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Solar Grazing as a Possible Vegetation Management Solution: A Budget Analysis

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Table of Contents

Abstract..2

Introduction..3

Literature Review...5

Methodology...10

Results...14

Conclusion and Discussion 20

References...21

Abstract

A growing response to climate change among agricultural producers is to integrate renewable energy production in their portfolio of enterprises. Nonetheless, land use competition for agricultural production and solar energy production exists. To alleviate some of this competition, and possibly generate income for sheep grazers, photovoltaic (PV) system operators may save on operations and maintenance by grazing forages under solar panels rather than using mechanical or chemical means of vegetation management. “Solar grazing” operations have been shown to be economically feasible for PV system operators who own the land and pay for sheep grazing as a method of vegetation management, but no economic research has been done for a scenario in which the solar grazer owns land on which a PV operator leases for operating the PV system without worrying about land management.

This study analyzed solar lambing and grazing operation budgets and synthesized them into one budget. The lambing and grazing budget was subsequently compared to two budgets for vegetation management that were generated in a similar manner. One used conventional mowing (currently most common option for PV systems) and a second relied on autonomous robot mowing (a less labor intensive and more environmentally friendly alternative).

The results of this study show both a possible income for grazers and possible savings for PV system operators. Robotic mowing may also be a cost saving method over conventional mowing. It was shown to be a more profitable method for a landowner in comparison to lambing and grazing, but importantly, eliminates agricultural production. These results suggested that solar grazing may be an option for small farms interested in a grazing and lambing operations, as without the solar lease operations at the scale investigated are not economically feasible. Also more research on lease agreement options and robot mowing for solar operations is needed.

Introduction

Climate change is continuing to affect the environment and the way energy is produced (Edenhofer et al., 2011). Climate change is a long-term change of the overall temperature and weather patterns primarily due to greenhouse gas (GHG) emissions (Mason-Delmotte et al., 2021; Edenhofer et al., 2011). Eighty-five percent of current energy is produced by fossil fuels, and those fossil fuels accounted for 35% of global GHG emissions in 2010 (Masson-Delmotte et al., 2021). Alternative energy sources have been used to mitigate the amount of GHG emissions by replacing fossil fuels with renewable energy such as wind power, hydroelectric power, and solar power. Solar power offers short- and long-term mitigation for climate change by producing virtually zero GHG emissions (Masson-Delmotte et al., 2021).

Photovoltaic (PV) systems are the most common form of solar-generated power, wherein PV cells directly convert sunlight into electricity through solar panels that are either mounted to freestanding frames or directly onto a building (Horowitz et al., 2020).

Shade from freestanding PV systems affects the growth of vegetation under the panel canopy and may also open the door to grow more higher-quality, cool season forage species in the midsouthern U.S. (Adeh et al., 2018; Andrew et al., 2021; Marrou et al., 2015). As such, the term ‘solar grazing’ has evolved to encompass the nexus of PV systems, forages grown in proximity, and finally forage utilization by grazing ruminants. The amount of solar radiation reaching the forage, soil moisture, and soil temperature are all impacted by the presence of the solar panels (Adeh et al., 2018). This can cause herbs to bloom more often (Graham et al., 2021) although not necessarily produce more forage (Andrew et al., 2021).

One important operational and maintenance cost of utility-scale PV systems is vegetation maintenance, traditionally done with either placing gravel under the PV system or mowing/trimming. Kochendoerfer, Hain, and Thonney (2019) found that grazing sheep is a cost-effective vegetation management option. For this reason, analysis of the interaction between PV systems operation and sheep grazing is deemed an opportunity to exploit (Shiflett, 2022). While several studies have examined a contractual relationship between a PV system owner and grazer in which the PV system owner also has ownership of the property, the literature does not examine an alternative contract in which the sheep producer is the landowner and leases grazing land to a PV systems owner operator. There is thus unexplored economic analysis on cost savings for a PV system owner to lease the land from a sheep producer who continues to graze sheep on that property, albeit possibly at a lower stocking rate.

Agri-photovoltaics is the colocation of agricultural land use and PV electricity generation. Agri-photovoltaics located on land used for livestock increases land use efficiency. Sheep could work well with PV systems because of their shorter stature compared to cattle and thereby lesser chance of damaging solar panels or the structures upon which they rest. The shade produced by PV systems reduces the amount of water the sheep consume, and sheep production can be efficiently co-located with solar energy production (Andrew et al., 2021; Kochendoerfer, Hain, and Thonney, 2019).

The hypothesis of this study is that creating a lease relationship between a land-owning sheep grazer and a PV system operator could possibly reduce the cost of maintaining forage underneath the solar panels, provide the sheep grazer with more income, and lessen their risk exposure due to shading. Concomitantly, this study compares sheep grazing to conventional, custom mowing and autonomous, robotic mowing without grazing as possible forage maintenance alternatives. Thus, the comparison allows a landowner the opportunity to compare potential earnings before taxes resulting from the aforementioned land use choices.

The general objective of this study is to determine whether solar grazing with sheep is economically feasible for a PV system operator whose system is located on leased land and/or for the landowner. Specific objectives will include i) developing enterprise budgets for estimating the income and expenses gained from a solar lease operation wherein a sheep producer owns the land and allows a PV system operator to lease and utilize the land in conjunction with sheep production, ii) calculating financial performance for estimated expenses of traditional grass and weed trimming vs. autonomous robot mowing, and iii) comparing earnings before taxes to the land owner across the three proposed alternatives along with implications for co-location of PV systems with or without grazing.

Literature Review

As the world searches for new ways to mitigate climate change, renewable energy is a popular solution (Fawzy et al., 2020). By examining previous research into the co-location of agriculture and PV systems, this study determines the economic value of varying leasing rates for sheep producers and PV system owners, as well as a comparison with conventional, manual mowing and autonomous (robot) mowing. This literature review is a synthesis of these studies and budgets used for calculations.

Solar Co-location

Several studies have analyzed dual-use land cover combining solar energy generation and agriculture, plant, or habitat development. Integrating solar generation and agricultural production can be a more efficient use of land (Sujith et al., 2016; Andrew et al., 2021; Patel et al., 2019) and can reduce GHG emissions (Fawzy et al., 2020; Patel et al. 2019).

There is a consensus across several studies about the production of forage underneath PV systems. Because of the partial shading, forage under a PV system generally grows slower than forage in full sunlight (Graham et al., 2021; Andrew et al., 2021; Marrou et al., 2013). Pollination habitat underneath PV systems produced delayed yet more abundant blooms according to Graham et al. (2021). Further, it was reported that crops needed little acclimation to change from regular to agri-photovoltaic cropping, except for juvenile stages where the reduced sunlight exposure could "delay development for the whole cycle but may also have positive effects on vegetable plant establishment during the warm season" (Marrou et al., 2013, p. 130).

Nutritional content of forage under a PV system is enough to sustain a sheep flock with proper management, allowing for no significant change in weight gain. (Andrew et al., 2021; Kochendoerfer et al., 2022). Andrew et al. (2021) found that solar pastures overall had greater crude protein content and metabolizable energy whereas open (non-solar) pastures had greater water-soluble carbohydrates and neutral detergent fiber. Overall dry matter (DM) production of forage is affected by solar grazing, resulting in less total DM in solar pastures than open pastures (Andrew et at., 2021; Kochendoerfer et al., 2022). The amount of DM varies depending on the time of year (Andrew et al., 2021) and the stocking density of the sheep (Kochendoerfer, Hain, and Thonney, 2019; Kochendoerfer et al., 2022). Sheep were healthy at the end of several studies utilizing solar grazing (Andrew et al., 2021; Kochendoerfer, Hain, and Thonney, 2019; Kochendoerfer et al., 2022). To maximize access to forage nutrients and DM, it is recommended that the sheep be rotationally grazed within a solar pasture (Andrew et al., 2021; Shiflett, 2022).

While, theoretically, any livestock could be used for solar field grazing, sheep are preferred, as the standard PV system is approximately two to seven feet tall, and because they do not usually damage the panels (American Solar Grazing Association (ASGA), 2021). Andrew et al. (2021) found that lambs were shown to have relatively the same weight gain when placed in either solar or open pasture, but lambs that were in a field with solar panels spent significant time under the panels and consumed less water. This implies that there could be animal welfare improvements and more efficient water use for sheep flocks co-located with PV systems.

The possible benefit to PV system owners is improved maintenance of the installation. At certain densities of sheep per acre, “sheep were successful in maintaining the vegetation in the solar site” (Kochendoerfer et al., 2022 p. 3). This can lower labor requirements and costs for forage maintenance (Kochendoerfer, Hain, and Thonney, 2019). The lower costs of land management have been explored by Shiflett (2022) in a contract-based grazing operation in which the PV system owner owns the land underneath the panels and allows a sheep grazer to graze their sheep on that land for the mutual benefits. However, a contract-based grazing operation, in which the grazer is also the landowner and allows a PV system to be installed on their land for a rental fee, has not been analyzed.

Custom Mowing and Robot Mowing

Currently, management of forage in solar fields is done through traditional manual mowing and lawn care. This is typically a custom service paid for by the landowner. This includes a cost of \$0.50 - \$1.80 per kW size of PV system per year (Enbar, Weng, and Klise, 2016). This service entails an environmental negative externality, because most conventional mowers and grass trimmers are gasoline powered, and release GHG emissions (Hossain and Komatsuzaki, 2021; Saidani et al., 2021). However, as a more environmentally-friendly option, battery-powered robotic mowers may provide an alternative method for forage maintenance. These are typically random path mowers, but programmable optimal path mowers use software and global positioning system (GPS) technology to distinguish which areas to mow and are thus far more efficient (Dai et al., 2021; Saidani et al., 2021). Robot mowers range in price from $600-$4,000, with optimal path mower prices belonging on the upper half of that range. Whether this is an economically beneficial method for agriculture or industry depends on multiple factors (Hossain and Komatsuzaki, 2021).

At present, no analysis of robot mower performance in a PV system environment is available. However, research in their performance on open fields, gardens, commercial areas, and even agriculture are available (Dai and Yang, 2021; Hossain and Komatsuzaki, 2021; Saidani et al., 2021; Wu, Yu, and Lin, 2022). Due to the many obstacles and wide area of a PV system, the expenses of an optimal path mower are included in this paper.

Costs and Budget

The economic value of investing in a co-located PV system can be determined by analyzing the tradeoff between financial costs and benefits. The next section describes what the previous literature found concerning the costs and benefits of PV systems, as well as the costs and benefits of custom grazing contracts. Several sheep production budgets were synthesized to calculate the inputs used in a Microsoft Excel^{TM} spreadsheet. Lamb prices were provided by USDA reports.

Differences in ground preparation, support structures, height of panels, number of panels, and spacing between panels all impact recurring maintenance costs (Horowitz et al., 2020). Maintenance of the PV system includes management of vegetative growth under the panels through some means (e.g., mechanical, chemical, or grazing). Costs associated with custom solar grazing contracts from a livestock owner's side can vary depending on the agreement. The management of livestock, their health costs, and fencing costs can be a responsibility of the land and livestock owner. Transportation and logistics costs are also usually the responsibility of the land and livestock owner. Finally, the landowner incurs forage maintenance costs as they establish and maintain the grazable forage underneath the PV system (Cates et al., 2013).

Multiple programs through the U.S. Department of Agriculture (USDA) and the Internal Revenue Service (IRS) incentivize investment in PV systems. USDA's Rural Energy for America Program (REAP) offers grants and loan guarantees for the installation of renewable or more efficient energy in rural areas (USDA, 2020). Specific limitations are written into the statutes and regulations, but for the purposes of this study, we will assume the operator does not receive these grants and tax credits, however this is something to consider when investing in PV systems. Further, a decision aid has recently been developed to analyze solar panel investment by poultry growers (https://agribusiness.uark.edu/decision-support-software.php#PSA) and an on-line tool developed by the National Renewable Energy Lab (NREL) is also available and a good source for verification of system operating and financial parameters (https://sam.nrel.gov/download.html).

Solar leasing rates can vary from approximately $800 - $2,400 per acre, with the most common rates being close to the middle (Kay, D. personal communication, February 17, 2023). Nonetheless, little research on solar leasing rates exists. This large variance is considered to be a function of land suitability for solar energy capture as well as proximity to existing energy infrastructure.

Kilowatt hours (kWh) or megawatt hours (MWh) are the typical energy metrics for a PV system. The amount of kWh produced by PV systems depends on the technology, location, and orientation of the system. Typically, a PV system size will need about 5 - 10 acres for every Megawatt (MW) of power (Kay, D. personal communication, February 17, 2023). Bolinger and Bolinger (2022) found that modern energy densities for PV systems are approximately 447 MWh per acre per year and power densities are roughly 0.35 MW of direct current (DC) power per acre.

Methodology

This section describes the research methods utilized to fulfill the objectives of the economic analysis. It includes information on the types of analysis and the specific ways and means the analyses were completed.

Research Design

The study follows a quantitative, non-experimental comparative data analysis design to examine and compute the economic benefits of a sheep grazing contract for a PV system owner by using existing data. This type of quantitative analysis “allows both quantifying the magnitude […] and computing statistical precision of estimation.” (Fröhlich et al., 2014, p. 112). This analysis will take secondary data gathered from existing literature to estimate revenue and expenses for a solar grazing scenario, as well as estimate expenses for both manual and autonomous mowing.

Rigor

Threats to the internal validity of this study include constructing the proper arithmetic equations and regressions. This is addressed by using considerations pulled from the literature and other experimental research and utilizing multilevel analysis (Maula and Stam, 2019), as well as keeping the analysis contained in Microsoft Excel^{TM}, with all files made available to the reader. The literature review and data drawn from it only includes data from reputable sources.

Certainly, many assumptions and averages were taken in this study to provide a general overview of the financial benefit. The primary purpose is merely to compare possibilities and to encourage more research and discussion about agri-photovoltaics and its economic benefits.

Data Collection

Data collection began with compiling a Microsoft Excel^{TM} spreadsheet from primary and secondary data gleaned from existing literature. The purpose of this spreadsheet was to calculate earnings before taxes to the landowner for the use of the land and the landowner's management. Sheep grazing financials were from data collected by Shiflett (2022), Hudson Valley Solar Grazing Model (2019), North Carolina Choices (n.d.), and University of Maryland Sheep Enterprise (2016) budgets.

Average and range of conventional mowing costs were calculated based on the kWh size of the PV system. Reported within are average, minima and maxima for costs at levels of low, medium, and high kWh potential per acre. The robotic mower budget was estimated using data primarily obtained by the Saidani et al. (2021) study. Conventional mowing cost estimates were similarly obtained from the literature review and primarily from Enbar, Weng, and Klise (2016).

Assumptions

It was assumed the co-located land will have access to adequate water to support livestock. System costs for watering sheep were assumed at $5,000 and are listed under assets. (Schoenian, S., 2016).

Fencing was estimated assuming permanent exterior fencing and fencing to subdivide the land into smaller pasture paddocks with movable electric fencing to allow for rotational grazing. Movable electric fencing was estimated to cost $0.045 per foot (Shiflett, 2022).

Sheep stocking rates and densities should be determined based on the land provided and the goals of the grazer. For this study, 100 ewes on 50 acres was assumed to model an operation that would not modify its flock size. This value is customizable within the spreadsheet, however, and would result in lower or higher stocking densities at the option of the user.

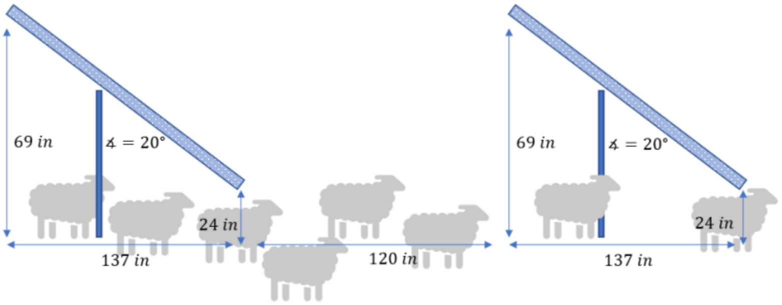


Figure 1*: Example of panel set-up (Kochendoerfer, Hain, and Thonney, 2019).*

A solar array orientation of east-west strips (180° azimuth from north) spaced ten feet apart, with panels on the strips inclined southward at an angle of 18° (20° shown in Fig. 1) were assumed for this study (Adeh et al., 2018; Kochendoerfer, Hain, and Thonney, 2019).

Summertime is the primary period of growth for vegetation and solar energy collection. Thus, the schedule for lamb production was assumed to include an early spring lambing, with sales of the lambs in October at an average of 90lbs.

Property tax and insurance were set at 0.75% and 0.55% of total assets, respectively. Labor was assumed at $15.00 per hour, estimated from a 5-year average of $14.948 (National Agricultural Statistics Service, 2022). Lamb selling prices were set at $156.90 per cwt., a 10-year average (Iowa State University Extension, 2022). Milage for truck use to check on the herd and transport animals to the auction barn was estimated assuming a distance of 30 miles from the auction barn with a 25-mpg truck and $3.50 per gallon of gas.

An optimal path robotic mower was used to determine the costs associated with automated forage and weed management as an optimal path mower is more efficient than a random path mower (Dai and Yang, 2021; Saidani et al., 2021; Wu, Yu and Lin, 2022). A median cost for such a mower was assumed to be $3,000 (Saidani et al., 2021). This price was depreciated using the capital recovery method at 4%. These mowers have a useful life of 10 years, require a battery replacement every 1,000 charges, and require blade replacement every 500 hours of cutting (Saidani et al., 2021).

Robotic mowers vary in model type and subsequent maintenance requirements. Their performance varies based on location, forage type, and terrain. This study used an average full-time performance rate of 1.2705 acres/day (Saidani et al., 2021). The robotic mower automatically returns to its charging dock as needed, spending about 90 minutes operating before needing 80 minutes to re-charge. Full-time operation of the mower assumes the robot does not stop cycling through operation and charging, in other words, the mower never stops trimming or charging.

The variability of grazing contracts requires customizable inputs that modify the values of leasing rates. Such leasing rate variability is a major subject of this study's sensitivity analysis. Many factors will affect the leasing rate a PV operator is willing to pay for land. Location will have a crucial impact on most of the values estimated, affecting water needs, fuel usage, site suitability for PV (and thus leasing rate, as a more desirable area for solar will command a higher lease), and forage type. This study used averages of multiple budgets across the United States and thus provides general guidelines. Nonetheless, an individual user can customize the spreadsheet to allow examination of different scenarios.

Conventional mowing was given in ranges to account for variability in location, labor, and forage. The median cost and median kWh generated on 50 acres was most consistent with other estimates for conventional mowing costs for 50-acre plots of land (Enbar, Weng, and Klise, 2016; Kochendoerfer, Hain, and Thonney, 2019; Soldat et al., 2020).

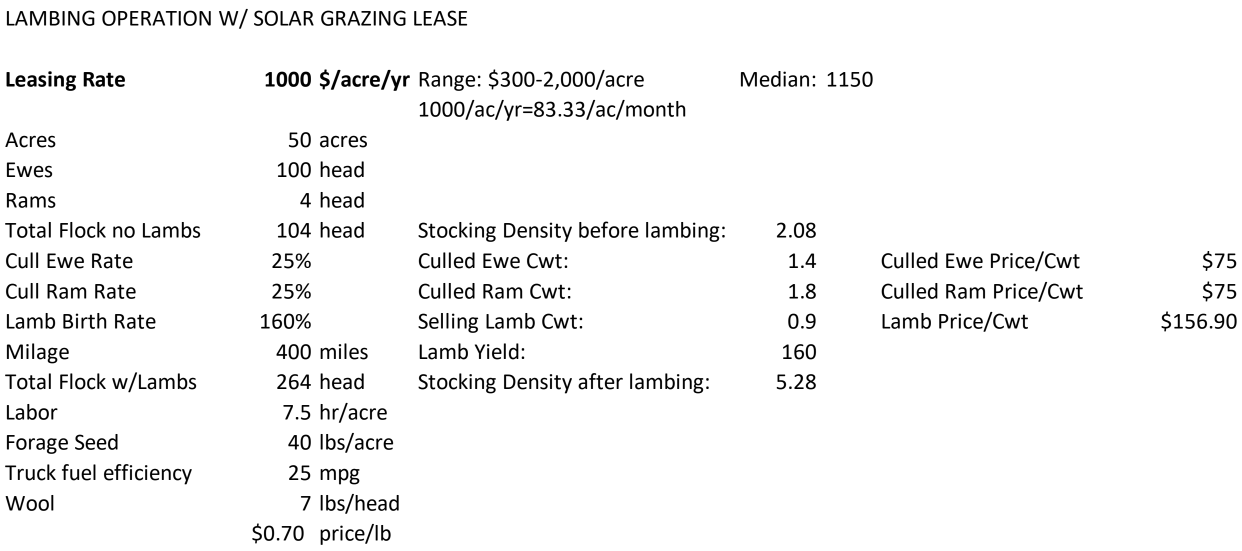
Comparison

After budgets were generated, earnings before taxes (EBT) including operating revenue from solar leasing and ovine sales (if any) less operating expenses of seed, feed, fertilizer, labor, chemicals, repair and maintenance, veterinary charges, along with fixed expenses of annual depreciation and insurance for capital investment in machinery and breeding stock were calculated for each forage maintenance scenario (solar grazing, conventional mowing, and robotic mowing). The expected labor intensity, capital intensity, and management intensity were compared alongside possible profitability and are described in the results section. For all three scenarios, income for the landowner was assumed at a solar leasing rate of $1,000 per acre, close to the median of the typical range for solar land lease rates.

Results

The sheep grazing budget was generated in a Microsoft Excel^{TM} workbook and is available via this link: https://1drv.ms/x/s!AiWtnFp8kFo1pEKcClNTSh_H1txt?e=2EOiyR. The sheets used specifically for this analysis are shown below in Figures 2 to 6.

The solar grazing budget is represented in Figures 2 to 4. It is evident that impactful measures of financial feasibility for a landowner rely heavily on the value of the solar contract's leasing rate, acreage, flock size, and capital investment. A landowner's EBT using the assumptions made was shown to be $40,106 (Figure 3A) and far exceeds the returns from grazing sheep alone – removing the solar lease income would result in an economic loss of -$8,894 that is mitigated by paid labor (which may go toward the owner but was included as an expense here since other scenarios demanded significantly less time committment). Nonetheless, the analysis indicates that grazing at this scale with the same assets may not be economically sustainable without solar lease revenue.



LAMBING OPERATION W/ SOLAR GRAZING LEASE

Leasing Rate	**1000**	**$/acre/yr**	Range: $300-2,000/acre	Median:	1150	
			1000/ac/yr=83.33/ac/month			
Acres	50	acres				
Ewes	100	head				
Rams	4	head				
Total Flock no Lambs	104	head	Stocking Density before lambing:	2.08		
Cull Ewe Rate	25%		Culled Ewe Cwt:	1.4	Culled Ewe Price/Cwt	$75
Cull Ram Rate	25%		Culled Ram Cwt:	1.8	Culled Ram Price/Cwt	$75
Lamb Birth Rate	160%		Selling Lamb Cwt:	0.9	Lamb Price/Cwt	$156.90
Milage	400	miles	Lamb Yield:	160		
Total Flock w/Lambs	264	head	Stocking Density after lambing:	5.28		
Labor	7.5	hr/acre				
Forage Seed	40	lbs/acre				
Truck fuel efficiency	25	mpg				
Wool	7	lbs/head				
	$0.70	price/lb				

Figure 2*: Lambing operation inputs, solar leasing rate and ovine yield and sale price assumptions. All inputs above are editable.*

SHEEP GRAZING BUDGET

INCOME	Qty	Price/Qty	Total Price
Solar Contract	50 acres	$ 1,000.00	$ 50,000
Lambs	144 cwt	$ 156.90	$ 22,594
Culled Ewes	35 cwt	$ 75.00	$ 2,625
Culled Rams	1.8 cwt	$ 75.00	$ 135
Wool	728 lbs	$ 0.70	$ 510
TOTAL			**$ 75,863**

EXPENSES	Qty	Cost/Qty	Total Cost
Replacement Ewes	25 head	$ 196.00	$ 4,900
Replacement Rams	1 head	$ 350.00	$ 350
Hay/Feed Adult	104 head	$ 9.00	$ 936
Protein/Vitamins Adult	104 head	$ 3.00	$ 312
Hay/Feed Lamb	160 head	$ 4.00	$ 640
Protein/Vitamins Lamb	160 head	$ 3.00	$ 480
Shearing	104 head	$ 5.00	$ 520
Veterinary	264 head	$ 1.60	$ 422
Vaccinations	264 head	$ 5.00	$ 1,320
Labor	375 hours	$ 15.00	$ 5,625
Pasture Maintenance	50 acres	$ 8.00	$ 400
Pasture Seed & Planting	2,000 lbs	$ 6.64	$ 2,213
Mowing	50 acres	$ 50.00	$ 2,500
Supplies	264 head	$ 7.00	$ 1,848
Fuel	16 gal	$ 3.50	$ 56
Lamb Check Off	18,080 lbs	$ 0.01	$ 127
Property Tax (.75%) & Insurance (.55%)	1.30% purchase price of all assets	$ 116,750.00 *	$ 1,518
Professional Solar Insurance	1 policy	$ 1,000.00	$ 1,000
Repair and Maintenance	1 deprec. assets (Fig. 4)	$ 1,311.25 *	$ 1,311
Depreciation	1 deprec. assets (Fig. 4)	$ 11,492.04 *	$ 9,279
TOTAL			**$ 35,757**
Earnings before income taxes (EBT)			**$ 40,106**

Figure 3*: Solar grazing budget on 50 acres with 100 lambing Ewes. Cells marked with an * (Mowing, Insurance, and Depreciation) are customizable by modifying information in Figure 4.*

SHEEP ASSETS

	Qty		Price/Qty	Total Price	
Ewes	100	hd	$ 250	$ 25,000	
Rams	4	hd	$ 500	$ 2,000	
Shed	1	barn	$ 50,000	$ 50,000	
Truck	1	truck	$ 20,000	$ 20,000	Used
Utility Trailer	1	trailer	$ 10,000	$ 10,000	Used
Fencing	50	thousand ft	$ 45	$ 2,250	$.045/ft
Vegetation Equipment	1	mower	$ 2,500	$ 2,500	
Water System	1	system	$ 5,000	$ 5,000	
TOTAL				**$ 116,750**	

DEPRECIABLE ASSETS

Asset	Purchase Price	Useful Life	Salvage Value	Repair Factor	Annual Depreciation	Annual Repairs
Shed	$ 50,000	20	$ 2,500	0.2	$ 3,595	$ 500
Truck	$ 20,000	5	$ 5,000	0.15	$ 3,569	$ 600
Utility Trailer	$ 10,000	10	$ 2,000	0.1	$ 1,066	$ 100
Fencing	$ 2,250	20	$ -	0.1	$ 166	$ 11
Vegetation Equipment	$ 2,500	10	$ 500	0.2	$ 267	$ 50
Pasture Establishment	$ 13,280	7	$ -	0	$ 2,213	$ -
Water System	$ 5,000	10	$ -	0.1	$ 616	$ 50
TOTAL	**$ 103,030**				**$ 11,492**	**$ 1,311**

Figure 4*: Assets for solar grazing. All values are customizable. Annual depreciation uses a capital cost recovery rate of 4% and includes opportunity cost of capital employed.*

Conventional mowing expenses are represented in Figures 5 and 6. These were both based on 50-acre plots to be comparable to the sheep budget, however this is changeable in the digital spreadsheet. The matrix in Figure 5 represents data from the Sandia National Lab (Enbar, Weng, and Klise, 2016). The budget in Figure 6A shows median EBT to the landowner with a solar lease of $41,333.

While a wide range of conventional mowing costs is expected, the median value of $7,667 was most consistent with other cost estimates (Enbar, Weng, and Klise, 2016; Kochendoerfer, Hain, and Thonney, 2019; Soldat et al., 2020).

CONVENTIONAL MOWING MATRIX			
Vegetation Management		$.50-$1.80	/kW/yr
Acres		50 acres	
	Low	Med	High
kW/acre	100	133.33	200
Cost	$0.50	$1.15	$1.80

Cost to kW	Cost/Acre	Total Cost
Low Cost-Low kW	$ 50.00	$ 2,500
Low Cost- Med kW	$ 66.67	$ 3,333
Low Cost- High kW	$ 100.00	$ 5,000
Med Cost- Low kW	$ 115.00	$ 5,750
Med Cost- Med kW	**$ 153.33**	**$ 7,667**
Med Cost- High kW	$ 230.00	$ 11,500
High Cost- Low kW	$ 180.00	$ 9,000
High Cost- Med kW	$ 240.00	$ 12,000
High Cost- High kW	$ 360.00	$ 18,000

Figure 5*: System size (kW/acre) and conventional mowing cost ($/kW) options on a 50-acre parcel of land. Median is bolded.*

CUSTOM MOWING BUDGET

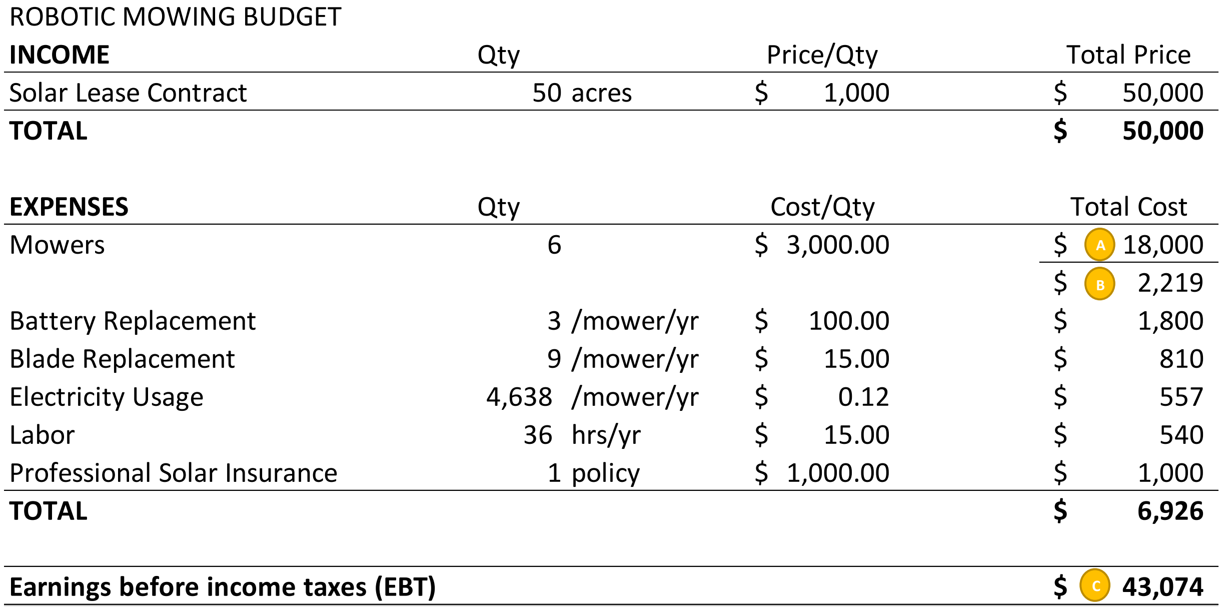
INCOME	Qty	Price/ Qty	Total Price
Solar Lease	50 acres	$ 1,000	$ 50,000
TOTAL			$ 50,000

EXPENSES	Qty	Cost/Qty	Total Cost
Custom Mowing	50 acres	$ 153.33	$ 7,667
Professional Solar Insurance	1 policy	$ 1,000.00	$ 1,000
TOTAL			$ 8,667
Earnings before income taxes (EBT)			$ 41,333

Figure 6*: Expected earnings before taxes to landowner with a solar leases and owner custom mowing charges at median value.*

The robotic mowing budget as shown in Figure 7, details maintenance and ownership charges associated with this method of forage management and includes high up-front investment cost in mowing equipment of $18,000 (A) which is calculated to have a yearly cost of $2,219 (B) assuming a 10 year useful life, 4% capital cost recovery and zero salvage value.

Despite higher ownership charges in comparison to conventional custom mowing, earnings before taxes are highest for this option (Figure 7C) in comparison to sheep grazing (Figure 3A) and custom mowing (Figure 6A) as summarized in Table 1.



ROBOTIC MOWING BUDGET

INCOME	Qty	Price/Qty	Total Price
Solar Lease Contract	50 acres	$ 1,000	$ 50,000
TOTAL			**$ 50,000**
EXPENSES	Qty	Cost/Qty	Total Cost
Mowers	6	$ 3,000.00	$ Ⓐ 18,000
			$ Ⓑ 2,219
Battery Replacement	3 /mower/yr	$ 100.00	$ 1,800
Blade Replacement	9 /mower/yr	$ 15.00	$ 810
Electricity Usage	4,638 /mower/yr	$ 0.12	$ 557
Labor	36 hrs/yr	$ 15.00	$ 540
Professional Solar Insurance	1 policy	$ 1,000.00	$ 1,000
TOTAL			**$ 6,926**
Earnings before income taxes (EBT)			**$ Ⓒ 43,074**

***Figure 7**: Expected earnings before taxes for a landowner using autonomous, robot mowing equipment at median solar lease value.*

	Decision Factors				
Landowner Choice	Labor Intensity	Capital Intensity	Management Intensity	Agricultural Output	Profitability (EBT)
Sheep Grazing only	High	High	High	Meat & Wool	-$8,894
Sheep Grazing (L)	High	High	High	Meat & Wool	$40,106
Custom Mowing (L)	None	None	Low	none	$41,333
Robot Mowing (L)	Low	Medium	Low	none	$43,074

***Table 1**: Labor, capital, and management intensity comparison of forage management options with attendant agricultural output and earnings before tax implications on 50 acres of land with a solar lease (L).*

Conclusions and Discussion

The goal of this study was to compare methods for PV system forage maintenance by providing enterprise budget information for a landowner interested in grazing sheep while at the same time leasing the grazing land to a PV system owner. Three different forage management scenarios (solar grazing, custom conventional mowing and ownership of robotic mowing equipment) were analyzed. The analysis did not intend to provide exact values for planning an agri-photovoltaic operation, but rather to encourage the reader to be informed about salient features (labor, capital, and management intensity differences) across these forage management scenarios and their attendant expected profitability estimates. The results of this study showed that solar revenue can make sheep grazing sustainable for landowners at a small scale on 50 acres. Forgoing agricultural production, however, led to greater economic returns with both robotic mowing and hiring out forage management with custom mowing. Utilizing robotic mowers, which are more environmentally friendly than conventional mowing, required some capital investment and repair and maintenance activities (battery and blade replacement as well as system setup) yet yielded a greater return to the landowner in comparison to custom hired mowing.

A goal of this study was to make the Microsoft Excel^{TM} Spreadsheet available to allow for customization of different values. For the sake of clarity, certain values or ranges were assumed at either general averages or specific values. As such, this study is considered a starting point for analysis for landowners interested in leasing their land for PV system installation.

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