitability and sustainability.

Not only are peach operations an ideal choice due to the energy demands on such operations, peaches are also an important fruit to Colorado. Colorado's peach production represents a significant portion of the state's fruit output, constituting 75% of total fruit production in 2023 across about 2,400 acres (Bunning et al., 2020). This amounted to 15,450 tons of peaches in 2023 — a 17% increase from the previous year, placing Colorado 6th in peach production in the US. In 2023, the value of peach production reached $43.23 million, marking a 33% surge from 2022 (Ott, 2024). This upward trend in peach yield is anticipated to continue, therefore the energy used in growing and cooling the fruit is also expected to increase. By looking into PV, farmers can balance out this energy consumption while being a part of the push for renewable energy.

In addition to the energy demanded by coolers, which is expected to increase over time as peach production grows, the amount of mechanized tools, vehicles and tractors used in agriculture is also projected to rise (Scolaro et al., 2021). With an increase in motorized tools and technologies being implemented on orchards, there will be a corresponding increase in the energy demand and consequently a rise in greenhouse gas emissions. Currently, agriculture contributes to 20% of carbon dioxide emissions and 75% of nitrogen oxides with these numbers expected to grow in the coming decades (Scolaro et al., 2021).

While the electrification of tools and vehicles can be a step towards reducing GHG emissions, the environmental benefits will only be fully realized if the source of electricity is sustainable. As of 2023, 60% of electric generation is from fossil fuels and other non-renewable sources (*U.S. Energy Information Administration (EIA) - Frequently Asked Questions (FAQs)*, n.d.). Transitioning to renewable energy sources, such as solar photovoltaic (PV) systems, presents an opportunity for orchards and farms to power their operations with clean energy, thereby minimizing their carbon footprint and contributing to a more sustainable agricultural sector.

1.2 Problem Statement

Given the difficulties and the lack of publicly available information regarding the cost of solar installations, as well as the prevalence of misleading slogans such as "free solar panels", it becomes challenging for farmers to make informed decisions or consider solar energy without consulting solar companies (Robles, 2021). Obtaining cost estimates for solar installations often requires paying consultation fees, creating a significant hurdle. Due to these obstacles, farmers interested in photovoltaic (PV) technology may struggle to figure out where to begin their exploration of whether PV is the right decision for their operations. Addressing these challenges requires an investigation guided by the proposed research questions.

1.3 Research Questions

This thesis aims to provide a decision support tool that addresses four critical questions for orchard farmers considering solar power implementation. The four questions are as follows:

1. What is the potential for on-farm energy production from solar power systems, and how does it compare to the energy demand of farm operations?
2. In what scenarios does the use of electric farm equipment offer cost advantages or disadvantages compared to traditional gas-powered equipment, and how does this factor into the decision to adopt solar power?
3. How do regulatory constraints imposed by local energy providers influence the potential solar energy production capacity from a farm's photovoltaic (PV) system(s), and how could this influence electrification decisions?
4. How do factors such as net present value (NPV), payback period, return on investment (ROI) and initial installation cost vary with different financing options and influence the economic viability of implementing solar power systems on farms?

By answering these questions, the tool may empower orchardists with data-driven insights to make informed decisions about integrating solar power into their operations.

1.4 Objective

The objective of this research is to assist orchard farmers in determining the economic viability and potential benefits of installing PV systems on their land. The Solar Orchard Analysis and Recommendation Tool (SOAR) web tool aims to achieve this objective by empowering Colorado's peach farmers through evaluating their evolving energy needs while balancing potential supply sources. By considering factors such as available area for PV, motorized tool and vehicle usage, local regulatory restrictions as well as financing options, the SOAR tool better enables farmers to make decisions about renewable energy.

The output of the tool centers on four key results tailored for western Colorado peach growers. Firstly, it determines the optimal locations and capacities for solar installations to supply the farm, while also considering the extent of electrification suitable for the farmer's motorized tools and vehicles, thereby aligning the energy supply and demand. Secondly, the tool analyzes the advantages and disadvantages of using electric farm equipment compared to traditional gas-powered equipment. Third, SOAR evaluates how local energy regulations impact a farm's potential solar energy production from PV systems, influencing electrification decisions. The final objective involves a comprehensive economic analysis, examining the costs associated with solar installations under various financing scenarios. This analysis enables farmers to identify the threshold at which external funding or incentives would make solar installations financially feasible to meet their projected energy demands. This tool is built through collaboration with peach orchard farmers as well as orchard researchers and engineers to ensure that the tool addresses real-world challenges faced by farmers and is accurate as well as user-friendly.

2. Literature Review

2.1 The Environment and PV Technology

The pursuit of renewable energy sources has gained significant momentum in the past decade as nations strive to achieve the United Nations' goal of net-zero emissions by 2050 as set in the 2015 Paris Agreement. This ambitious target is crucial in mitigating the impacts of climate change, as the energy sector accounts for approximately three fourths of global greenhouse gas emissions today (United Nations, 2023). Therefore, the advancement and widespread use of photovoltaic (PV) technology is playing an increasingly pivotal role in this transition towards a sustainable energy future.

Although the concept of PV technology has existed since the 1950s with the invention of the silicon PV cell in the United States, its widespread adoption and efficiency improvements have been more recent developments (Energy.gov- *The History of Solar, n.d.*). The continuous evolution of PV technology, including advancements in panel designs, inverters, and battery storage systems, has further enhanced the efficiency of solar energy and its cost-effectiveness (Kavlak et al., 2018). As a result, PV systems can be incorporated into almost any environment; this includes on a farm.

2.2 PV on Farm Rooftops

One viable option for farm operations to begin implementing photovoltaic (PV) systems is by utilizing their rooftop spaces. A study by Tudisca et al. (2013) evaluated the economics of installing PV systems on farm buildings in Sicily. The researchers found that even without external financing, the revenues generated by the PV systems outweighed the associated costs, with internal rates of return ranging from 15.92% to 23.63% and consistently positive net present values. Furthermore, the study highlighted that the integration of PV systems enabled farmers to diversify their income streams and transform their land into multifunctional spaces.

The findings from Tudisca et al. (2013) aligns with other research that demonstrates the potential of rooftop PV installations to offset a significant portion of the energy consumed within farm buildings. For instance, a study by Hosouli et al. (2023) explored the feasibility of using PV systems to meet the heating demands of dairy farms, ultimately reducing their reliance on grid-supplied electricity.

For peach orchards, rooftop PV installations could be particularly advantageous given the large energy demands associated with cooling and storage operations. By leveraging the available rooftop areas on these storage facilities and packing sheds, peach orchards can potentially offset a portion of their cooling and storage energy expenses. This aligns with findings from studies like Lakomiak and Zhichkin (2019), which explored the feasibility of rooftop PV to offset the energy used in fruit growing, specifically for apples and peaches in Poland. They found that energy costs account for 6% of the costs of an orchard and that installing PV panels on the roof could cut the cost in half, conditional that financial support is given to install the panels. They also found that such an array does not guarantee energy independence. Nonetheless, the integration of rooftop PV systems presents a promising opportunity for peach orchards to embrace sustainable energy practices and potentially reduce their operating costs by offsetting a portion of their energy expenses.

2.3 PV on Farmland

In addition to rooftop installations, there is significant potential for integrating photovoltaic (PV) systems directly onto farmland. This could be farmland that is not productive and thus has no crops being grown on it or idle land that is not being used for any cropping purpose. Regardless of location, when considering the implementation of ground-mounted, on-farm PV systems, it is crucial to balance the energy demand of agricultural operations with the potential electricity supply from the PV array. Nacer et al. (2016) conducted a study focused on small Algerian dairy farms, employing an energy balance method to optimally size the PV system. Their objective was to design a ground-mounted PV array capable of meeting the energy requirements of the farm without generating excess or insufficient electricity. This approach, which excludes battery storage, relies on the grid to inject surplus energy when production exceeds demand and drawing electricity when demand outpaces production. By aligning the PV system's capacity with the farm's energy needs, such studies aim to maximize the economic and environmental benefits of on-farm renewable energy integration.

This method is common for sizing many PV systems, and as such a similar method was used by Brazen and Brown (2009) to size a PV system fit to meet the energy demands on a poultry farm. Other studies, such as one by Gorjian et al. (2020) were able to evaluate the various placement opportunities of PV on a farm, for instance near water pumps, on top of bodies of water and ground-mounted systems to provide shade for livestock.

In addition to sizing, government incentives and policies play a significant role in the economic viability of on-farm PV systems. Bazen and Brown (2009) assessed the potential of PV systems in the poultry farming industry in Tennessee, considering efficiency limits and financial aid. Their cost-benefit model indicated that PV installation would only yield a positive net present value with a 10% decrease in costs or with the support of full federal and state incentives.

2.4 Agrivoltaics

The challenges surrounding the integration of solar technology within orchards, which is called agrivoltaics, along with the lack of research concerning its influence on crop growth and soil health, have historically impeded the widespread adoption of PV systems in agricultural settings. When integrated into crops, there is a one- or two-way symbiosis between the crops and PV that can yield net positive or negative economic outcomes. However, recent studies have substantially contributed to addressing these questions. A study by Juillion et al. (2022) revealed that apple trees grown underneath conventional PV panels results in lower flower intensity, and therefore a lower number of fruit yield, although there was an increase in soil moisture retention and protection from frost damage. Despite peaches being a stone fruit, many of the same conclusions from this study can be applied to peaches as well, with the main issue of PV integration on orchards resulting in a reduction in sunlight. Although there is now more research regarding the yield effect of panels on fruit trees, there is still little research regarding the cost of such agrivoltaic orchard systems.

One study that looked at the implementation of semi-transparent solar panels over a pear orchard to act as hail nets found that an agrivoltaic system would result in a loss of 6,000 euros per hectare due to smaller fruit size, and with subsidies, the average energy income must be at least 10 euros per MWh to break even. The shading effects reduced the yield of pears and such PV installations that go above trees are costlier than normal ground-mounted solar (Willockx et al., 2024). This same study also found that the panels provided frost protection for the trees by increasing the temperature under the panels at night. Another study on orchard agrivoltaics by Trommsdorff et al. (2023) conducted an economic analysis of agrivoltaics on an apple orchard in Germany. They found that they could reduce the investment cost of the system by 26% because the PV arrays replaced the hail net system, thus also reducing the operating costs of the farm by 9% due to lower land and maintenance work. However, annual revenues from apple cultivation decreased by 9% due to shading.

Despite these challenges, agrivoltaic systems can serve multiple benefits through protective functions for peach orchards, such as hail nets, frost shields, and moisture retention aids. For Colorado peach orchards, these protective features could potentially outweigh the associated costs and yield reductions. The critical nature of such protection was illustrated in 2020, when a severe frost event in Western Colorado devastated entire peach crops in several orchards (Paul, 2020). This incident shows the vulnerability of peach cultivation to unpredictable weather events and highlights the potential value of agrivoltaic systems in mitigating such risks. This situation also highlights the need for more research regarding the installation of solar panels over peach trees, especially in dry climates like Colorado. Currently, there is not enough research specific to peach orchards on the crop production side or economic side to determine the value of an agrivoltaic system.

While very few studies address integrating photovoltaic (PV) systems onto orchards, the limited literature that does exist predominantly focuses on rooftop installations, ground mounted installations and agrivoltaics on apples or pears orchards, thus overlooking the broader possibilities for solar integration within peach orchards. Using methods similar to the studies mentioned above, a comparable analysis can be conducted on peach orchards in Western Colorado, where the size of the PV system varies, as do the financial incentives. One crucial aspect that will be included in this study is evaluating multiple PV array locations within the same farm, including rooftop, ground-mounted, and agrivoltaic systems. By considering these diverse installation options, the study aims to provide a comprehensive assessment of the potential for solar adoption in peach orchards.

2.5 The Environment and Electrification

The electrification of tools and equipment is another crucial sustainability initiative that complements the adoption of renewable energy sources like PV technology. As the world transitions towards a low-carbon future, the replacement of traditional fossil fuel-powered machinery with electric alternatives is gaining momentum across various sectors, including agriculture.

The agricultural industry has historically relied on gasoline and diesel-powered equipment for tasks such as tilling, harvesting, and transportation (Chel & Kaushik, 2011). These conventional engines contribute significantly to greenhouse gas emissions and air pollution, with diesel consumption accounting for 44 percent of direct energy consumption on farms (Hitaj, 2018). By electrifying agricultural tools and machinery, farms can reduce their dependence on fossil fuels and minimize their carbon footprint. Additionally, electric motors offer several advantages over their internal combustion counterparts, including higher efficiency, lower maintenance costs, and quieter operation (Scolaro et al., 2021).

The electrification of agricultural equipment becomes even more environmentally beneficial when combined with the implementation of PV systems on farms. By generating renewable electricity through solar panels, agricultural operations can power their electric tools and machinery using a sustainable energy source. This synergy between electrification and solar energy not only reduces greenhouse gas emissions but also promotes energy independence and resilience for farmers. This study aims to produce a tool allowing farmers to find this synergy.

2.6 Current Decision Support Tools for Farms

The present status of decision support tools for farmers primarily encompasses sizing solar on a farm and focuses on one type of installation - a rooftop or a ground mounted system. One tool that is free of charge and available for everyone to use is the National Renewable Energy Lab (NREL) PVWatts tool. This tool incorporates the use of google maps to determine the possible output of a PV array either on land or on a rooftop. Additionally, this tool evaluates one location at a time (Psomopoulos et al., 2015**).** While the NREL PVWatts tool is able to tell users their predicted output in kWh, the tool does not include information about how much a PV array of its calculated size would cost.

Several researchers have developed tools to aid in the evaluation of solar adoption by looking at costs. For instance, Banik et al. (2022) created the "Solar-Cost Calculator," a mobile phone application designed to assist households in Bangladesh in determining the cost of installing solar panels to power their homes. This tool is specifically localized for the Bangladeshi context. Another cost related tool was developed by Sandia Laboratories of the Department of Energy in New Mexico, USA. Sandia is used to calculate the payback period for rooftop photovoltaic (PV) installations. This tool is implemented in Microsoft Excel and considers technical details of PV installation such as tilt angle of the panels, system degradation rate, annual system production as well as the increase in utility costs (Riley et al., 2016).

In addition to researchers, photovoltaic (PV) array installation companies often have their own software to size and price PV arrays for various customers, ranging from households to businesses and farmers. For instance, EnergySage.com provides a solar calculator that looks at an individual's location and current electricity bill cost. While this tool considers the federal tax credit available for household solar installations, it is limited to evaluating rooftop PV arrays and does not account for other configurations, such as ground-mounted or agrivoltaic systems.

Many other PV installation companies have developed their own software tools to comprehensively size and analyze the costs of PV arrays for specific applications. However, these tools are typically not publicly available and often require local installers to visit the site to provide a quote.

The proposed tool for Western Colorado peach orchards aims to be an open-source, publicly accessible resource that empowers farmers to independently evaluate various photovoltaic (PV) array configurations tailored to their specific orchard conditions and energy requirements. In addition to the tool being publicly accessible, the source code will be available for anyone to view through GitHub. The primary objective is to give farmers a clear understanding of their current and projected electricity needs, enabling them to make an informed decision about the suitability of solar adoption for their operations. By leveraging this tool, farmers can gain a preliminary assessment of the potential benefits and feasibility of solar integration, allowing them to subsequently engage with local PV array installers for more detailed and accurate quotes. Ultimately, this tool serves as a starting point to equip farmers with the knowledge necessary to initiate the process of solar adoption given PV makes sense for their needs.

3. Methods

3.1 Accessing SOAR

In order to access SOAR, clicking on the following link will direct you to the app: https://samanthabryan.shinyapps.io/SOAR/ . Upon clicking the link, you will be directed to the initial page of the tool, which opens on the questionnaire tab. From there, the tool can be easily explored by the user. SOAR is hosted on the Shinyapps.io cloud which is a platform for tools developed in shiny to be published for free. This allows for anyone to access the tool, ensuring farmers can easily benefit from the insights provided by SOAR.

3.2 Focus area

The focus area for the web tool encompasses four western Colorado counties: Mesa, Delta, Montrose, and Montezuma, renowned for their substantial peach cultivation (Bunning et al., 2020). These counties are known for their tasty peaches, a result of Colorado's extended periods of hot, dry, sunny summer days coupled with cool summer nights, facilitating the development of sugars within the fruits. Particularly noteworthy is Mesa County, home to the city of Palisade, where the popular Palisade peaches come from. Mesa county benefits from an optimal peach-growing microclimate created by warm winds from the surrounding mesas (Outcalt, 2014). Collectively, these counties host the majority of Colorado's 405 peach farms (Ott, 2024). Local considerations, such as quantity of solar radiation and crops costs and prices are integrated in the tool.

3.3 Programming the Tool in R Shiny

3.3.1 Introduction to R Shiny

To tailor solutions to the unique requirements and preferences of peach farmers the web-based tool Solar Orchard Analysis and Recommendation Tool was developed using the R Shiny framework. R is an open-source programming language widely utilized for statistical analysis. It offers powerful capabilities for data manipulation, visualization, and statistical modeling tasks. With a large and active community of users, R has extensive support and is a popular choice among researchers, data scientists, and economists.

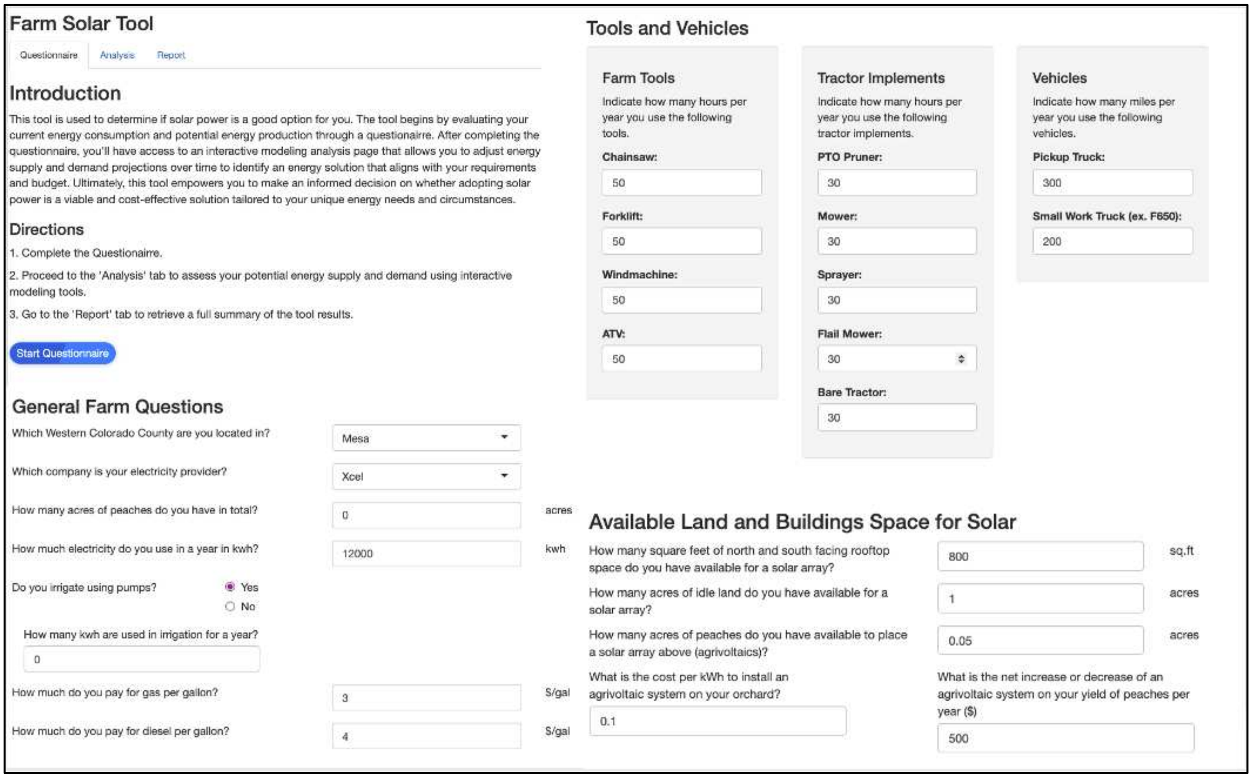
R Shiny is a web application framework built within R, enabling users to create interactive web tools. The basic structure of an R Shiny application consists of two main components: the user interface (UI) and the server. The UI component defines the layout and visual elements that the application's users will interact with, while the server component handles the data processing, calculations, and backend operations.

3.4 Tool Architecture

3.4.1 Layout and Structure of the User Interface (UI)

The decision tool is structured into three tabs within the user interface (UI) component of R Shiny. The first tab, the questionnaire, provides instructions and a questionnaire specifically designed for farmers, as shown in figure 1. The second tab, the analysis, as shown in figure. 2 and 3, acts as the analysis hub, featuring interactive graphics and an economic analysis table to explore various aspects of PV applications within a farm. The third tab, the report, seen in figures 4 through 6, presents a comprehensive report by consolidating the results from the first and second tabs to give a complete overview of the analysis.

3.4.2 Tab 1: Questionnaire



Farm Solar Tool

Introduction

This tool is used to determine if solar power is a good option for you. The tool begins by evaluating your current energy consumption and potential energy production through a questionaire. After completing the questionnaire, you'll have access to an interactive modeling analysis page that allows you to adjust energy supply and demand projections over time to identify an energy solution that aligns with your requirements and budget. Ultimately, this tool empowers you to make an informed decision on whether adopting solar power is a viable and cost-effective solution tailored to your unique energy needs and circumstances.

Directions

1. Complete the Questionairre.
2. Proceed to the 'Analysis' tab to assess your potential energy supply and demand using interactive modeling tools.
3. Go to the 'Report' tab to retrieve a full summary of the tool results.

General Farm Questions

Which Western Colorado County are you located in? Mesa

Which company is your electricity provider? Xcel

How many acres of peaches do you have in total? 0 acres

How much electricity do you use in a year in kwh? 12000 kwh

Do you irrigate using pumps? ● Yes ○ No

How many kwh are used in irrigation for a year? 0

How much do you pay for gas per gallon? 3 S/gal

How much do you pay for diesel per gallon? 4 S/gal

Tools and Vehicles

Farm Tools

Indicate how many hours per year you use the following tools.

Chainsaw: 50

Forklift: 50

Windmachine: 50

ATV: 50

Tractor Implements

Indicate how many hours per year you use the following tractor implements.

PTO Pruner: 30

Mower: 30

Sprayer: 30

Flail Mower: 30

Bare Tractor: 30

Vehicles

Indicate how many miles per year you use the following vehicles.

Pickup Truck: 300

Small Work Truck (ex. F650): 200

Available Land and Buildings Space for Solar

How many square feet of north and south facing rooftop space do you have available for a solar array? 800 sq.ft

How many acres of idle land do you have available for a solar array? 1 acres

How many acres of peaches do you have available to place a solar array above (agrivoltaics)? 0.05 acres

What is the cost per kWh to install an agrivoltaic system on your orchard? 0.1

What is the net increase or decrease of an agrivoltaic system on your yield of peaches per year ($) 500

Figure 1: Tab 1- Questionnaire

Section 1 of the questionnaire gathers general information about the farm. It determines the county in Western Colorado where the orchard is located, the electricity provider, and the current prices for gasoline and diesel. This section also captures the farmer's existing electricity usage, including their current kWh demand as indicated on their electricity bill, while also accounting for energy consumption related to irrigation practices.

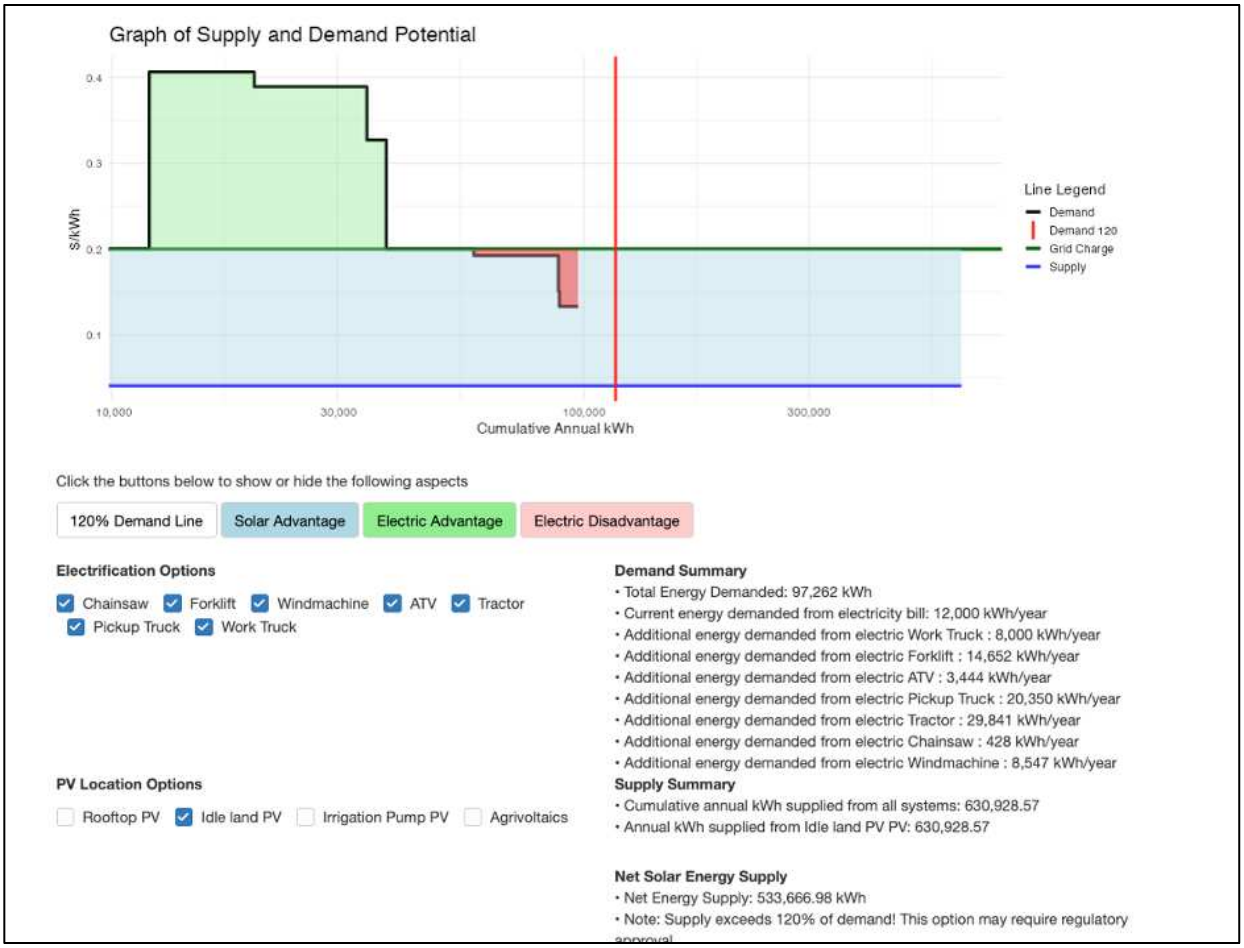
The second part of the questionnaire asks farmers to provide the annual usage hours for various motorized tools and the annual milage for farm vehicles that currently have electric options. Farm vehicles such as semi-trucks are not included in the questionnaire, as they can not feasibly be electrified. This information helps estimate the potential increase in electricity demanded as farmers gradually transition to electric equipment and vehicles.

The third part of the questionnaire inquires about the square footage and acreage that farmers are willing to allocate for solar panel installations on their current land and operations. This information sets constraints on the area that the tool can consider for solar energy production. Once the farmer has completed the questionnaire, they can proceed to the second tab of the tool.

3.4.3 Tab 2: Analysis

The second tab of the tool presents an analysis section featuring a comprehensive graphic as well as an economic table. The graphic allows users to determine where their adjustable energy demanded meets their adjustable energy supply. It also allows users to see their electrification advantage and disadvantage and their PV advantage or disadvantage. These features are designed to answer the research questions presented in my introduction.

The Graphic



Click the buttons below to show or hide the following aspects

Electrification Options

☑ Chainsaw ☑ Forklift ☑ Windmachine ☑ ATV ☑ Tractor
☑ Pickup Truck ☑ Work Truck

PV Location Options

☐ Rooftop PV ☑ Idle land PV ☐ Irrigation Pump PV ☐ Agrivoltaics

Demand Summary
- Total Energy Demanded: 97,262 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year
- Additional energy demanded from electric Tractor : 29,841 kWh/year
- Additional energy demanded from electric Chainsaw : 428 kWh/year
- Additional energy demanded from electric Windmachine : 8,547 kWh/year

Supply Summary
- Cumulative annual kWh supplied from all systems: 630,928.57
- Annual kWh supplied from Idle land PV PV: 630,928.57

Net Solar Energy Supply
- Net Energy Supply: 533,666.98 kWh
- Note: Supply exceeds 120% of demand! This option may require regulatory approval

Figure 2: Tab 2 - Dynamic Supply and Demand Graph

The graphic's y-axis represents the price per kilowatt-hour ($/kWh), while the x-axis displays the total kilowatt-hour (kWh) consumption or production. The first three components that always present on the graph are the grid charge line, the supply line and the demand line. The grid charge line is depicted with a green line, the demand line in black and the supply line in blue. An example graph is seen in figure 2 above.

The grid charge line represents the farmer's current electricity rate based on their responses from the first section on the questionnaire. This line intersects the y-axis at a fixed point, reflecting the farmer's present-day grid charge.

The supply line illustrates the cumulative kWh output from potential solar installations on the farmer's land. The y-axis values for this line represent the cost per kWh for different solar installation options, which vary based on the farmer's geographic location and responses from the questionnaire. The x-axis values correspond to the cumulative kWh output from the selected solar installations. For instance, if the farmer opts to install solar panels on rooftops and idle land, the x-axis will display the combined kWh output from these two options while arranging them from least to most expensive based on a calculated cost per kWh. Four possible supply sources are considered: rooftops, idle land, pumps and agrivoltaics.

The demand line depicts the increasing demand for electricity as more tools and vehicles are electrified. The y-axis values for this line represent the operational breakeven cost compared to gas or diesel of electrifying a tool or vehicle expressed in $/kWh. It is important to note that the operational break-even does not include any fixed costs such as the ownership cost of the tools or vehicles. The operational breakeven cost indicates the cost per kWh at which the electrical version of the tool or vehicle becomes cost-equivalent to its gas-powered counterpart. For example, if the operational breakeven cost for an electric truck is $1.50/kWh, it means that the cost of drawing electricity from the grid would need to exceed $1.50/kWh for the gas version to be the more cost-effective option. If the grid cost is lower, there is an electrification advantage. The x-axis values show the cumulative electricity demand from the electrified tools and vehicles based on the usage hours provided by the farmer in the second part of the questionnaire. The electrification ranking from left to right is established by organizing options based on their operational breakeven, with the most financially advantageous tools and vehicles listed first, and the least advantageous ones following, encompassing only the user selected tools for electrification.

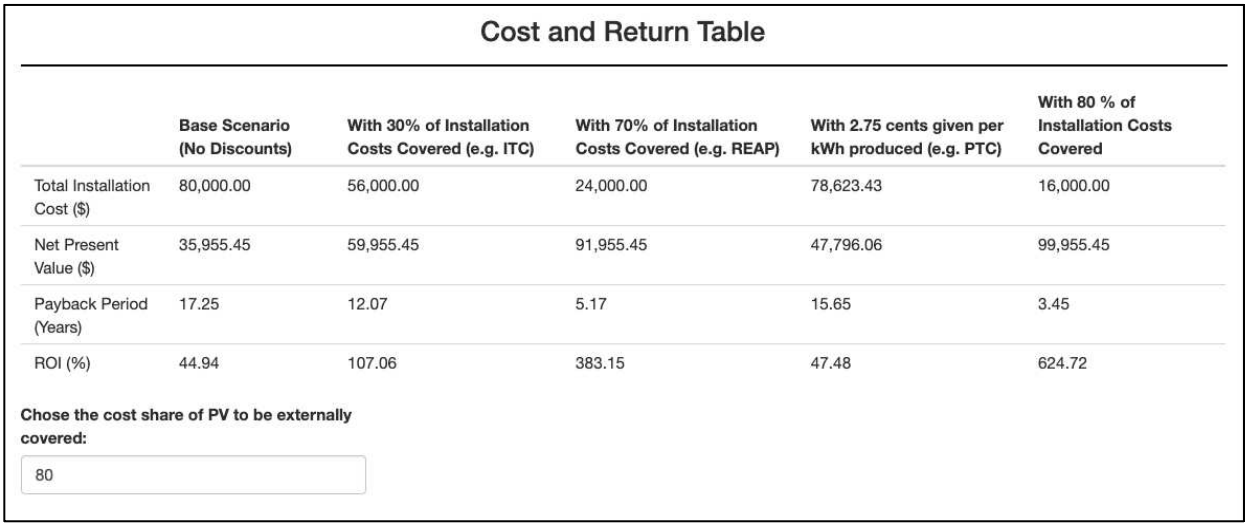
One of the values of SOAR is that it can help producers avoid oversupplying PV energy that cannot be sold or used on farm. The 120% demand line indicates the intersection point where the electricity supplied reaches 120% of the current demand, which is depicted with a vertical red line. This line serves as a reference, as most electricity providers have regulatory restrictions preventing on-site electricity generation from exceeding 120% of the customer's demand (*Empire Electric Association, Inc*, n.d.). When the supply line intersects this line, it suggests that the farmer should explore adjusting the solar installation area or acreage to align with the regulatory limits or they should increase the number of tools they want electrified, thus increasing their demand.

The electric advantage button shows on the graph where there is cost savings achieved by using electric tools compared to their gas-powered counterparts. This is shown on the graph as the space below the demand line and above the grid line and is highlighted in green. It's important to note that electrical advantage doesn't necessarily require installing PV arrays; it's only about comparing electric and gas tools.

The electric disadvantage button at the bottom of the graphic shows where there is no longer any cost savings from converting to electric, thus the gas version of the tool or vehicle is cheaper to operate. This happens if the demand line is below the grid line, creating an area below the grid line but above the demand line, which is highlighted in red.

The solar advantage button represents when a solar advantage occurs. A solar advantage occurs when all the energy needed on the farm can be supplied by solar power and is cheaper than buying energy from the grid. This is shown on the graph as the area below the grid line and above the supply line and shaded in blue. However, if the supply line crosses the grid line from below, it suggests that installing more PV arrays might not be economically wise anymore. This button shows the solar advantage compared to drawing from the grid regardless of regulatory constraints such as the supplying 120% of demand limitation.

The Cost and Return Table



Cost and Return Table

	Base Scenario (No Discounts)	With 30% of Installation Costs Covered (e.g. ITC)	With 70% of Installation Costs Covered (e.g. REAP)	With 2.75 cents given per kWh produced (e.g. PTC)	With 80 % of Installation Costs Covered
Total Installation Cost ($)	80,000.00	56,000.00	24,000.00	78,623.43	16,000.00
Net Present Value ($)	35,955.45	59,955.45	91,955.45	47,796.06	99,955.45
Payback Period (Years)	17.25	12.07	5.17	15.65	3.45
ROI (%)	44.94	107.06	383.15	47.48	624.72

Chose the cost share of PV to be externally covered:

80

Figure 3: Tab 2- The Cost and Return Table with Example Results

In addition to the visual analysis presented in the graphic, the tool provides a comprehensive table of economic indicators and financing options to aid farmers in their decision-making process as seen in figure 3. This table dynamically updates based on the supply and demand scenarios selected using the sliders in the previous section.

The economic indicators displayed in the table include the net present value (NPV), initial investment cost, return on investment (ROI), and payback period associated with the chosen solar installation and electrification options. These metrics offer farmers a quantitative assessment of the financial viability and potential returns of their proposed renewable energy and electrification decisions. Moreover, the tool evaluates these economic indicators under five distinct financing scenarios, recognizing that access to various incentives and financing options can significantly impact the overall economic feasibility of a PV system. This approach is similar to the analysis done by Brazen and Brown (2009), in which state and federal incentives were considered in their evaluation of PV power. The scenarios considered include:

1. Base Case: Solar installations are paid for out-of-pocket, without any external financing or incentives.

2. Federal Investment Tax Credit: A 30% tax credit is applied to offset the upfront costs of the solar installation. (*Summary of Inflation Reduction Act Provisions Related to Renewable Energy | US EPA*, 2023)

3. Federal Production Tax Credit: A tax credit of 2.75 cents per kWh is received for the first ten years of the solar installation's operation. (*Summary of Inflation Reduction Act Provisions Related to Renewable Energy | US EPA*, 2023)

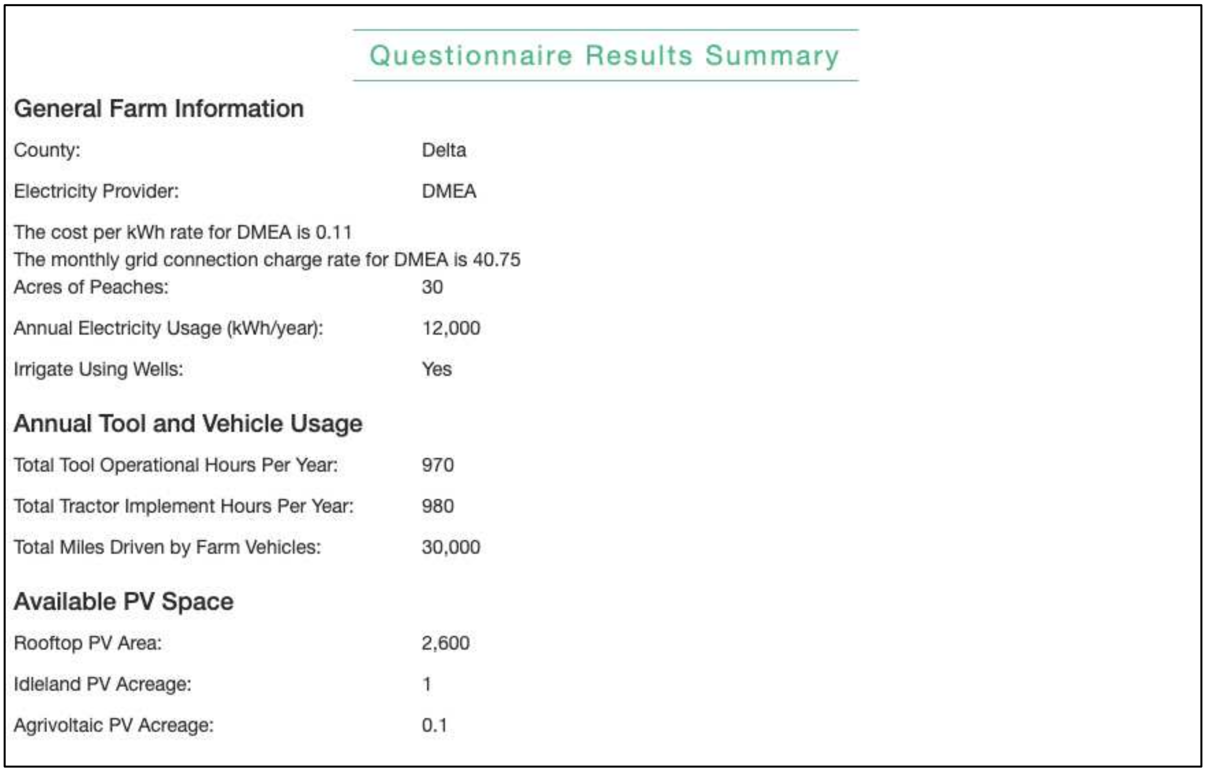
4. REAP Program: The Rural Energy for America Program (REAP) covers 75% of the project's cost, reducing the initial investment required. (*Rural Energy for America Program (REAP)*, 2024)

5. Choose your own financing amount: The user selects the percentage of PV installation costs to be covered externally.

For example, in the base case scenario, the initial investment cost is $80,000. In comparison, the initial investment costs in the other four scenarios are $56,000 under the ITC, $24,000 with the REAP program, $78,623.43 with the PTC, and $16,000 under the scenario where 80% external financing is chosen. These example results clearly illustrate which financing programs offer more significant benefits. Similar differentiation can be done with the ROI and payback period as well. By presenting these economic indicators and financing scenarios side-by-side, the tool allows farmers to compare the financial implications of their supply choices and make informed decisions regarding the most suitable approach for their specific circumstances.

3.4.4 Tab 3: Report

The third tab of the tool presents a comprehensive report summarizing the farmer's inputs and the results from the analysis. This report serves as a centralized resource, providing a holistic overview of the farmer's current farm scenario, as well as detailed breakdowns of the selected supply and demand stages.



Questionnaire Results Summary

General Farm Information

County: Delta

Electricity Provider: DMEA

The cost per kWh rate for DMEA is 0.11
The monthly grid connection charge rate for DMEA is 40.75

Acres of Peaches: 30

Annual Electricity Usage (kWh/year): 12,000

Irrigate Using Wells: Yes

Annual Tool and Vehicle Usage

Total Tool Operational Hours Per Year: 970

Total Tractor Implement Hours Per Year: 980

Total Miles Driven by Farm Vehicles: 30,000

Available PV Space

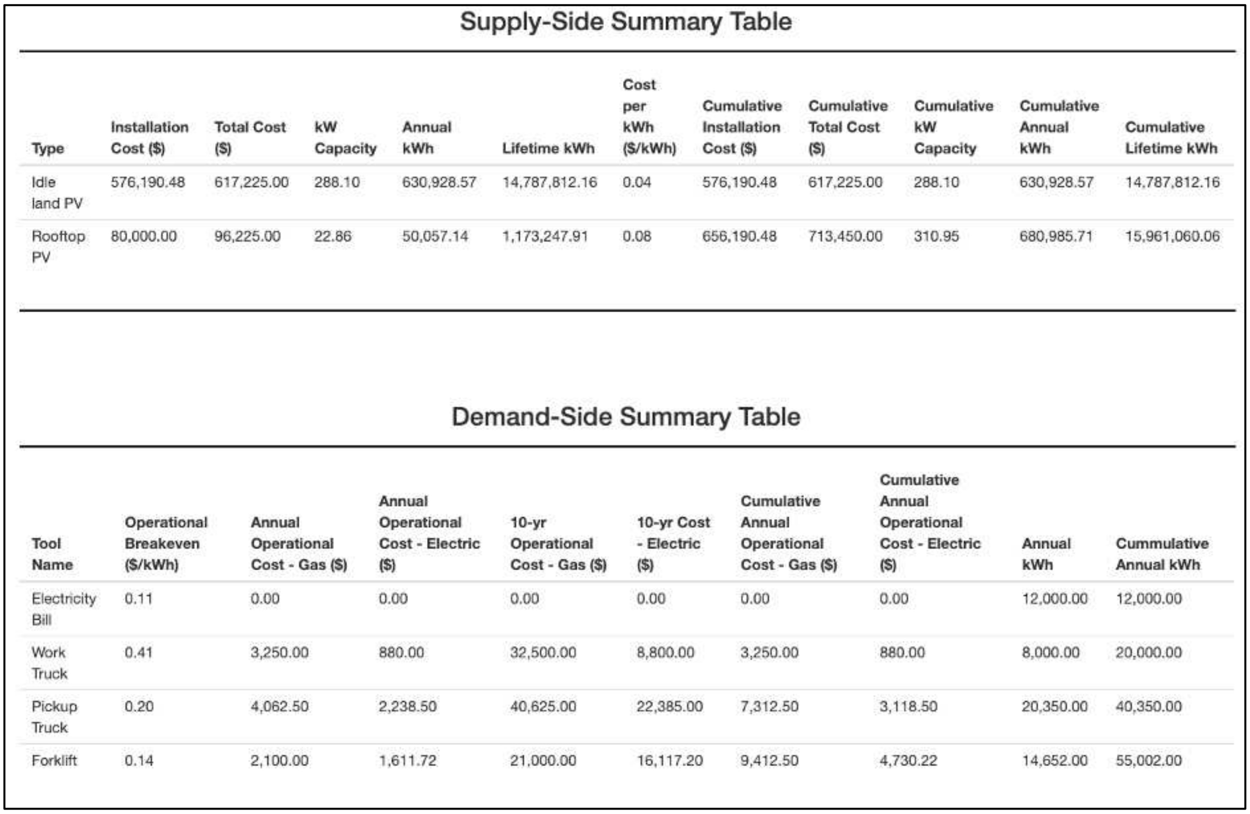
Rooftop PV Area: 2,600

Idleland PV Acreage: 1

Agrivoltaic PV Acreage: 0.1

Figure 4: Tab 3 - Questionnaire Summary Report

The report begins with a summary section that recounts the answers provided in the initial questionnaire, ensuring transparency and allowing the farmer to review their inputs. This questionnaire summary is seen in figure 4.



Supply-Side Summary Table

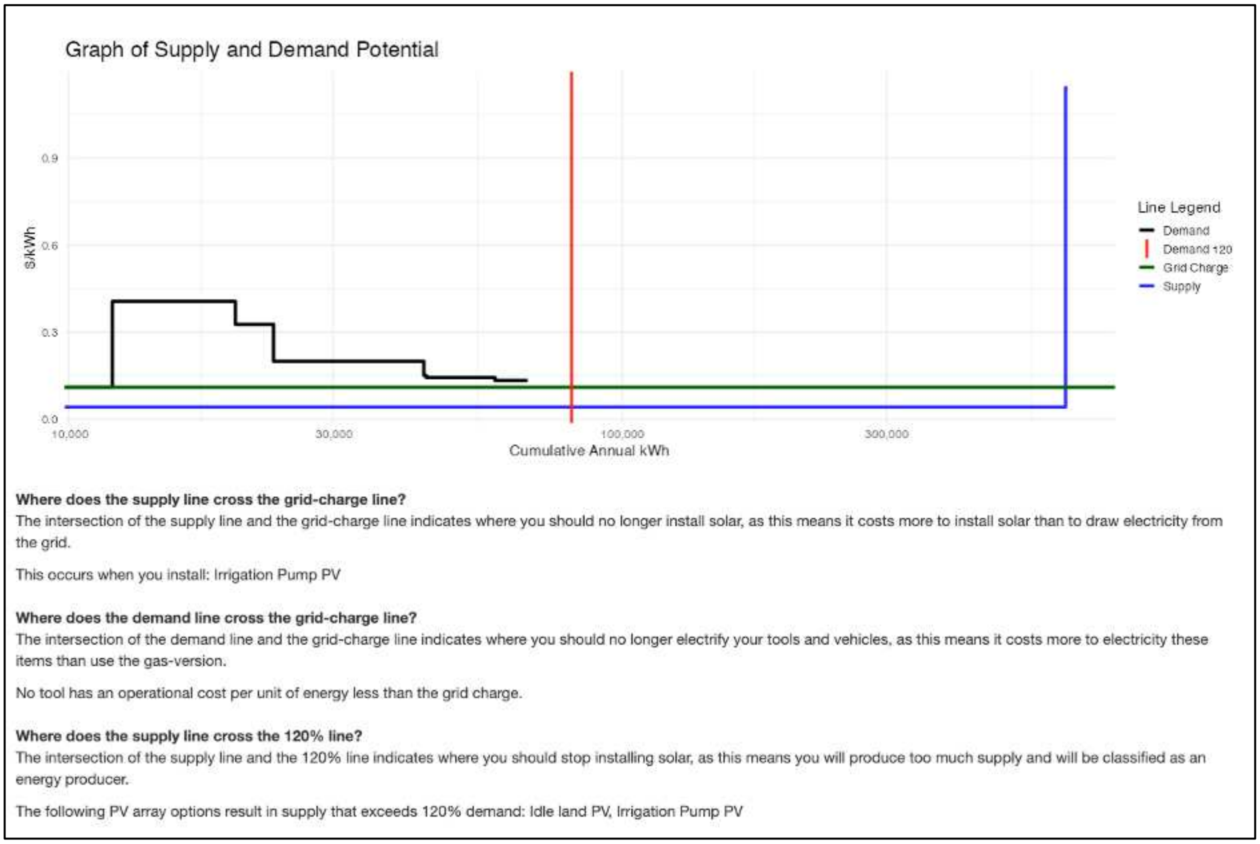
Type	Installation Cost ($)	Total Cost ($)	kW Capacity	Annual kWh	Lifetime kWh	Cost per kWh ($/kWh)	Cumulative Installation Cost ($)	Cumulative Total Cost ($)	Cumulative kW Capacity	Cumulative Annual kWh	Cumulative Lifetime kWh
Idle land PV	576,190.48	617,225.00	288.10	630,928.57	14,787,812.16	0.04	576,190.48	617,225.00	288.10	630,928.57	14,787,812.16
Rooftop PV	80,000.00	96,225.00	22.86	50,057.14	1,173,247.91	0.08	656,190.48	713,450.00	310.95	680,985.71	15,961,060.06

Demand-Side Summary Table

Tool Name	Operational Breakeven ($/kWh)	Annual Operational Cost - Gas ($)	Annual Operational Cost - Electric ($)	10-yr Operational Cost - Gas ($)	10-yr Cost - Electric ($)	Cumulative Annual Operational Cost - Gas ($)	Cumulative Annual Operational Cost - Electric ($)	Annual kWh	Cummulative Annual kWh
Electricity Bill	0.11	0.00	0.00	0.00	0.00	0.00	0.00	12,000.00	12,000.00
Work Truck	0.41	3,250.00	880.00	32,500.00	8,800.00	3,250.00	880.00	8,000.00	20,000.00
Pickup Truck	0.20	4,062.50	2,238.50	40,625.00	22,385.00	7,312.50	3,118.50	20,350.00	40,350.00
Forklift	0.14	2,100.00	1,611.72	21,000.00	16,117.20	9,412.50	4,730.22	14,652.00	55,002.00

Figure 5: Tab 3 - Supply and Demand Summary Tables

Additionally, the report provides comprehensive data on both the supply and demand aspects through the use of two separate tables, as shown in Figure 5. One table focuses on the supply side, displaying the various costs associated with different PV array options, as well as various values for measuring kilowatt-hours and kilowatt output of a system. The kW capacity is the maximum power that the system can generate and put into the grid at any given moment. The second table covers the demand side, presenting the operational costs of gas-powered and electric versions of the tools over time. This demand table is particularly helpful as it provides farmers an easy way to compare the operational costs of gas and electric vehicles and vehicles, beyond using the operational break-even. Furthermore, the demand table shows the kWh consumption of the electric versions of the tools, as similarly illustrated in the graphical portion of Tab 2. Overall, these two tables serve to provide farmers with a comprehensive and detailed report encompassing all calculated information.



Where does the supply line cross the grid-charge line?

The intersection of the supply line and the grid-charge line indicates where you should no longer install solar, as this means it costs more to install solar than to draw electricity from the grid.

This occurs when you install: Irrigation Pump PV

Where does the demand line cross the grid-charge line?

The intersection of the demand line and the grid-charge line indicates where you should no longer electrify your tools and vehicles, as this means it costs more to electricity these items than use the gas-version.

No tool has an operational cost per unit of energy less than the grid charge.

Where does the supply line cross the 120% line?

The intersection of the supply line and the 120% line indicates where you should stop installing solar, as this means you will produce too much supply and will be classified as an energy producer.

The following PV array options result in supply that exceeds 120% demand: Idle land PV, Irrigation Pump PV

Figure 6: Tab 3 - Interpreting the Graph

The third part of the report tab goes into depth on how to interpret the graph. This is done by walking the users through three main questions regarding the various components of the graph. A reproduction of the graph as well as the guiding questions are seen in figure 6. Each guiding question is designed to highlight specific aspects of the graph which includes the most advantageous amount of electrification, the ideal quantity of solar power to produce and the amount of supply that would result in too much energy production. With a comprehensive understanding of the graph facilitated by this section, farmers will be better-informed to make decisions about their operations.

4. Data Collection and Calculations

4.1 Data Collection

The development of this decision-making tool required data collection from a variety of primary and secondary sources. The data collection process was divided into two main categories: static parameter values that remain fixed within the tool, and non-static values, or variables, that are dynamically calculated based on user inputs and the static parameters. This static data serves as the foundation for the tool's calculations and analyses.

4.1.1 Solar Radiance Data

Solar radiance data is used to calculate both the kW capacity and kWh output of the four solar array options and is thus used in equation 1.4. The data was obtained from the National Solar Radiation Database provided by NREL (*NSRDB*, n.d.). The solar radiance data is measured in kWh/m^2/Day and the average values per county were found. These county values can be found in Table 1. Using average annual solar radiation data ensures consistency and allows for generalization based on county. If the farmer does not live in a given county, Colorado's average solar radiation of 5.37 kWh/m^2/Day will be used (Marsh & Brown, 2024). While solar installers may use additional information to achieve precise estimations of kW and kWh, this foundational data provides farmers with a preliminary understanding of anticipated energy supply outcomes.

Table 1: Solar Radiance Data	
County	Average Annual Daily Solar Radiance (kWh/m^2/Day)
Mesa	6.5
Delta	6.0
Montezuma	5
Montrose	6.4
Other	5.37

4.1.2 Panel Data – Sizing, Output and Price

The panel data is broken up by size, output and price based on whether the panels are ground or rooftop mounted. This data is used to estimate the kW capacity and kWh output along with the solar radiance data in equations 1.1 through 1.8. The average price per watt to install the ground or rooftop mounted panels are used in calculating installation costs and the cost per kWh of the given PV arrays in their respective locations. The panel sizing, output and price data is seen in Table 2. Although every solar installation company and solar panel producer have different panel sizing, spacing as well as output in watts and pricing, the given dimensional numbers are typical and similar to the dimensions used by Lee et al. (2023) and Routray et al. (2021). The pricing data is sourced from EnergySage.Com (E. Walker & Aggarwal, 2024). This data was also derived with the help of CSU Engineer, Amit Munshi.

Table 2: Photovoltaic Panel Specifications		
Location	Rooftop	Ground mounted
Dimensions (L’ x W’)	5.4 feet by 3.3 feet	5.4 feet by 3.3 feet
Row Spacing (ft.)	NA	7.9 feet
Sq.ft of panel footprint	17.5	60.48
Output per panel (W)	400	400
Cost per watt($/W)	3.50	2.00

4.1.3 Electric Municipality Data

To thoroughly compare the cost implications of sourcing electricity from the grid versus drawing from a personal PV array, relevant data from utility providers was collected. Initially, the electrical territories of different utility companies across the four counties of interest are delineated. This territorial data is sourced from the Colorado Energy Office (*Colorado Electric Utilities*). Subsequently, grid pricing, and net metering limitations were extracted directly from the websites of the respective utility companies. Additionally, it is assumed that all farmers will participate in indefinite roll-over, a scenario where excess electricity generated by the panels in one month is carried over to the next month. This approach is preferred over annual true-up, where excess electricity is paid for at wholesale rates, which are typically less than half of the grid rates.

The extracted data is detailed in Table 3. The cost per kWh of pulling from the grid is particularly significant, as changes in grid pricing can influence the electrical advantage of tools and vehicles as well as solar advantage over time.

Table 3: Electric Municipality Data						
Electricity Provider	County	Classification	Classification Criteria (kW Load)	Energy Demand Charge ($/kWh)	Monthly Small Commercial Connection Charge ($/kWh)	On-Farm PV Supply Capacity
Xcel	Mesa	Commercial	Demand < 50 kW	0.0708	11.68	120% of historical demand
Grand Valley Power	Mesa	Small Commercial	Demand < 50 kW	0.1035	52.50	< 25 kW and ≤ 120% of demand
DMEA	Montrose and Delta	Small Commercial-Three Phase	Demand < 50 kW	0.111	40.75	50 kW
Empire Electric	Montezuma	General Service Single phase	< 75 kVA of equipment capacity	0.10599	42.50	< 25 kW and ≤ 120% of demand

Data compiled from: (Xcel Energy, n.d.; Grand Valley Rural Power lines, Inc, n.d.; DMEA, n.d.; Empire Electric Association, Inc ,n.d.)

4.1.4 Vehicle, Tractor and Tool Data

To calculate the energy demanded on a farm in current use and as tools and vehicles become electrified, a collaborative approach was employed to determine the electrification process. First, all motorized orchard equipment potentially eligible for electrification, was identified through interaction with a peach orchard research associate and validated from a peach farmer in Hotchkiss, Colorado. This list of vehicles used on a farm is listed in Table 4, while the list of tractor implements is in Table 5 and motorized tools are listed in Table 6. Secondly, collaboration with engineering faculty from CSU resulted in gaining information about the energy used by each internal combustion tool and vehicle as well as the electric conversion rates of these tools to gain an understanding of the energy used by the electric equivalents of these tools (Amit Munshi, personal communication, 2024). These calculations were performed using available specifications for conventionally powered vehicles and implements, compared against their electric counterparts and normalizing the power consumption to kilo watt hour (kWh) equivalent (Dahham et al., 2022; Marchenko et al., 2022).

Table 4: Vehicle Information

Vehicle	Fuel Used	Miles per Gallon (MPG)	Gas kWh per 100 Miles	Electric kWh per 100 mile	Lifetime (years)
Ford F-150 pick up	Gas	20	167.05	40	10
Ford F650 Work Truck	Diesel	8	508.75	203.550	10

Table 5: Tractor Implement Information

Tractor Implement	Diesel – gal/hour	Diesel – kWh/hour	Electric - kWh/hour	Lifetime (years)
Pruner	0.3	13.42	8.05	10
Mower	0.5	22.37	13.42	10
Sprayer	20	814	488.4	10
Flail Mower	30	1221	732.6	10
Tractor w/o Implement	7.5	305.25	183.15	10

Table 6: Orchard Tools Gas and Electric Specifications

Tool	Diesel or Gal/hour	Gas - kWh/hour	Electric - kWh/hour	Lifetime (years)
Chainsaw	0.1323	4.75	2.85	10
Forklift	1.5	61.05	36.63	10
Wind Machine	10	407	244.2	10
ATV	0.9	14.91	8.95	10

4.2 Supply-Side Calculations

In order to determine the point where supply and demand meet, the potential on-farm energy production from solar power systems must first be calculated. The four locations of interest for PV systems – rooftop, idle land, irrigation pumps, and agrivoltaics – have different calculations employed for each system to determine aspects related to the energy output and various associated costs. The energy outputs of interest include kW capacity/power, annual kWh output, and total kWh output. The cost aspects of interest are cost per kWh, initial installation costs, annual system cost, and total system cost. Total kWh output and total system costs consider the 25-year lifetime of the PV array.

These various aspects are considered individually for each of the four systems and cumulatively, where the total energy production and costs are calculated by combining the outputs and costs from multiple locations. These calculations provide the necessary information to identify the equilibrium point between energy supply and demand as well as provide economic insight, enabling informed decision-making for on-farm PV system implementation.

4.2.1 Rooftop PV Array Calculations

Rooftop PV array equations 1.1 through 1.8 show how the program calculates kilowatt hours used. The variables are italicized, and the parameters can be found in Table 1 and 2.

Eq. 1.1 Total rooftop PV Panels ($\mathrm{T_p}$):

$$\mathrm{T_p} = (\textit{Sq.ft of Rooftop available})/(\text{Total sq.ft of panels})$$

Eq. 1.2 Output in Watts ($\mathrm{Y_w}$):

$$\mathrm{Y_w} = \mathrm{T_p} * \text{output per panel}$$

Eq. 1.3 Output in kW (Y_{kW}) :

$$\mathrm{Y_{kW}} = \frac{\mathrm{Y_W}}{1000}$$

Eq. 1.4 Annual kWh Output ($\mathrm{Y_{kWh}}$):

$$\mathrm{Y_{kWh}} = \mathrm{Y_{kW}} * Annual\ Sunlight\ Hours$$

Eq. 1.5 Total kWh Output ($\mathrm{Y_{TkWh}}$):

$$\mathrm{Y_{TkWh}} = \sum_{t=1}^{25} \mathrm{Y_{kWh}} * (1 - 0.005)^{t}$$

Eq. 1.6 Installation Cost ($\mathrm{C_i}$):

$$\mathrm{C_i} = \mathrm{Y_w} * \mathrm{Cost\ per\ Watt}$$

Eq. 1.7 Total Cost ($\mathrm{C_t}$):

$$\mathrm{C_t} = [(\mathrm{C_i} * 1.05) + (Monthly\ Grid\ Charge * 12)] * 25$$

Eq. 1.8 Cost per kWh (Q):

$$Q = C_t / \mathrm{Y_{TkWh}}$$

Equation (1.1) calculates the total number of PV panels that can fit in the given rooftop area, using the available rooftop area input and the parameter, area of a single PV panel, as inputs. Equation (1.2) determines the annual output in watts produced by the panels by considering the number of panels determined in equation (1.1) and the output per panel. Equation (1.3) converts the annual output in watts found in equation (1.2) to kilowatts. Equation (1.4) calculates the annual kWh output of the rooftop PV array by using the annual output in kW determined in equation (1.3) and the annual effective sunlight hours for solar radiation in an inputted Colorado county. Equation (1.5) gives the total expected kWh output over the 25-year lifetime of the array, using the annual kWh output given in equation (1.4) and accounting for an annual efficiency loss of 0.5% as the array ages (Mow, 2018). Equation (1.6) calculates the installation cost of the PV array by considering the total output in watts derived from equation (1.2) and the cost per watt parameter. Equation (1.7) determines the total cost of the array over the 25-year lifetime, including the installation cost from equation (1.6), maintenance costs, which is assumed to be 5% of the total installation cost per year, and the monthly grid charge input under a net metering system (Walker et al., 2020). Lastly, equation (1.8) calculates the cost per kWh by dividing the total cost over the system lifetime, determined in equation (1.7) , by the total expected kWh output, determined in equation.

4.2.2 Idle Land PV Array Calculations

Equations 2.1 through 2.9 are used to calculate the cost per kWh of a ground-mounted PV array on idle land. Similar to above, the variables are italicized, and parameters can be found in Table 1 and 2.

Eq. 2.1 Available Acres in Sq.ft (X_a):

X_a: *input of acres* * 43,560

Eq. 2.2 Total panels within the Acreage (T_p):

T_p =(X_a)/(Total sq.ft of ground-mounted panels)

Eq. 2.3 Output in Watts ($\mathrm{Y_w}$):

$$\mathrm{Y_w = T_p * output\ per\ panel}$$

Eq. 2.4 Output in kW (Y_{kW}) :

$$\mathrm{Y_{kW}} = \frac{\mathrm{Y_W}}{1000}$$

Eq. 2.5 Annual kWh Output ($\mathrm{Y_{kWh}}$):

$$\mathrm{Y_{kWh}} = \mathrm{Y_{kW}} * Annual\ Sunlight\ Hours$$

Eq. 2.6 Total kWh Output ($\mathrm{Y_{TkWh}}$):

$$\mathrm{Y_{TkWh}} = \sum_{t=1}^{25} \mathrm{Y_{kWh}} * (1 - 0.005)^{t}$$

Eq. 2.7 Installation Cost ($\mathrm{C_i}$):

$$\mathrm{C_i} = \mathrm{Y_w} * \mathrm{Cost\ per\ Watt}$$

Eq. 2.8 Total Cost ($\mathrm{C_t}$):

$$\mathrm{C_t} = [(\mathrm{C_i} * 1.05) + (Monthly\ Grid\ Charge * 12)] * 25$$

Eq. 2.9 Cost per kWh (Q):

$$\mathrm{Q} = \mathrm{C_t} / \mathrm{Y_{TkWh}}$$

The process for calculating the cost per kWh of PV systems on idle land is similar to rooftop arrays, with two key differences. First, the available acreage of idle land must be converted to square feet, as shown in equation (2.1), which uses the conversion factor of 43,560 square feet per acre as well as the user input of acreage available for a PV array on ide land. Second, for ground-mounted solar panels installed on idle land, the spacing between rows of panels is accounted for in the area allocated per panel. However, this does not alter the mathematical equation in (2.2). Instead, it uses a different parameter value from Table 2. Therefore, after converting the acreage to square feet, equations (2.2) through (2.9) serve the same purpose as equations (1.1) through (1.8) used in the rooftop calculations.

4.2.3 Irrigation Pump PV Array Calculations

Equations 3.1 through 3.7 calculate the cost per kWh for sizing a PV array that would offset the entire energy demanded from an irrigation pump. It is assumed that this array would be installed on a raise platform that sits above the irrigation pump and thus the rooftop panel specifications in Table 2 are used as the parameter values

Eq. 3.1 Annual Energy Yield per Panel in kWh (Y_p):

$$Y_p = \frac{(\text{output per panel} * \mathit{annual\ sunlight\ hours})}{1000}$$

Eq. 3.2 Total Panels Used (T_p):

$$T_p = \frac{\mathit{Irrigation\ Pump\ kWh}}{\text{Yp}}$$

Eq. 3.3 Annual kWh Output (Y_{kWh}):

$$Y_{kWh} = T_p * Y_p$$

Eq. 3.4 Total kWh Output (Y_{TkWh}):

$$Y_{TkWh} = \sum_{t=1}^{25} Y_{kWh} * (1 - 0.005)^t$$

Eq. 3.5 Installation Cost (C_i):

$$C_i = T_p * \text{output per panel (watts)} * \text{cost per watt}$$

Eq. 3.6 Total Cost (C_t):

$$C_t = [(C_i * 1.05) + (Monthly\ Grid\ Charge * 12)] * 25$$

Eq. 3.7 Cost per kWh (Q):

$$Q = C_t / Y_{TkWh}$$

Equation (3.1) determines the energy generated per year per panel in kWh by considering the output per panel in watts and the annual effective sunlight hours as well as the conversion between watts and kilowatts. Equation (3.2) calculates the number of panels needed to meet the energy demand of the irrigation pump by dividing the annual kWh used by the pump by the energy generated per year per panel derived in equation (3.1). Equation (3.3) determines the real kWh produced by the panels, as there can only be a whole number of panels installed, so the result from equation (3.2) is rounded down to the nearest whole number and used with the annual output in kWh per panel from equation (3.1). Equation (3.4) then calculates the total kWh output over the system's 25-year lifetime using the annual kWh output determined in equation (3.3) and assumed a 0.5% efficiency loss every year. Equation (3.5) determines the initial installation of the system using the total number of panels calculated in equation (3.2) as well as the output per panel in watts and the cost per watt parameter values. Similar to equation (1.7) for rooftop systems, equation (3.6) finds the total cost of the system over its 25-year lifetime, including parameters and inputs such as maintenance costs and grid charges, respectively. Finally, equation (3.7) calculates the cost per kWh of an irrigation pump PV array by using the total lifetime cost of the system derived in equation (3.6) and the total kWh output of the system calculated in equation (3.4).

4.2.4 Agrivoltaics Calculations

Equations 4.1 through 4.4 are used to calculate relevant information for an agrivoltaic array. Due to the limited research on the economics of agrivoltaic systems integrated with peach orchards, many of the values are user inputs rather than predetermined parameters. These user inputs aim to provide an estimation based on individual preferences and willingness to pay, rather than a precise representation of real-world scenarios.

Eq. 4.1 Output in kW (Y_{kW}) :

$$\mathrm{Y_{kW}} = \frac{Y_{kWh}}{annual\ sunlight\ hours}$$

Eq. 4.2 Total kWh Output ($\mathrm{Y_{TkWh}}$):

$$\mathrm{Y_{TkWh}} = \sum_{t=1}^{25} Y_{kWh} * (1 - 0.005)^{t}$$

Eq. 4.3 Installation Cost ($\mathrm{C_i}$):

$$\mathrm{C_i} = \$/kWh * Y_{kWh}$$

Eq. 4.4 Total Cost ($\mathrm{C_t}$):

$$\mathrm{C_t} = [(\mathrm{C_i} * 1.05) + (Monthly\ Grid\ Charge * 12) - net\ yield\ effect] * 25$$

Equation (4.1) calculates the kW capacity of a farmers chosen agrivoltaic system by using the user input of the annual kWh output wanted from such a system and the annual sunlight hours which is determined by the county the farmer states they are located in. Equation (4.2) determines the total kWh output from the system over the course of 25 years, assuming a 0.5% degradation rate as is applied to all PV systems and uses the annual kWh user input. Equation (4.3) finds the installation cost of such a system by using the price per kWh the farmer is willing to pay for an agrivoltaic system as well as the inputted annual kWh output from the system. Equation (4.4) calculates the total cost of the PV systems lifetime by incorporating the installation cost calculated in equation (4.3), the annual maintenance cost of the system, the monthly grid charge as well as the monetary net yield effect of an agrivoltaic system on peaches.

4.3 Demand Side Calculations

To evaluate how the energy demanded on a farm changes overtime, the energy that different tools and vehicles would take if they were electrified must be calculated. This enables us to determine the electric advantage or disadvantage of various tools by calculating their operation breakeven costs.

The operational breakeven is the point at which the cost of operating an electric tool or vehicle becomes equal to the cost of operating a conventional gas or diesel tool or vehicle, measured in price per kWh. This does not use the cost of purchasing the different gas tools and vehicles or any other ownership costs within the calculation.

4.3.1 Operation Breakeven – Vehicles

Equations 5.1 through 5.3 calculate the operational breakeven cost of internal combustion (IC) vehicles vs electric vehicles using the information in tables 4.

Eq. 5.1 Cost of gas per mile (C_m):

$$C_m = 1/MPG * \$/gal$$

Eq. 5.2 Electric kWh per mile (Y_{em}):

$$Y_{em} = (\text{gas kWh} * 1.6) / 100 \text{ miles}$$

Eq. 5.3 Operational Breakeven (Q_{BE}) :

$$Q_{BE} = C_m / Y_{em}$$

Equation (5.1) determines the operating cost per mile of an IC vehicle, this is how much is costs to drive one mile considering the cost of gas (or diesel) per gallon user input and the mileage per gallon of a vehicle parameter value. Equation (5.2) computes the kilowatt-hours (kWh) used per mile for an electric vehicle. This equation adjusts the gas vehicle's kWh consumption parameter value, factoring in a 60% efficiency gain, to derive the electric kWh per

100 miles driven. Equation (5.3) establishes the operational breakeven point in terms of $/kWh by using the cost per mile of gas calculated in equation (5.1) by the electric kWh per mile calculated in equation (5.3).

4.3.2 Operational Breakeven – Tools and Tractor Implements

To find the operational breakeven of electric tools and tractor implements, the same logic from the operational breakeven of vehicles is used with the primary difference being everything is measured in hours operated rather than miles driven. This is seen in equations 6.1 through 6.3 below and the data used in these calculations is in tables 5 and 6.

Eq. 6.1 Cost of gas per hour (C_h):

$$C_h = \text{gal/hour} * \textit{\$/gal}$$

Eq. 6.2 Electric kWh per hour (Y_{eh}):

$$Y_{eh} = \text{gas kWh} * 1.4$$

Eq. 6.3 Operational Breakeven (Q_{BE}) :

$$Q_{BE} = C_h / Y_{eh}$$

Equation (6.1) calculates the cost of gas per hour of operating an internal combustion tool by using the gallons per hours used, a parameter value, and the price per gallon, a user input. Equation (6.2) calculates the kWh used per hour of an electric tool and uses a 40% conversion factor to reflect that electric tools are 40% more efficient in kWh consumption that gas tools.

Equation (6.3) calculates the operational breakeven in $/kWh by using the cost per hour of gas tools derived from equation (6.1) and the electric kWh per hour calculated in equation (6.2).

4.3.3 Annual kWh - Tools and Vehicles

The graphic on tab 2 of the tool uses the annual kWh for tools and vehicles. This helps to show how much energy the tools and vehicles cumulatively demand in a year as they become electrified, requiring electricity from the grid or from PV arrays. Equation 7.1 calculates the energy demand for tools, and equation 7.2 calculates the same for vehicles

Eq 7.1 Electric Tool Annual kWh Demanded (Y_{kWht}):

Y_{kWht} = kWh/hour * *total annual hours*

Eq 7.2 Electric Vehicle Annual kWh Demanded (Y_{kWhv}) :

Y_{kWhv} = Electric kWh/mile * *total annual miles*

Equation (7.1) calculates the annual kWh demanded by electric tools, based on the parameter value of energy consumption in kWh for one hour of tool use and the total hours the tool is used in a year, as provided by the user. Equation (7.2) is used to calculate the annual kWh demanded from electric vehicles by using the parameter value of energy used in kWh for one mile of the vehicle and the input value, total miles driven by the vehicle in a year.

4.3.4 Annual Operational Costs

To compare the operating costs of gas verses electric tools, the annual operating costs of both the gas and electric tools must be calculated. To calculate the annual operating cost of IC tools and vehicles, equation (8.1) and (8.2) are used. Equation (9.1) and (9.2) are used to calculate the annual operating cost of electric tools and vehicles. The data used in both calculations is in Table 4.

Eq. 8.1 Gas Tool Annual Operational Cost (C_{gt}):

$$C_{gt} = \text{gal/hour} * \mathit{\$/gal} * \mathit{total\ annual\ hours}$$

Eq. 8.2 Gas Vehicle Annual Operational Cost (C_{gv}):

$$C_{gv} = \text{gal/mile} * \mathit{\$/gal} * \mathit{total\ annual\ miles}$$

Equation (8.1) calculates the cost per year of operating an IC tool by utilizing the cost of gas per hour to use the tool and the inputted total hours the tool is used in a year. Equation (8.2) calculates the cost per year of operating an IC vehicle by utilizing the cost of gas per mile and the inputted total miles the tool is used in a year.

Eq 9.1 Electric Tool Annual Operational Cost (C_{et}):

$$C_{et} = Y_{kWht} * \$/\text{kWh}$$

Eq. 9.2 Electric Vehicle Annual Operational Cost (C_{vt}):

$$C_{vt} = Y_{kWhv} * \$/\text{kWh}$$

Equation (9.1) computes the annual operating cost of an electric tool. This is achieved by using the annual kWh consumed by of the tool, which is calculated in equation (7.1), and the applicable price per kilowatt-hour, which varies depending on whether the tool is drawing power from the grid or utilizing on-site PV power. Equation (9.2) calculates the annual operating cost of an electric vehicle by using the results of annual kWh used by a vehicle as calculated in equation (7.2) and the price per kWh.

4.4 Cost and Return Table Calculations

4.4.1 Net Present Value

The base case Net Present Value (NPV) is calculated in equations (10.1) through (10.3). The method used below is similar to that of Chalgynbayeva et al., (2024).

Eq. 10.1 Annual Revenue in Year t from PV Installations ($R(t)$):

$$R(t) = \sum Y_{kWh} (1 - 0.005)^t * C_g (1 + 0.02)^t$$

Eq. 10.2 Present Value of Revenue at Year t from PV Installations ($R_d(t)$):

$$R_d(t) = R(t) \frac{1}{(1+0.03)^t}$$

Eq. 10.3 Net Present Value (NPV):

$$NPV = \sum_{t=0}^{25} R_d(t) - \sum C_i$$

To find the NPV, the annual revenue from all the installed PV arrays must first be calculated. This is done in equation (10.1) by using the sum of the kWh produced from the systems considering a 0.5% decrease per year in the kWh output and the current grid charge per kWh (C_g) considering the grid charge will increase 2% a year (Gorski, 2024). Equation (10.2) finds the discounted annual revenue by using the results from (10.1) and using a discount rate of 3%. Equation (10.3) finds the NPV by using the discounted revenues across all 25 years of the PV array's life and the cumulative installation cost of all the chosen arrays to be installed ($\sum C_i$) , which is chosen by the farmer and calculated in equations (1.6), (2.7), (3.5) and (4.3).

Eq. 10.4 NPV with External Financing (NPV_{EF}):

$$NPV_{EF} = \sum_{t=0}^{25} R_d(t) - \left(\sum C_i * (1 - \text{percent covered externally})\right)$$

Equation (10.4) calculated the NPV given there is external financing to help offset the installation cost of the PV array. This is done by slightly adjusting equation (10.3) to include the percent of the installation that is covered externally.

Eq. 10.5 Annual Revenue from PV Installations with a Production Tax Credit (PTC) ($R_{ptc}(t)$):

$$R_{ptc}(t) = \left[\sum Y_{kWh}\, (0.995)^t * C_g\, (1 + 0.02)^t\right] + \left[\sum_{t=0}^{10} Y_{kWh}\, (0.995)^t * 0.0275\right]$$

Eq. 10.6 Present Value of Revenue at Year t from PV Installations ($R_d(t)$):

$$R_{ptcd}(t) = R_{ptc}(t)\, \frac{1}{(1+0.03)^t}$$

Eq. 10.7 NPV with PTC (NPV_{ptc}):

$$NPV_{ptc} = \sum_{t=0}^{25} R_{ptc}(t) - \sum C_i$$

Equation (10.5) through (10.7) finds the NPV for the scenario under the PTC in which the farmer gains 2.75 cents per kWh produced for the first ten years of the PV arrays life. Equation (10.5) finds the annual revenue with the production tax credit by considering the 2.75 cent gain per kWh produced per year for the first ten years of the PV arrays life in addition to the normal revenue gained without the credit. Equation (10.6) is the same as (10.2) but uses the results from equation (10.5) to accounting for a 3% discount rate. Equation (10.7) calculated the NPV under the PTC by using the results from (10.6) and the cumulative installation costs.

4.4.2 Return on Investment

The base case return on investment (ROI) is calculated in equations (11.1) below.

Eq. 11.1 Return on Investment ROI(t):

$$ROI = \sum_{t=0}^{25} \frac{\mathrm{Rd(t)} - \sum C_i}{\sum C_i}$$

Equation (11.1) find the ROI over the course of 25 years by using the results from equation (10.2) and the cumulative initial investment cost of the panels ($\sum C_i$).

Eq. 11.2 ROI with external Financing (ROI_{EF}):

$$ROI_{EF} = \sum_{t=0}^{25} \frac{\mathrm{Rd(t)} - (\sum \mathrm{C_i} * (1 - \text{percent covered externally}))}{\sum \mathrm{C_i} * (1 - \text{percent covered externally})}$$

Equation (11.2) finds the return on investment for the scenario in which there is external financing for the installation cost of the solar arrays by including the percentage that is covered within the original base case ROI equation (11.1).

Eq. 11.3 ROI under the Production Tax Credit ($\mathrm{ROI}_{\mathrm{PTC}}$):

$$\mathrm{ROI}_{\mathrm{PTC}} = \sum_{t=0}^{25} \frac{\mathrm{Rptcd(t)} - \sum C_i}{\sum C_i}$$

Equation (10.7) finds the ROI under the PTC scenario by using the results from equation (10.6) and following a similar method to (11.1).

4.4.3 Payback Period

In the context of solar photovoltaic (PV) system adoption, the payback period provides an estimate of how long it will take for the energy cost savings to equal the upfront costs of installing the solar array. Equation (12.1) is used to calculate the payback period of a PV array.

Eq. 12.1 Payback Period (PP):

$$PP = \frac{\sum C_i}{Avg\ (R_d(25))}$$

In equation (12.1), the cumulative investment cost of all the chosen arrays to be installed ($\sum C_i$) and the discounted revenue (R_d) from equation (10.2) across 25 years is used. The payback period is evaluated under different financing scenarios in which the amount the farmer pays out of pocket for the array varies. To calculate this, the numerator of the payback period changes and is seen in equation (12.2).

Eq. 12.2 Payback Period Under Varying % Based Financing Scenarios (PP_{EF}):

$$PP_{EF} = \frac{\sum C_i * (1 - \text{percent covered externally})}{Avg\ (R_d(25))}$$

Equation (12.2) uses the cumulative investment costs of all the installed arrays, the percent covered externally and the average discounted revenue over the 25 year period. To calculate the payback period under the federal production tax credit in which 2.75 cents are given per kWh produced from a system, the denominator of the original equation in (12.1) changes as seen in equation (12.3).

Eq. 12.3 Payback Period Under the PTC (PP_{ptc}):

$$PP_{ptc} = \frac{\sum C_i}{Avg\ (R_{ptcd}(25))}$$

Equation (12.3) uses the discounted revenue considering the effects of the ptc across the 25 years from equation (10.6) and the cumulative installation cost. These three equations, (12.1) through (12.3), calculate the payback period under the different financing scenarios available to farmers to cover their PV arrays.

5. Example Results

5.1 Scenario Specification

Three different analysis scenarios of an example farm are used to demonstrate how the Solar Orchard Analysis and Recommendation Tool can be used to help orchardists' decision making when it comes to solar power and electrification. In the first scenario, the farm assumes no PV array installation but electrifies all tools. This type of scenario allows farmers to clearly see the electric advantage or disadvantage of the different tools and vehicles. The second scenario involves determining where supply and demand are closest to balancing each other. This scenario shows how various levels of electrification, and various levels of PV array installation can be flexible to meet the wants of the farmer. The third scenario evaluates a situation in which all tools and vehicles are electrified and all available area for PV has an array on it. Such a scenario allows the farmers to see their maximum demand and their maximum supply capacity.

The example farm is an operational orchard located in Hotchkiss, Colorado, that will remain anonymous. This data was gathered through direct in-person visits to the farmer. The inputs provided for tab 1 of the tool are documented in Table 7 below and will remain unchanged for all the example scenarios.

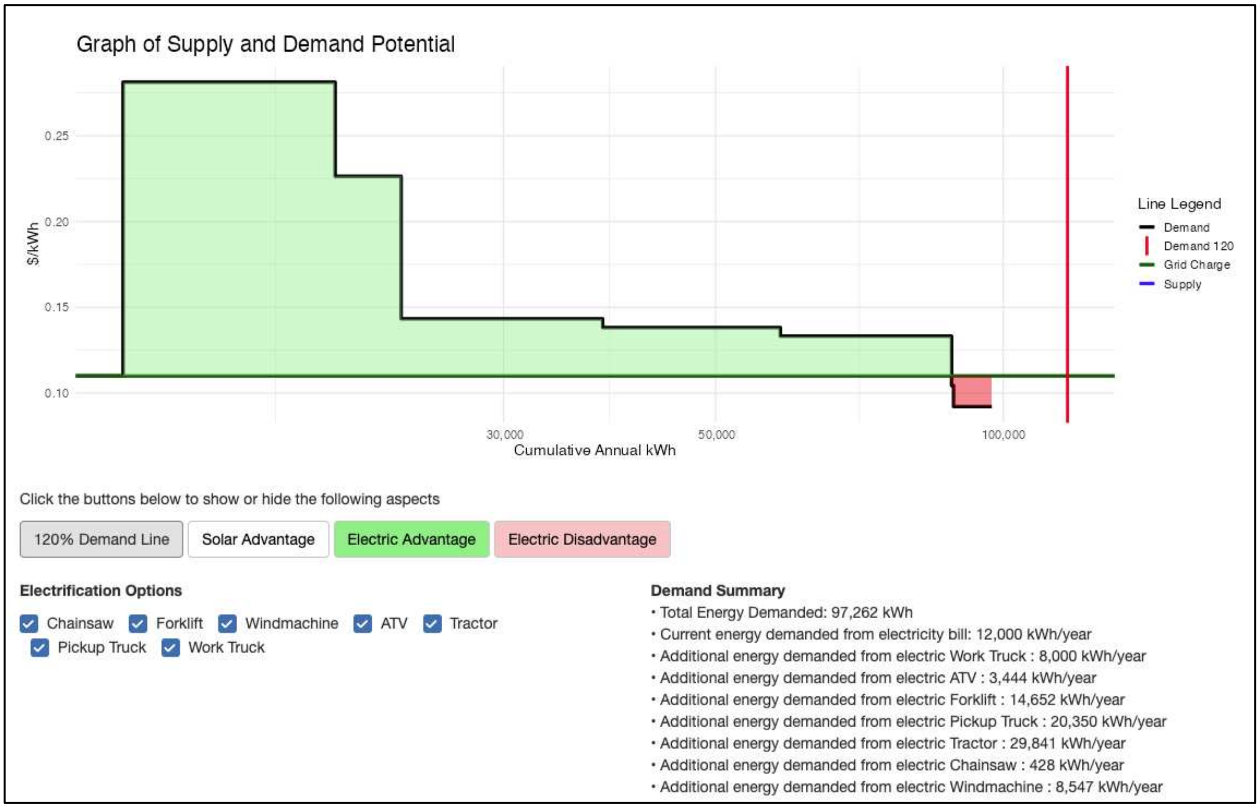
Table 7: Case Study Questionnaire Results	
General Farm Information	**Inputs**
County	Delta
Electricity Provider	DMEA
Acres of Peaches	30
Annual kWh Consumption	12,000
Annual kWh used in Irrigation*	5,000
Cost of Gas ($/gal)	3.25
Cost of Diesel ($/gal)	3.50
Farm Tools	**Annual Hours Used**
Chainsaw	150
Forklift	400
Wind machine	35
ATV	385
Tractor Implements	**Annual Hours Used**
PTO Pruner	0
Mower	300
Sprayer	300
Flail Mower	80
Tractor (No implement)*	300
Vehicles	**Annual Miles Driven**
Pickup Truck	20,000
Work Truck	10,000
PV Area Constraints	**Inputs**
Square feet of efficient Rooftop Space for Solar (sq.ft)	2,600

Acres of Idle land for Solar (acres)	1
Acres for Agrivoltaics (acres)	0.1
Willingness to Pay - Cost per kWh for Agrivoltaics ($/kWh)	0.09
Net Increase/Decrease on Peach Profit due to Agrivoltaic Effects ($)	0
Expected Annual kWh for Agrivoltaic System*	5000

An asterisk (*) denotes inputs that were not provided by the farmer and thus were estimated.

5.2 Scenario 1 – All Tools are Electrified

The first scenario provides farmers with valuable insights into electrification options that can be considered independently of installing a PV array. Exploring the conversion of gas and diesel-powered tools and vehicles is crucial for environmental sustainability and may serve as a preliminary step towards installing a PV array. This is particularly significant for farmers who do not use a cooling shed or a packing house for their peaches, as these are often the most energy-intensive components of a peach orchard. By transitioning to electric alternatives, farmers can reduce their carbon footprint and enhance operational efficiency. Additionally, such a shift can lead to long-term cost savings and contribute to a more sustainable agricultural practice.



Electrification Options

☑ Chainsaw ☑ Forklift ☑ Windmachine ☑ ATV ☑ Tractor
☑ Pickup Truck ☑ Work Truck

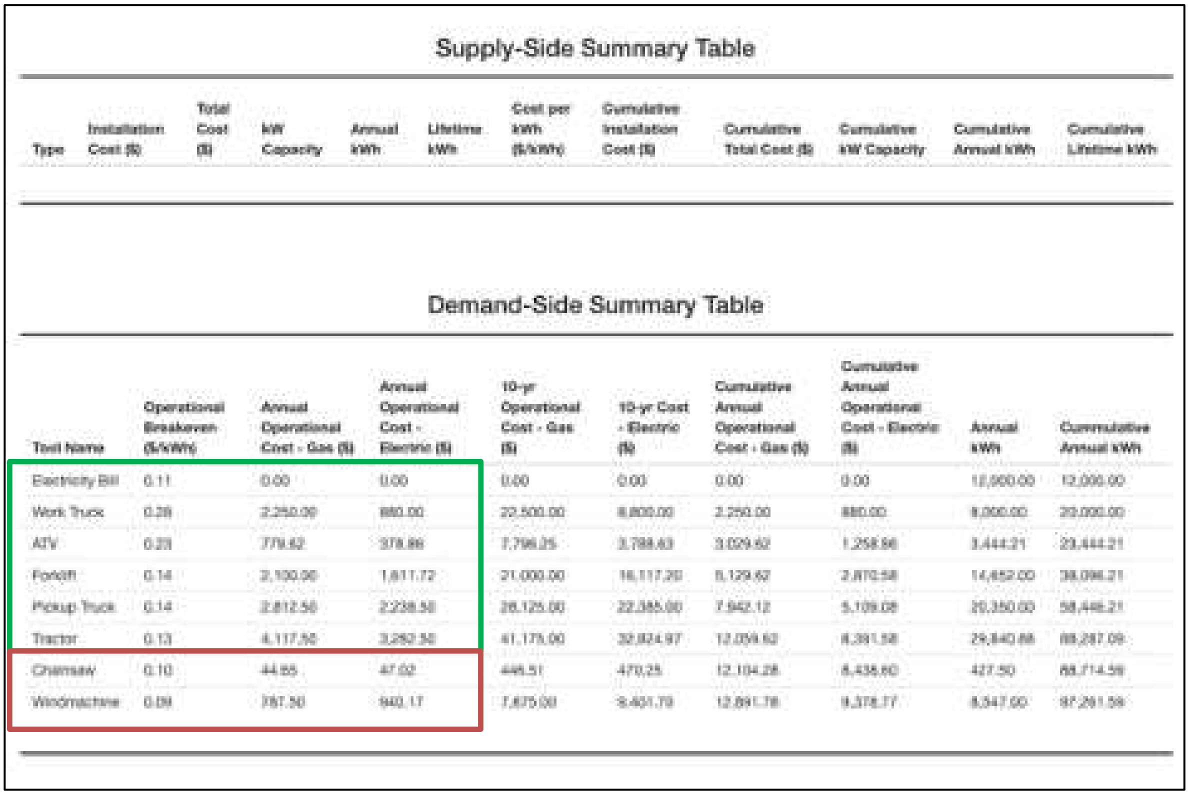
Demand Summary

- Total Energy Demanded: 97,262 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year
- Additional energy demanded from electric Tractor : 29,841 kWh/year
- Additional energy demanded from electric Chainsaw : 428 kWh/year
- Additional energy demanded from electric Windmachine : 8,547 kWh/year

Figure 7: Scenario 1 - Tab 2 Graphic Results

Through using the inputs in Table 6 in tab 1, the questionnaire of the web tool, it is then possible to create a scenario in tab 2 in which all the possible tools and vehicles are electrified, but no solar arrays are installed. The result of this decision is seen in figure 7 above. By thoroughly examining the graph, users can observe that the green area represents the total kWh demanded by electric tools and vehicles in which there exists an advantage of using electric versions over the internal combustion counterparts. When the area between the grid line and the demand line turns red, it indicates that electrifying the tools or vehicles is no longer beneficial beyond this intersection point and the kWh demanded from electrifying does not serve the farmers an advantage to switch to electric.

Further interpretation of the graph is done by examining the steps on the graph. The first step always shows the current amount of kWh demanded, as indicated in the electricity bill. The y-axis for the current electricity demand will always match the current grid price. The current electricity bill captures what is not captured in the tool, such as lighting, powering electrical outlets, heating and cooling, etc. In the next five steps of the graph, the area is highlighted in green. These five steps indicate that five tools or vehicles can be electrified and maintain an electric advantage over their internal combustion counterparts. Each of the five steps highlighted in green has operational breakeven prices above the current grid price. This means the grid prices would have to exceed these operational breakeven points for the tools to lose their electric advantage over gas or diesel equivalents.



Supply-Side Summary Table

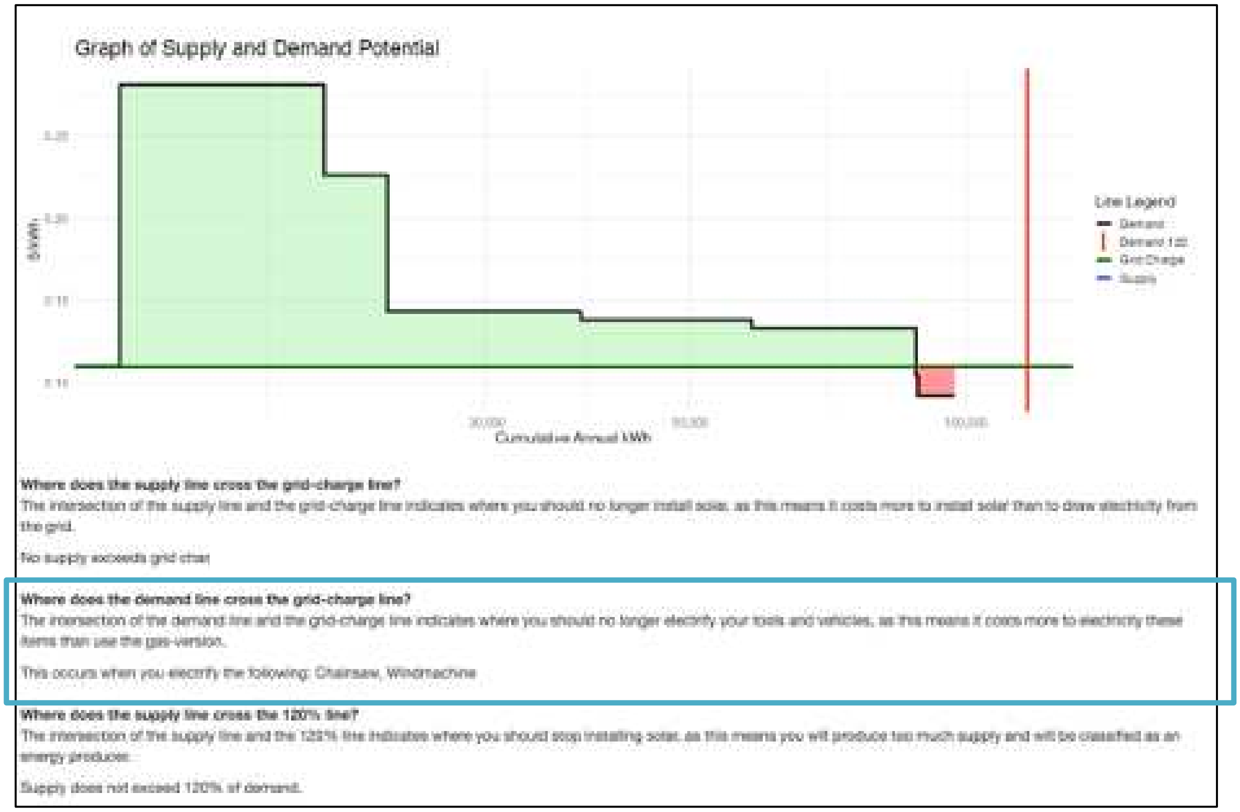
Type	Installation Cost ($)	Total Cost ($)	kW Capacity	Annual kWh	Lifetime kWh	Cost per kWh ($/kWh)	Cumulative Installation Cost ($)	Cumulative Total Cost ($)	Cumulative kW Capacity	Cumulative Annual kWh	Cumulative Lifetime kWh

Demand-Side Summary Table

Tool Name	Operational Breakeven ($/kWh)	Annual Operational Cost - Gas ($)	Annual Operational Cost - Electric ($)	10-yr Operational Cost - Gas ($)	10-yr Cost - Electric ($)	Cumulative Annual Operational Cost - Gas ($)	Cumulative Annual Operational Cost - Electric ($)	Annual kWh	Cummulative Annual kWh
Electricity Bill	0.11	0.00	0.00	0.00	0.00	0.00	0.00	12,000.00	12,000.00
Work Truck	0.28	2,250.00	880.00	22,500.00	8,800.00	2,250.00	880.00	8,000.00	20,000.00
ATV	0.23	779.62	378.86	7,796.25	3,788.63	3,029.62	1,258.86	3,444.21	23,444.21
Forklift	0.14	2,100.00	1,611.72	21,000.00	16,117.20	5,129.62	2,870.58	14,652.00	38,096.21
Pickup Truck	0.14	2,812.50	2,238.50	28,125.00	22,385.00	7,942.12	5,109.08	20,350.00	58,446.21
Tractor	0.13	4,117.50	3,282.50	41,175.00	32,824.97	12,059.62	8,391.58	29,840.88	88,287.09
Chainsaw	0.10	44.66	47.02	446.51	470.25	12,104.28	8,438.60	427.50	88,714.59
Windmachine	0.09	787.50	940.17	7,875.00	9,401.70	12,891.78	9,378.77	8,547.00	97,261.59

Figure 8: Scenario 1 - Demand-Side Summary Table

To gain more insight into the economic implications of electrifying certain tools and vehicles, the Demand-Side Summary Table contained in tab 3 of the tool can be looked at and is depicted in figure 8 above. As seen in figure 8, there is a green box and a red box. The green box encapsules the tools and vehicles that correspond to the steps and area highlighted in green on the graphic. This indicates that electrifying the work truck, forklift, pick-up truck, ATV and tractor all have an electric advantage, whereas the chainsaw, and wind machine have an electric disadvantage. This is further confirmed when comparing the annual operational costs of the gas and electric versions as seen in the third and fourth column of the table. The tools in the green box have lower annual operational costs for the electric versions compared to the gas versions. Conversely, the tools in the red box show that the annual operational costs for the gas versions are lower than those for the electric versions. This intuitive comparison helps users understand the cost-effectiveness of electrifying their equipment.



Where does the supply line cross the grid-charge line?
The intersection of the supply line and the grid-charge line indicates where you should no longer install solar, as this means it costs more to install solar than to draw electricity from the grid.

No supply exceeds grid char

Where does the demand line cross the grid-charge line?
The intersection of the demand line and the grid-charge line indicates where you should no longer electrify your tools and vehicles, as this means it costs more to electrify these items than use the gas-version.

This occurs when you electrify the following: Chainsaw, Windmachine

Where does the supply line cross the 120% line?
The intersection of the supply line and the 120% line indicates where you should stop installing solar, as this means you will produce too much supply and will be classified as an energy producer.

Supply does not exceed 120% of demand.

Figure 9: Scenario 1 - Tab 3, Understanding the Graph

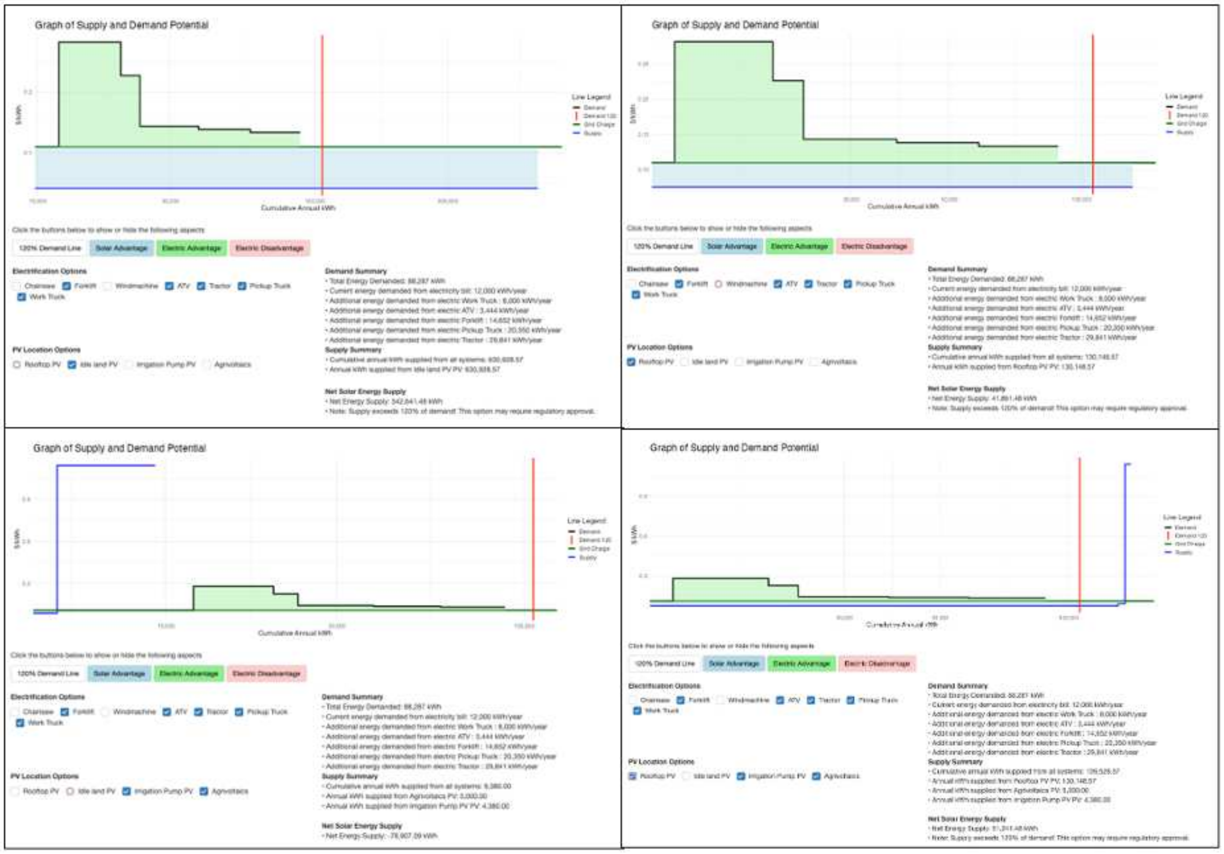
A complete understanding of the graph and its implications can be found in the report tab, which includes guiding questions. In this scenario, the relevant question for electrification is outlined in the blue box in Figure 9. This section provides a list of tools that have an electric disadvantage. Reviewing these details ensures that users can make well-informed decisions about which tools are most economically feasible to electrify. Complete data as well as interpretations is provided to the user to help with the decision-making process.

The results of this scenario could change under two conditions. First, if the electric grid price changes, and second, if the cost of gas and diesel changes. The cost of gas and diesel affects the operational breakeven points for the tools and vehicles, while the electric grid price determines whether the operational breakeven is less than or greater than the grid price, thereby effecting the electric advantage and disadvantage results.

Additionally, understanding which tools to electrify and the impact of this electrification on total kWh demand can provide insights into whether a PV array should be considered at all. If there is insufficient energy demand or if it is less costly to draw power from the grid than to install solar panels, a large PV array might be more trouble than it is worth as there are regulatory considerations and limitations from producing too much power. In such cases, a smaller PV array might be more appropriate than maximizing the available space for a PV array. This assessment helps in making a cost-effective decision regarding solar energy investment as well as electrification investments.

5.3 Scenario 2 – Supply Meets Demand

The second scenario provides farmers with a complete understanding of what an ideal PV array and electrification scenario looks like. Under this scenario, only tools that have an electric advantage are considered and the PV array that most closely matches the kWh demand in kWh supply is determined. Closely matching the kWh demand and supply allows farmers to produce within the regulatory constraints of only producing 120% of demand imposed by most utility providers. This scenario also allows a comparison of the different financing options of such a sized system, through the economic table in tab 2.



Electrification Options

☐ Chainsaw ☑ Forklift ☐ Windmachine ☑ ATV ☑ Tractor ☑ Pickup Truck
☑ Work Truck

PV Location Options

☐ Rooftop PV ☑ Idle land PV ☐ Irrigation Pump PV ☐ Agrivoltaics

Demand Summary

- Total Energy Demanded: 88,287 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year
- Additional energy demanded from electric Tractor : 29,841 kWh/year

Supply Summary

- Cumulative annual kWh supplied from all systems: 630,928.57
- Annual kWh supplied from Idle land PV PV: 630,928.57

Net Solar Energy Supply

- Net Energy Supply: 542,641.48 kWh
- Note: Supply exceeds 120% of demand! This option may require regulatory approval.

Electrification Options

☐ Chainsaw ☑ Forklift ○ Windmachine ☑ ATV ☑ Tractor ☑ Pickup Truck
☑ Work Truck

PV Location Options

☑ Rooftop PV ☐ Idle land PV ☐ Irrigation Pump PV ☐ Agrivoltaics

Demand Summary

- Total Energy Demanded: 88,287 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year
- Additional energy demanded from electric Tractor : 29,841 kWh/year

Supply Summary

- Cumulative annual kWh supplied from all systems: 130,148.57
- Annual kWh supplied from Rooftop PV PV: 130,148.57

Net Solar Energy Supply

- Net Energy Supply: 41,861.48 kWh
- Note: Supply exceeds 120% of demand! This option may require regulatory approval.

Electrification Options

☐ Chainsaw ☑ Forklift ○ Windmachine ☑ ATV ☑ Tractor ☑ Pickup Truck
☑ Work Truck

PV Location Options

☐ Rooftop PV ○ Idle land PV ☑ Irrigation Pump PV ☑ Agrivoltaics

Demand Summary

- Total Energy Demanded: 88,287 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year
- Additional energy demanded from electric Tractor : 29,841 kWh/year

Supply Summary

- Cumulative annual kWh supplied from all systems: 9,380.00
- Annual kWh supplied from Agrivoltaics PV: 5,000.00
- Annual kWh supplied from Irrigation Pump PV PV: 4,380.00

Net Solar Energy Supply

- Net Energy Supply: -78,907.09 kWh

Electrification Options

☐ Chainsaw ☑ Forklift ☐ Windmachine ☑ ATV ☑ Tractor ☑ Pickup Truck
☑ Work Truck

PV Location Options

☑ Rooftop PV ☐ Idle land PV ☑ Irrigation Pump PV ☑ Agrivoltaics

Demand Summary

- Total Energy Demanded: 88,287 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year
- Additional energy demanded from electric Tractor : 29,841 kWh/year

Supply Summary

- Cumulative annual kWh supplied from all systems: 139,528.57
- Annual kWh supplied from Rooftop PV PV: 130,148.57
- Annual kWh supplied from Agrivoltaics PV: 5,000.00
- Annual kWh supplied from Irrigation Pump PV PV: 4,380.00

Net Solar Energy Supply

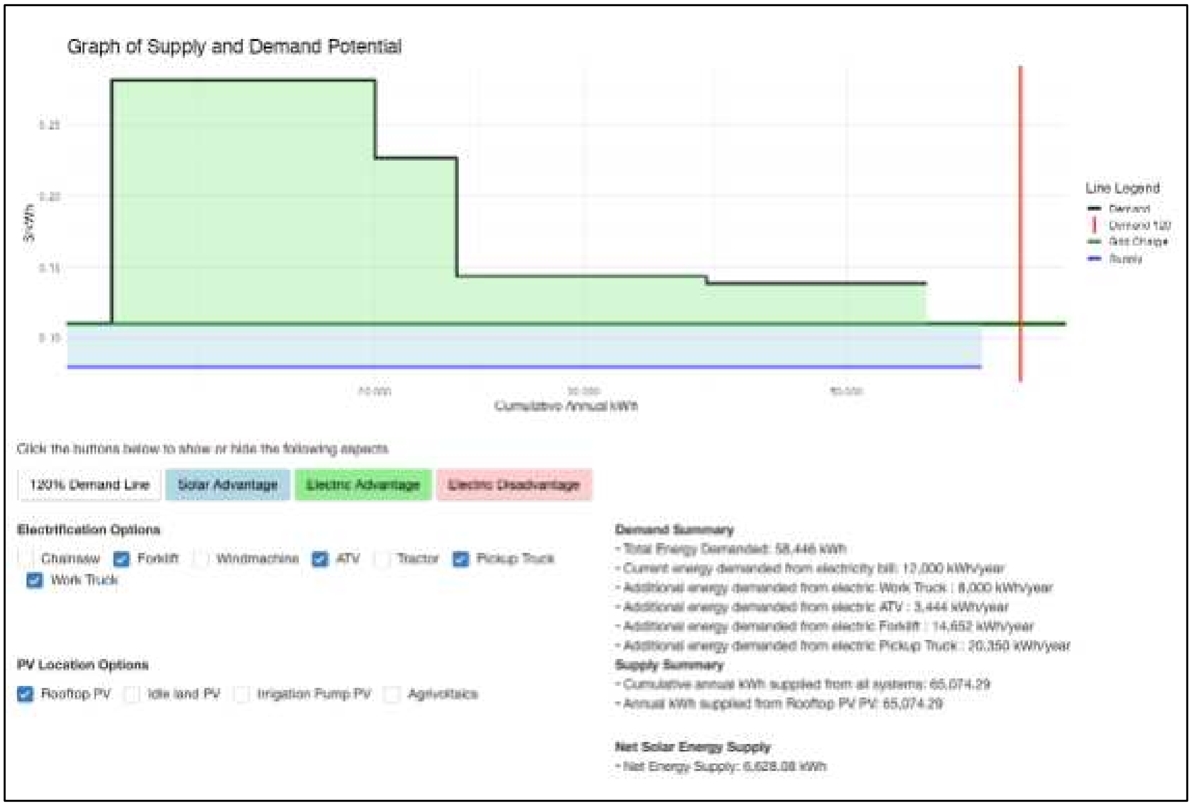
- Net Energy Supply: 51,241.48 kWh
- Note: Supply exceeds 120% of demand! This option may require regulatory approval.

Figure 10: Scenario 2 - Supply and Demand Scenarios - Upper left: Idle Land PV supplies energy. Upper Right: Rooftop PV supplies energy. Bottom left: Irrigation and Agrivoltaics supply energy. Bottom Right: Rooftop, Irrigation and Agrivoltaics PV supply energy.

Using only the inputs from the case-study farmer as found in Table 7, it is evident that supply and demand cannot be closely matched given those parameters as seen in figure 10. When considering only the tools and vehicles with an electric advantage, both rooftop and idle land PV systems independently generate too much supply in kWh, exceeding the 120% demand limitation. This is depicted in the upper left and upper right quarter where the blue supply line crosses the red 120% of demand line. Conversely, when both an agrivoltaic system and the irrigation PV pump system are installed together, they fall short of meeting the demand by 78,907.09 kWh as seen in the bottom left quarter of figure 10. Since the rooftop PV system already exceeds the 120% demand line, adding it to the agrivoltaic and irrigation PV systems results in further exceeding the 120% demand line and to a solar disadvantage, as shown in the bottom right quadrant of Figure 10.

Various options can be used to set supply and demand closely equal to each other. The first option is electrifying all tools and vehicles, regardless of any electric advantage or disadvantage, resulting in a total kWh demand of 97,262 kWh. However, no PV array configuration closely matches this demand. One acre of idle land PV produces roughly 630,000 kWh, 2600 sq.ft of rooftop PV produces close to 130,000 kWh, 0.1 acre of agrivoltaics produce about 5,000 kWh, and the irrigation pump PV system produces about 4,380 kWh. Given these numbers, complete electrification is not feasible

The first option did not work, as the PV arrays produce too much or too little energy. This leads to the second option of reducing the amount of space the PV arrays occupy by changing the inputs in the questionnaire. In this case, if we want to only consider the tools with the electric advantage, as it is an ideal component of this scenario, and we reduce the PV array space from 2600 ft to 1300 ft, then we obtain a result more closely matching our goal. The results of reducing the sq.ft of rooftop array to 1,300 sq.ft is seen in figure 11 below. In this scenario, supply exceeds demand by 6,628.08 kWh, which is less than 120% of the demand, this a feasible option.



Electrification Options

☐ Chainsaw ☑ Forklift ☐ Windmachine ☑ ATV ☐ Tractor ☑ Pickup Truck
☑ Work Truck

PV Location Options

☑ Rooftop PV ☐ Idle land PV ☐ Irrigation Pump PV ☐ Agrivoltaics

Demand Summary

- Total Energy Demanded: 58,446 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year

Supply Summary

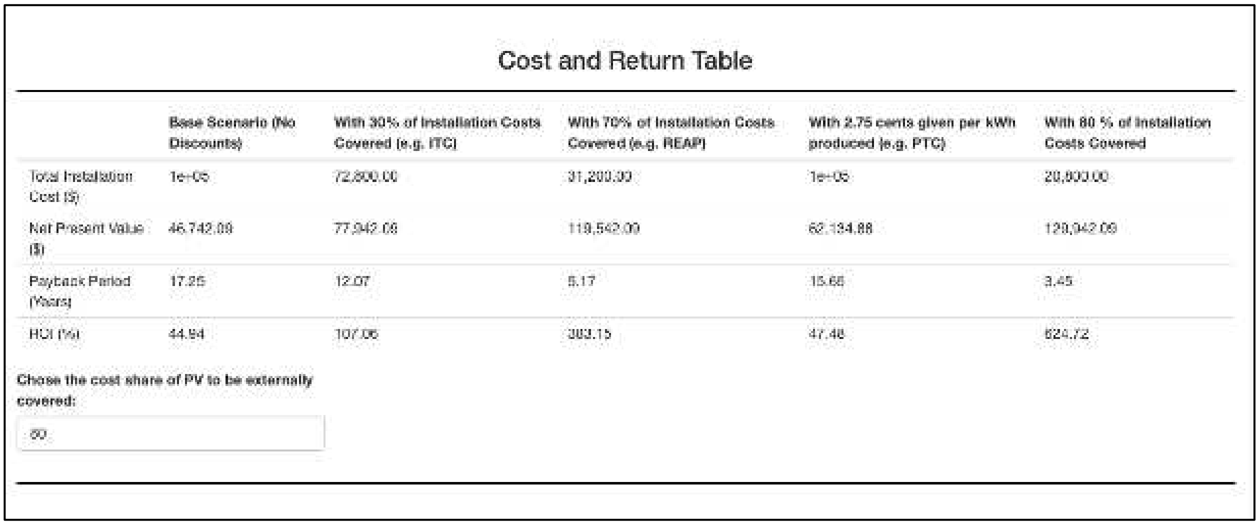
- Cumulative annual kWh supplied from all systems: 65,074.29
- Annual kWh supplied from Rooftop PV PV: 65,074.29

Net Solar Energy Supply

- Net Energy Supply: 6,628.08 kWh

Figure 11: Scenario 2 - Matching Supply and Demand

After the ideal electrification choices and PV options are chosen, the economic implication of this scenario is seen in the cost-return table located below the graph as well as the summary tables in the report tab as depicted in figure 12 and figure 13 respectively. The cost - return table shows how different financing options affect the Total Cost of the PV arrays, which is the cost over 25-year lifetime, the annual system cost, Payback period, Return on Investment as well as the cost per kWh of the system. This table enables farmers to see the percent of the PV array that must be externally paid for in order for the array to fit their preferred budget. As seen in figure 8, as more of the PV array is externally covered, this lowers the cost per kWh of the system, implying that the solar advantage of such a system would increase as externa financing increases.


Cost and Return Table

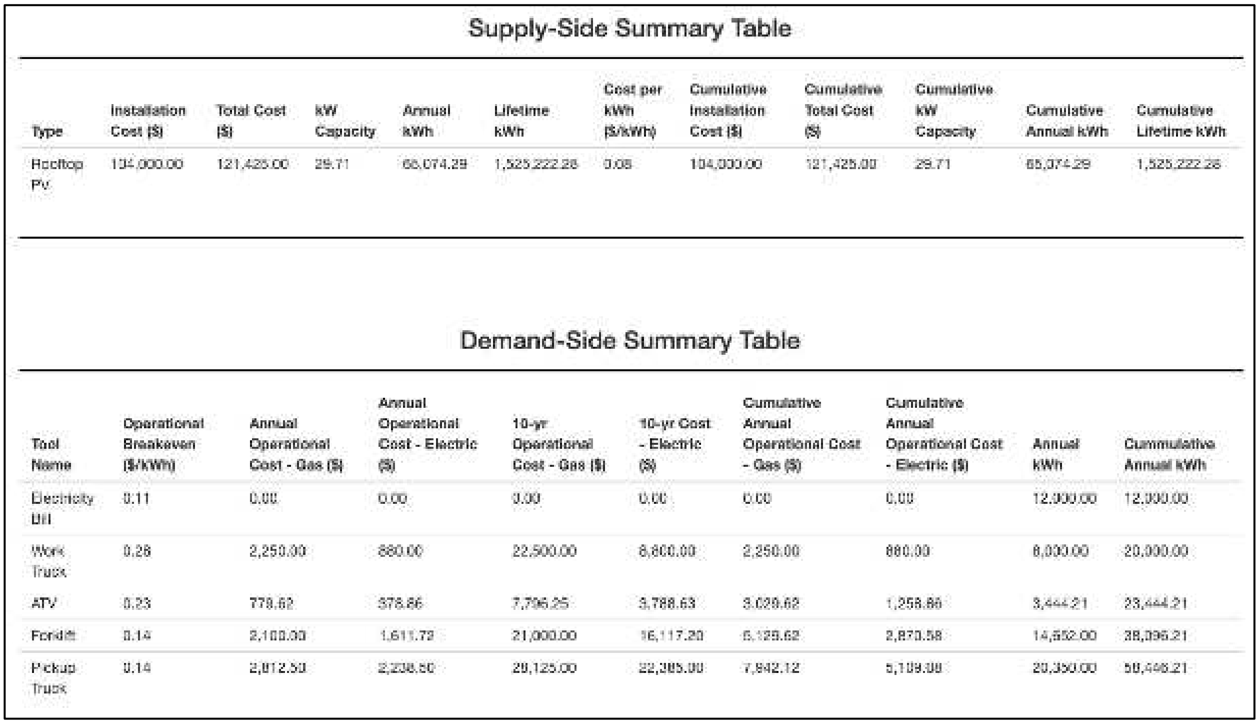
	Base Scenario (No Discounts)	With 30% of Installation Costs Covered (e.g. ITC)	With 70% of Installation Costs Covered (e.g. REAP)	With 2.75 cents given per kWh produced (e.g. PTC)	With 80 % of Installation Costs Covered
Total Installation Cost ($)	1e+05	72,800.00	31,200.00	1e+05	20,800.00
Net Present Value ($)	46,742.09	77,942.09	119,542.09	62,134.88	129,942.09
Payback Period (Years)	17.25	12.07	5.17	15.66	3.45
ROI (%)	44.94	107.06	383.15	47.48	624.72

Chose the cost share of PV to be externally covered:

80

Figure 12: Scenario 2, Cost-Return Table

The summary tables depicted in figure 13 provide a comprehensive report summarizing the various PV array options alongside the selected electrified tools and vehicles. These tables offer a detailed overview, presenting key metrics such as energy generation capacity and output as well as different cost considerations. They serve as a crucial tool for decision-making, offering insights into how different configurations of PV arrays and electrified equipment contribute to meeting energy demands effectively and economically.



Supply-Side Summary Table

Type	Installation Cost ($)	Total Cost ($)	kW Capacity	Annual kWh	Lifetime kWh	Cost per kWh ($/kWh)	Cumulative Installation Cost ($)	Cumulative Total Cost ($)	Cumulative kW Capacity	Cumulative Annual kWh	Cumulative Lifetime kWh
Rooftop PV	104,000.00	121,425.00	29.71	65,074.29	1,525,222.28	0.08	104,000.00	121,425.00	29.71	65,074.29	1,525,222.28

Demand-Side Summary Table

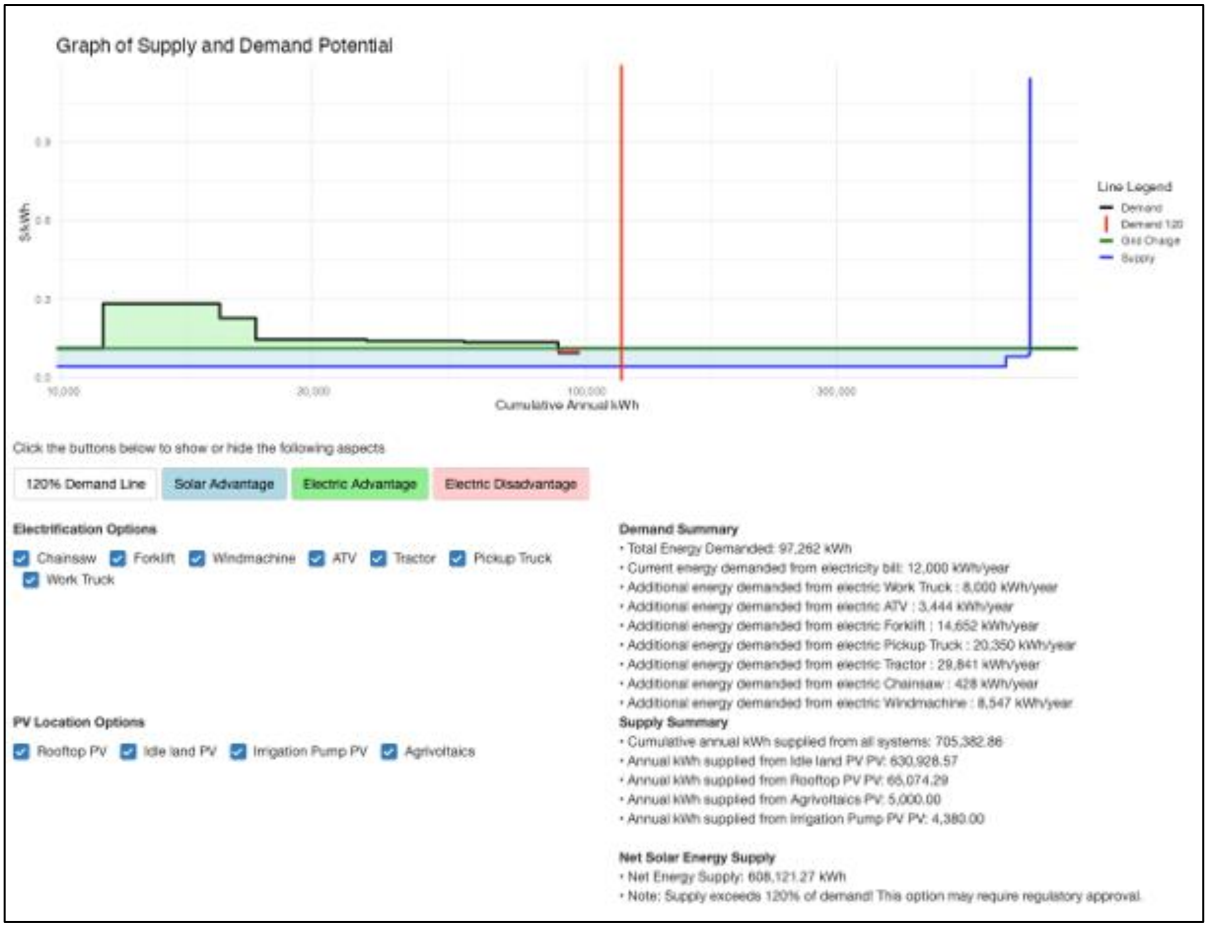
Tool Name	Operational Breakeven ($/kWh)	Annual Operational Cost - Gas ($)	Annual Operational Cost - Electric ($)	10-yr Operational Cost - Gas ($)	10-yr Cost - Electric ($)	Cumulative Annual Operational Cost - Gas ($)	Cumulative Annual Operational Cost - Electric ($)	Annual kWh	Cummulative Annual kWh
Electricity Bill	0.11	0.00	0.00	0.00	0.00	0.00	0.00	12,000.00	12,000.00
Work Truck	0.28	2,250.00	880.00	22,500.00	8,800.00	2,250.00	880.00	8,000.00	20,000.00
ATV	0.23	779.62	378.86	7,796.25	3,788.63	3,029.62	1,258.86	3,444.21	23,444.21
Forklift	0.14	2,100.00	1,611.72	21,000.00	16,117.20	5,129.62	2,870.58	14,652.00	38,096.21
Pickup Truck	0.14	2,812.50	2,238.50	28,125.00	22,385.00	7,942.12	5,109.08	20,350.00	58,446.21

Figure 13: Scenario 2, Supply and Demand Summary Tables

By using the tool to find where supply meets demand, considering the regulatory constraints on supply, the farmer gains insight into the ideal amount of tools and vehicles to electrify as well as the ideal amount of area as well as the best location to install a PV array over. By first knowing the supply and demand energy scenario, the farmer can then look into the economic feasibility of the PV arrays. This is accomplished through seeing what options are presently available for financing as well as creating a solution to meet their needs by being able to choose the amount of the PV array that is externally financed. These components provide farmers with a clear understanding of their energy needs and the economic conditions necessary to implement a PV array given their individual criteria.

5.4 Scenario 3 – Maximize Supply and Demand

The third scenario provides farmers with insight into the maximum amount of energy they may demand as well as the maximum amount of energy they could supply given there are no changes to the inputs in Table 6. By maximizing both the supply and demand, farmers are given a holistic picture into the options that results in advantages and disadvantages on both the supply and demand side. It also informs farmers about the costs involved in electrification and installing PV arrays.



Click the buttons below to show or hide the following aspects

Electrification Options

☑ Chainsaw ☑ Forklift ☑ Windmachine ☑ ATV ☑ Tractor ☑ Pickup Truck ☑ Work Truck

PV Location Options

☑ Rooftop PV ☑ Idle land PV ☑ Irrigation Pump PV ☑ Agrivoltaics

Demand Summary

- Total Energy Demanded: 97,262 kWh
- Current energy demanded from electricity bill: 12,000 kWh/year
- Additional energy demanded from electric Work Truck : 8,000 kWh/year
- Additional energy demanded from electric ATV : 3,444 kWh/year
- Additional energy demanded from electric Forklift : 14,652 kWh/year
- Additional energy demanded from electric Pickup Truck : 20,350 kWh/year
- Additional energy demanded from electric Tractor : 29,841 kWh/year
- Additional energy demanded from electric Chainsaw : 428 kWh/year
- Additional energy demanded from electric Windmachine : 8,547 kWh/year

Supply Summary

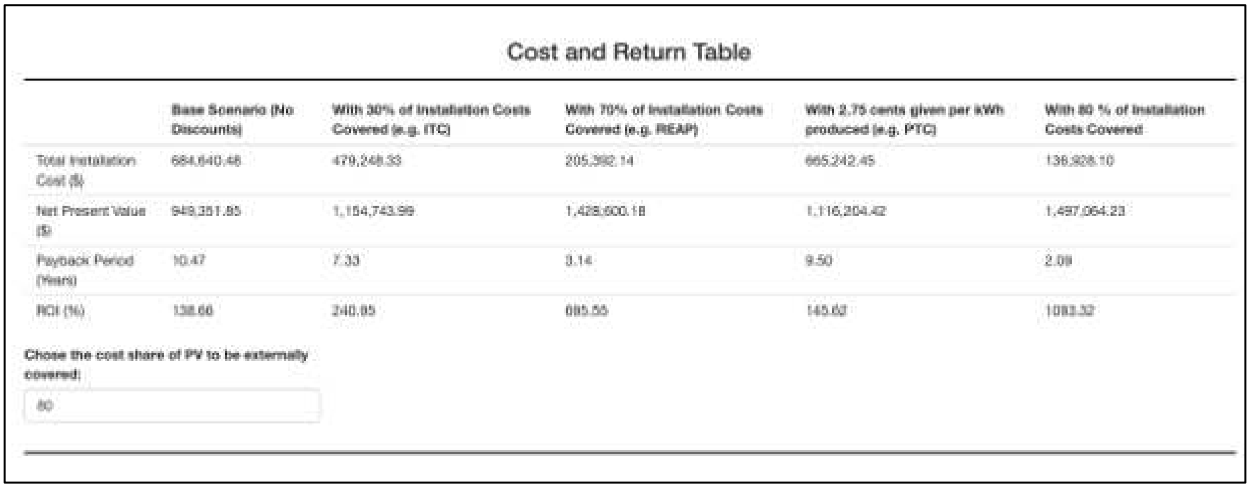
- Cumulative annual kWh supplied from all systems: 705,382.86
- Annual kWh supplied from Idle land PV PV: 630,928.57
- Annual kWh supplied from Rooftop PV PV: 65,074.29
- Annual kWh supplied from Agrivoltaics PV: 5,000.00
- Annual kWh supplied from Irrigation Pump PV PV: 4,380.00

Net Solar Energy Supply

- Net Energy Supply: 608,121.27 kWh
- Note: Supply exceeds 120% of demand! This option may require regulatory approval.

Figure 14: Scenario 3, Supply and Demand Graphic

Figure 14 graphically shows the advantages and disadvantages of complete electrification and PV array installation. The area in blue indicates that there exists an economic advantage to installing PV arrays and drawing energy from the PV arrays rather than drawing energy from the grid. As the supply line intersects the grid line, there no longer exists an advantage to installing PV arrays. In this graph, it is also evident that it would not be wise to install PV arrays in all four locations, as this would result in too much supply being put into the grid. If this occurs, the farmer may no longer qualify for a net metering system and might need to be classified as an energy provider. This determination varies case by case. Another aspect evident in this graph is the area highlighted in red, similar to scenario 1, it is not recommended to electrify tools that fall under this red highlighted area, especially if the farmer is only drawing electricity from the grid. Even if the farmer is drawing power from the PV array it may still be less costly to continue using the gas/diesel version of the tool. This once again could change depending on the price of gas and diesel.



Cost and Return Table

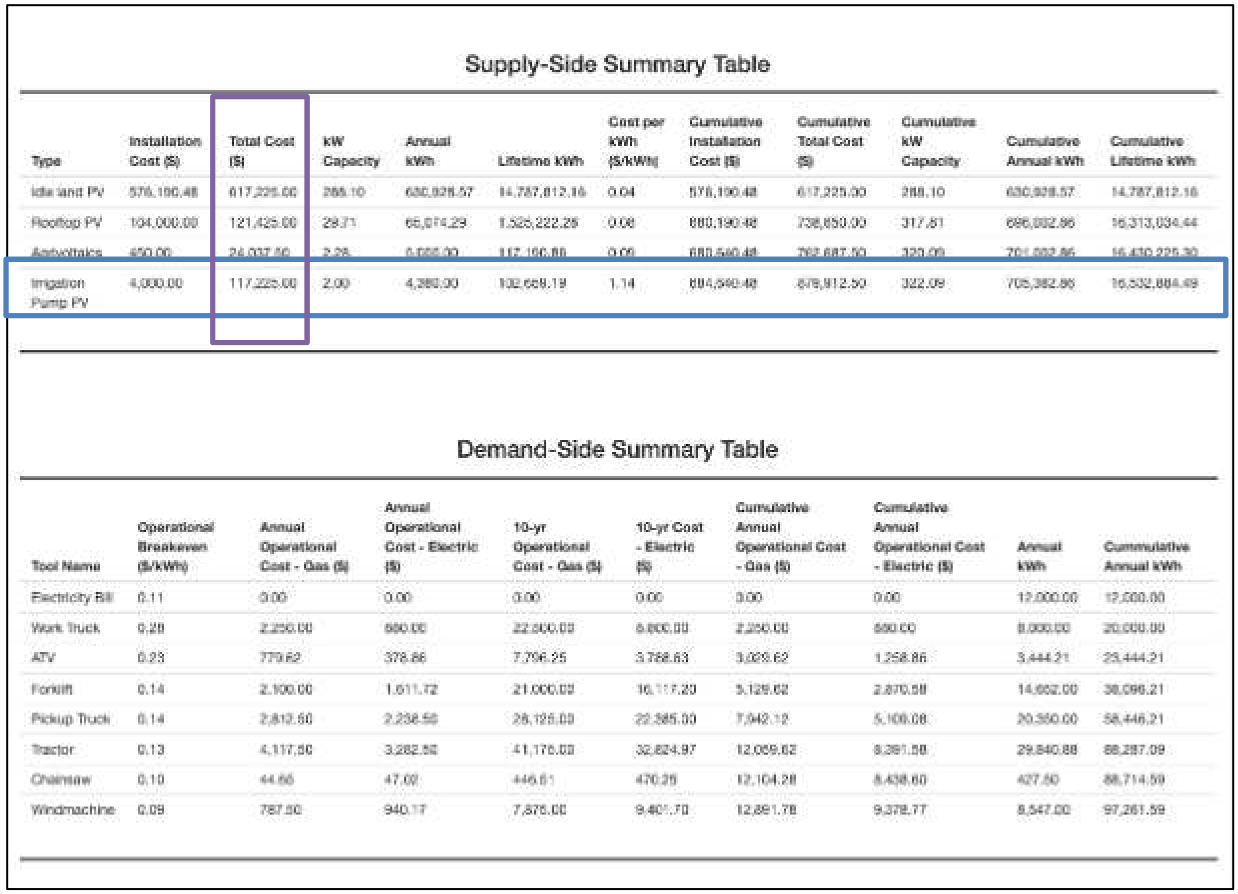
	Base Scenario (No Discounts)	With 30% of Installation Costs Covered (e.g. ITC)	With 70% of Installation Costs Covered (e.g. REAP)	With 2.75 cents given per kWh produced (e.g. PTC)	With 80 % of Installation Costs Covered
Total Installation Cost ($)	684,640.48	479,248.33	205,392.14	665,242.45	136,928.10
Net Present Value ($)	949,351.85	1,154,743.99	1,428,600.18	1,116,204.42	1,497,064.23
Payback Period (Years)	10.47	7.33	3.14	9.50	2.09
ROI (%)	138.66	240.95	695.55	145.62	1083.32

Chose the cost share of PV to be externally covered:

80

Figure 15: Scenario 3, Cost-Return Table

Although the graphic gives farmers a good understanding of what should and should not be electrified as well as what PV arrays should and should not be installed based on the energy demanded and supplied, this does not tell farmers what is feasible for their pockets. The cost-return table, as depicted in figure 15, shows the cumulative costs of installing all four PV array systems. Installing all systems could work given the amount of land and rooftop space a farmer has available but could become infeasible due to too much supply as well as potential economic infeasibility as determined in the cost-return table. Therefore, it is crucial for farmers to carefully evaluate the cost-return analysis in conjunction with the graphical representation to ensure a balance between energy needs and financial constraints. Such evaluation can be further examined in depth by looking at the supply and demand summary tables on the report tab as depicted in figure 16. The blue box surrounds the PV option that fails to have a solar advantage over drawing electricity from the grids. Numerically, this can be quickly deduced by looking at the cost per kWh column, in which the Irrigation Pump PV has the highest cost per kWh value and exceeds the cost per kWh value of drawing from the grid which is 0.11 $/kWh as seen in the graph. Another important aspect that farmers can look at is the kW capacity of the different PV arrays boxed in purple. This gives farmers the option to consider any kW power constraints set by utility providers in addition to the120% demand constraint depicted in the graph.



Supply-Side Summary Table

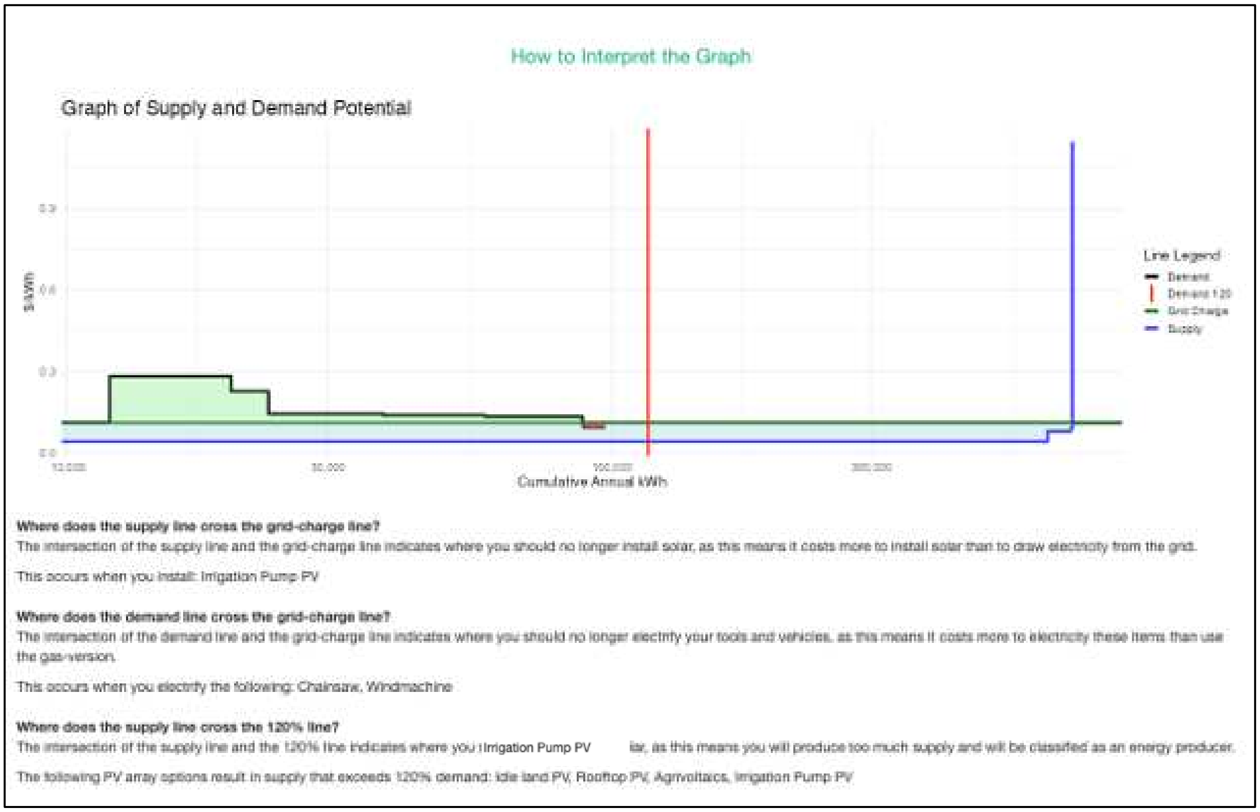
Type	Installation Cost ($)	Total Cost ($)	kW Capacity	Annual kWh	Lifetime kWh	Cost per kWh ($/kWh)	Cumulative Installation Cost ($)	Cumulative Total Cost ($)	Cumulative kW Capacity	Cumulative Annual kWh	Cumulative Lifetime kWh
Idle land PV	576,190.48	617,225.00	288.10	630,928.57	14,787,812.16	0.04	576,190.48	617,225.00	288.10	630,928.57	14,787,812.16
Rooftop PV	104,000.00	121,425.00	29.71	65,074.29	1,525,222.28	0.08	680,190.48	738,650.00	317.81	696,002.86	16,313,034.44
Agrivoltaics	450.00	24,037.50	2.28	5,000.00	117,190.86	0.06	680,640.48	762,687.50	320.09	701,002.86	16,430,225.30
Irrigation Pump PV	4,000.00	117,225.00	2.00	4,380.00	102,659.19	1.14	684,640.48	879,912.50	322.09	705,382.86	16,532,884.49

Demand-Side Summary Table

Tool Name	Operational Breakeven ($/kWh)	Annual Operational Cost - Gas ($)	Annual Operational Cost - Electric ($)	10-yr Operational Cost - Gas ($)	10-yr Cost - Electric ($)	Cumulative Annual Operational Cost - Gas ($)	Cumulative Annual Operational Cost - Electric ($)	Annual kWh	Cummulative Annual kWh
Electricity Bill	0.11	0.00	0.00	0.00	0.00	0.00	0.00	12,000.00	12,000.00
Work Truck	0.28	2,250.00	880.00	22,500.00	8,800.00	2,250.00	880.00	8,000.00	20,000.00
ATV	0.23	779.62	378.86	7,796.25	3,788.63	3,029.62	1,258.86	3,444.21	23,444.21
Forklift	0.14	2,100.00	1,611.72	21,000.00	16,117.20	5,129.62	2,870.58	14,652.00	38,096.21
Pickup Truck	0.14	2,812.50	2,238.50	28,125.00	22,385.00	7,942.12	5,109.08	20,350.00	58,446.21
Tractor	0.13	4,117.50	3,282.50	41,175.00	32,824.97	12,059.62	8,391.58	29,840.88	88,287.09
Chainsaw	0.10	44.66	47.02	446.61	470.25	12,104.28	8,438.60	427.50	88,714.59
Windmachine	0.09	787.50	940.17	7,875.00	9,401.70	12,891.78	9,378.77	8,547.00	97,261.59

Figure 16: Scenario 3, Supply and Demand Summary Tables

Figure 17 shows how the guiding questions to help users understand the graph changes based on the tools and vehicles selected as well as the PV array options selected. The results of the guiding questions are different compared to the results as seen in figure 9. The guiding questions serve to clarify which PV arrays fail to offer a solar advantage, as well as which tools do not demonstrate a clear benefit from electrification, providing users with a precise understanding of the circumstances under which these alternatives may not be advantageous. Now it is evident that the questions tell users exactly which PV arrays do not hold a solar advantage as well as which tools do not have an electric advantage.



Where does the supply line cross the grid-charge line?
The intersection of the supply line and the grid-charge line indicates where you should no longer install solar, as this means it costs more to install solar than to draw electricity from the grid.

This occurs when you install: Irrigation Pump PV

Where does the demand line cross the grid-charge line?
The intersection of the demand line and the grid-charge line indicates where you should no longer electrify your tools and vehicles, as this means it costs more to electricfy these items than use the gas-version.

This occurs when you electrify the following: Chainsaw, Windmachine

Where does the supply line cross the 120% line?
The intersection of the supply line and the 120% line indicates where you Irrigation Pump PV lar, as this means you will produce too much supply and will be classified as an energy producer.

The following PV array options result in supply that exceeds 120% demand: Idle land PV, Rooftop PV, Agrivoltaics, Irrigation Pump PV

Figure 17: Scenario 3, Interpreting the Graph

6. Limitations

There are several limitations present within the development of this tool. On the supply side, the solar panel output in watts, sizing and pricing data used in the development of the tool are subject to significant variability across different solar installers as there are no industry-wide standards. This results in variability in the energy output analyses as well as the cost analyses. Thus, the results provided are only meant to give a rough estimation of an outcome and further evaluation by local solar installers is needed. In addition to the PV panel data affecting aspects of supply, the hours of effective sunlight, regulatory constraints and local grids pricing affect the supply side. In this study, the data is limited to Western Colorado counties and cannot be applied to other counties in Colorado or other states.

The energy consumption data used to determine the energy demand needs are also approximate values. The energy consumed by tools and vehicles vary based on the different brands and models available for farmers to choose from. Moreover, the energy consumed by the tools and vehicles would fluctuate based on the intensity of the work as well. These variations in energy demand could impact the accuracy of the solar system sizing recommendations.

This study does not account for ongoing technological advancements in both PV technology and agricultural equipment. Solar panel efficiency continues to improve annually, and specialized panels for unique agricultural environments are emerging (Thompson et al., 2020). Concurrently, both gasoline-powered and electric agricultural tools and vehicles are becoming more energy-efficient. These technological progressions could alter the cost-benefit dynamics of solar adoption in agriculture in the near future.

These limitations underscore the need for ongoing research in this field, particularly studies that can account for technological advancements and more precise energy consumption data in agricultural settings.

7. Future Research Directions

Future work will enhance the capabilities and applicability of this tool. A key area for future research is an evaluation of how battery technology impacts farm energy systems. This could involve analyzing a farmer's willingness to pay for integrating batteries with solar panels, enabling farmers to rely more on stored energy rather than the grid. Such an assessment also needs to consider current and projected battery costs, as well as the future trajectory of battery storage technology. This analysis will provide insights into the viability of off-grid agricultural operations.

Another area of potential exploration is the economic implications of removing current supply restrictions, such as the 120% of demand limit, which prevents supplying more than 120% of the farm's energy demand in kWh. This research could investigate the costs and benefits of farms being classified as both agricultural entities and energy producers. These investigations could also inform policy discussions and help shape future regulations regarding on-farm energy production to make such scenarios more accessible.

The tool could also be expanded beyond peach operations to encompass a wider range of agricultural activities by adapting it to account for diverse energy needs and usage patterns. This would require an expanded inventory of electrifiable farm equipment and an analysis of potential solar panel locations for different farm layouts. This broader application could help identify which agricultural sectors are most suitable for solar integration. By addressing these areas, future research could significantly enhance the tool's utility and provide valuable insights for the agricultural sector's transition to renewable energy sources through photovoltaic adoption.

8. Conclusion

I had four basic research questions, one related to supply and demand, second one related to electrification of tools and vehicles, third related to the influence of regulatory constraints on supply and demand and the fourth evaluating the economic feasibility of solar power. Through the graphic and the table which are provided when using the program and in the final report that growers can print, each of these questions have been addressed. For example, a grower can compare where his or her own supply and demand meet. This helps the grower avoid having too much or too little supply or demand. Having too much supply for example, may put a grower at risk of paying to produced energy he can't use or sell to the grid. Too much demand through electrifying tools and vehicles with an electrification disadvantage could result in the grower increasing their operational costs without it being offset by solar.

The graph provides a visual of when there is an advantage and disadvantage to electrifying tools and vehicles. This occurs through an evaluation of the operational breakeven of the tools and vehicles. The operational breakeven in $/kWh is the price electricity would have to cost per kWh for the gas tool or vehicle to be a more economic option than the electric tool. The operational breakeven of the tools and vehicles change based on the cost of gas and the cost of diesel. The advantage or disadvantage of electrifying a tool or vehicle can change based on the cost of drawing electricity from the grid. If the operational breakeven is above the grid price, there exists an economic advantage to electrifying the tool or vehicle. This advantage exists without having a solar array installed on the farm, and the advantage increases if a solar array is installed.

The graph also depicts the regulatory constraint on supply by incorporating a line that represents the point where supply would exceed 120% of demand in kWh. It is crucial to note the occurrences of this threshold, as growers who generate electricity beyond this level may be classified as electricity providers by their utility company. This classification can have significant implications, altering their tax status and regulatory considerations. This issue is partly related to grid capacity constraints and the lack of efficient battery storage systems. Currently, the storage of electricity is not very efficient, and growers' own electricity needs may not be met solely by their on-site generation, as peach growers experience a substantially higher demand for electricity the months during and after peach harvest, compared to other times of the year. Being disconnected from the grid could pose challenges if their demand exceeds their supply during these months, ultimately affecting their profitability from peach operations. If growers cannot decrease their supply, they could look at ways to increase their demand through this tool. This allows them to find a level in which supply and demand fall within the regulatory constraints.

The cost-return table and the supply and demand summary tables found in the tool help the growers understand the economics behind their supply and demand choices. Although growers can find a supply and demand solution that works for them in terms of energy, this does not always equate to a solution that works for them economically. The cost-return table gives the growers a way to view the cost of the different PV arrays under five different external financing scenarios, one scenario in which they are able to customize themselves. This gives growers an idea of the financing options that are currently available to them as well as allowing them to figure out what their ideal financing scenario would consist of. The demand summary table gives growers a way to quickly compare the annual and total operating costs of gas and electric vehicles and tools. This is a more intuitive way for growers to understand the economic advantages and disadvantages of electrification. The supply summary table gives a clear breakdown by PV array location of the different costs and energy outputs. These three tables give growers an in-depth understanding of the economic implications of their energy choices, enabling them to make well-informed decisions that align with their financial objectives and constraints.

This tool gives peach growers a personalized approach to evaluating solar energy and electrification in a way that accounts for changing preferences in tools and vehicles as well as location choices. It allows these individualized preferences to build on each other and evolve to meet the growers wants as well as any regulatory needs. Although SOAR can not give a precise estimation of energy supply and demand or an exact economic evaluation, the tool gives growers an idea of the range of possibilities and trade-offs they may encounter. By providing a comprehensive yet flexible analysis, it empowers growers to explore various "what-if" scenarios, experiment with different configurations, and develop a tailored energy strategy that aligns with their specific operational requirements, financial constraints, and long-term sustainability goals. Ultimately, this interactive tool serves as a friendly decision-support system, guiding peach growers through the complexities of energy management and enabling them to make informed choices that fit with their farming practices while embracing the transition towards renewable and efficient energy sources.

Similar decision aid tools can ultimately help a wide range of farmers integrate new technologies into their operations, whether it involves renewable energy, electric tools and vehicles, or future technological advancements such as farm robots. It is essential for researchers to collaborate closely with farmers to develop and explore tools that are practical and beneficial for their specific needs. By merging technical insights with economic analysis, these tools can provide farmers with a holistic understanding of the potential impacts and benefits of new technologies, empowering them to make informed decisions for their operations.

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