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Renewable Energy in Sustainable Agricultural Production: Real Options Approach to Solar Irrigation Investment under Uncertainty

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ABSTRACT

Solar-powered irrigation system (SPIS) is a sustainable technology that utilizes renewable energy to pump water for agricultural production. Despite its environmental benefits, its adaptation is challenged by its high investment cost, particularly for small-scale farmers in most developing countries. This study aims to evaluate the attractiveness of shifting to SPIS from diesel-powered irrigation using the case of small-scale farmers in the Philippines. Considering the cost savings from adopting SPIS, this study analyzes the economic viability and optimal timing of investment under diesel price uncertainty. Results found that SPIS is economically attractive with USD 556.26/ha annual cost savings, USD 229.68/ha net present value, 12.49% internal rate of return, and a 5.58-year payback period. Considering the uncertainty in diesel prices, it is more optimal to invest immediately as waiting incurs losses. Investment decisions for SPIS are further favored by decreasing technology costs for solar PV systems, multiple utilization, cost-sharing among farmers, and negative externality of diesel. Findings provide recommendations for the widespread adoption of SPIS for more environment-friendly and sustainable production in agricultural countries.

Index-words: *Optimal Timing, Real Options, Renewable Energy, Small-scale Farmers, SPIS, Sustainable Agriculture.*

Nomenclature:

Abbreviations	
APS	**Announced pledges scenario**
BAU	**Business-as-usual**
CBA	**Cost-benefit analysis**
GBM	**Geometric Brownian motion**
GHG	Greenhouse gas
IRR	Internal rate of return
NEDA	**National Economic Development Authority**
NPV	Net present value
NZS	Net-zero emission scenario
PBP	Payback period
PV	Photovoltaics
ROA	Real options approach
SPIS	Solar-powered irrigation system
STEPS	Stated policies scenario

Symbols	
C_d	Average annual operations and maintenance costs for diesel
C_{SPIS}	Average annual operations and maintenance costs for SPIS
ε_t	Error term at period t
E_d	Negative externality of diesel combustion
I_{SPIS}	Investment cost for SPIS
J	Monte Carlo simulations
$P_{d,t}$	Price of diesel at period t
Q_d	Average annual diesel consumption
r	Discount rate
ρ	Discount factor
S_t	Average annual cost savings
T_{SPIS}	Valuation period for SPIS
τ	Decision period of shifting to SPIS
μ_d	Percentage drift of diesel prices
σ_d^2	Percentage volatility of diesel prices
V_t	Option value at period t
$V_{waiting}$	Value of postponing the investment
W_t	Wiener process

I. INTRODUCTION

The agriculture sector is both a vital contributor to global food security and a significant source of greenhouse gas (GHG) emissions from pre- and post-production activities, land use change, and farm-gate emissions [1, 2]. Currently, the agriculture sector accounts for 30 percent of total global anthropogenic emissions equivalent to 53 Gt CO_2eq [1]. Addressing the challenges of climate change urges the need to mitigate these emissions while ensuring sustainable food production to meet the needs of a growing population. Among the innovative solutions are crop and microbial genetics, electrification, and climate-smart agriculture including carbon-smart, energy-smart, weather-smart, nutrient-smart, and knowledge-smart technologies and practices [3, 4].

Another promising technology is the solar-powered irrigation system (SPIS), which can significantly reduce the GHG emissions associated with conventional diesel or electric pumps [5, 6]. SPIS utilizes solar photovoltaics (PV) to convert sunlight into electricity that powers the water pumping system to provide access to water in areas with no or limited connectivity to electricity networks or irrigation systems [7, 8]. Compared with fuel-powered generators, SPIS provides several benefits including operation safety, durability, lower operating costs, and a smaller carbon footprint [7]. While numerous countries have widely adopted SPIS, the success of this technology depends on various elements like climatic conditions, crop type, groundwater availability, government support, and the cost and availability of conventional electricity [9]. Moreover, its higher upfront cost relative to other pumps, lack of credit facilities, and technical capacity limit its widespread utilization particularly to small-scale farmers in most developing countries [5, 10]. These serve as an impetus to study the viability of SPIS as climate mitigation technology in the agriculture sector from the perspective of small-scale farmers.

Several studies analyze the viability of SPIS using various economic tools. Haffaf et al. [11] applied HOMER to design a cost-effective and sustainable solution to provide a water irrigation system based on the technical, economic, and environmental criteria. In another study, Falchetta et al. [12] devised a spatially explicit integrated modeling framework to show that over one-third of unmet crop water requirements of 19 major crops in smallholder cropland could be supplied with standalone SPIS that can be paid back by farmers within 20 years. Studies [5, 8] combined the socio-economic and environmental aspects of introducing SPIS to small-scale farmers in developing countries and found that SPIS is socially acceptable to farmers, reduces the cost of using diesel generators, is economically viable, reduces GHG emissions, and avoids air pollution. Moreover, Raza et al. [13] evaluated the socio-economic and climatic impact of PV-operated high-efficiency irrigation systems in a rural community and found that the installation of PV systems has resulted in the increased adoption of high-efficiency irrigation systems, a reduction in the high-operational costs incurred on account of old diesel-powered pumping systems, an increase in farmer's income, a reduction of GHG emissions, and savings in water.

However, these studies do not account for the uncertainties that affect investment decisions. For instance, the volatility of fossil fuel prices, CO_2 prices, technology learning, supporting policies, and social acceptance affect decisions to invest in renewable energy technologies [14-18]. On the other hand, the real options approach (ROA) overcomes these limitations by combining risks and uncertainties with management flexibility in making irreversible investments [18]. To date, there are only limited studies applying ROA to sustainable agricultural production. For instance, Jalić et al. [19] proposed a sustainable economic model for milk production using cost-benefit analysis as well as the Black–Scholes and binomial models ROA for shifting to cheese production [19]. In another study, Rocha et al. [20] analyzed whether investment projects in photovoltaic (PV) panels to produce electrical energy in a forest nursery are economically viable through binomial decision tree ROA with various managerial flexibilities such as deferral, expansion of the energy production capacity, and the abandonment of the project. Moreover, Heumesser et al. [21] applied a stochastic dynamic programming ROA to analyze a farmer's optimal investment strategy to adopt a water-efficient drip irrigation system or a sprinkler irrigation system under uncertainty about future production conditions. The ROA has not yet been applied to investment in SPIS, particularly to developing countries where small-scale farmers struggle to finance the technology due to its high investment cost. Yet, its huge potential in terms of cost savings from the volatile diesel prices has not been accounted for in previous studies.

This study bridges this gap by applying ROA to

SPIS investment under diesel price uncertainty. Specifically, this aims to analyze the viability of shifting irrigation technology from diesel to solar using cost savings, NPV, IRR, and PBP; identify the optimal timing of investment in SPIS under diesel price uncertainty, and evaluate how solar PV costs, multiple utilization of SPIS, cost-sharing among small-scale farmers, and negative externality of diesel combustion impact the investment decisions to SPIS. This finally aims to suggest policy recommendations to support the adoption of SPIS for more inclusive, environment-friendly, and sustainable production in agricultural countries.

II. METHODOLOGY

A. Research Framework

This research applies layers of analyses to evaluate the attractiveness of shifting irrigation technology from diesel to solar PV. This includes cost-benefit analysis, real options valuation, and scenario analysis as shown in Figure 1. First, the CBA is applied to evaluate the potential costs and benefits of SPIS compared to diesel-powered irrigation systems. CBA is the systematic and analytical process of comparing benefits and costs in evaluating the desirability of a project and answering the questions as to whether a proposed project is worthwhile to undertake [22]. Among the different CBA tools, this study utilizes the net present value (NPV), internal rate of return (IRR), and payback period (PBP). These tools aim to provide an informed decision on the viability of SPIS, making sure that the expected benefits of the project outweigh the costs, as well as an overview of how long it takes to recover the cost of SPIS technology.

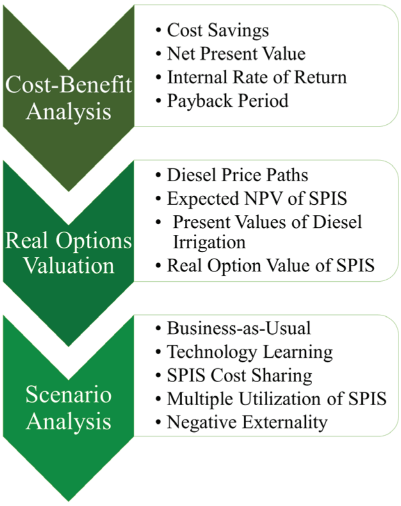

Fig. 1. Flowchart of the economic analysis of SPIS

The second layer of analysis supplements the CBA by incorporating flexibility in making investment decisions considering the uncertainties in SPIS technology. The real options approach (ROA), real options analysis, or real options valuation provides a competitive advantage over traditional valuation methods by capitalizing on the uncertainties and opportunities in the market, making more informed and flexible investment decisions [18]. This study applies ROA to analyze the value of flexibility to postpone the investment in SPIS over continue using a diesel-powered irrigation system. Considering the uncertainty in diesel prices, future price paths are first estimated. These prices are then incorporated in the NPV in CBA to calculate the expected NPV of SPIS for various initial prices of diesel. Then, the expected NPV of using SPIS is compared with the value of continuing diesel for irrigation to get the real option value of SPIS.

To test the robustness of the investment decisions for SPIS, several scenarios are analyzed including the business-as-usual (BAU), technology learning, SPIS cost sharing, multiple utilization of SPIS, and negative externality of diesel combustion. The BAU scenario refers to the analysis in the second layer, the real options valuation based on the historical prices of diesel, current technology cost, sole farmer utilization of SPIS, and cost savings without externalities. The technology learning scenario analyzes the investment decisions considering changes in the cost of SPIS based on climate policies. Cost sharing refers to the number of small-scale farmers sharing the costs and utilization of SPIS, while multiple utilization considers the possibility of utilizing SPIS for other purposes such as a source of electricity for home use. Finally, the negative externality scenario integrates the value of reduced GHG emissions as well as the savings from the health costs associated with the combustion of diesel fuel.

B. Real Options Valuation

This study takes the perspective of a small-scale farmer who has to decide whether to continue using diesel-powered pumps for irrigation, invest in SPIS now, or invest later. Using the fuel cost savings, shifting to SPIS now generates a net present value (NPV) as shown in Equation 1

$$\mathrm{NPV} = \sum_{t=1}^{T_{SPIS}} \rho^{t} \left(S_{t} - C_{SPIS} \right) - I_{SPIS} \qquad (1)$$

where ρ is the discount factor equal to $\frac{1}{1+r}$, r is the discount rate, t is the valuation period, T_{SPIS} is the lifetime of SPIS, $S_t = P_{d,t}Q_d + C_d + E_d$ is the cost savings from shifting to SPIS from diesel equal to fuel price $P_{d,t}$ and quantity Q_d , the annual operations and maintenance cost C_d of using diesel-powered irrigation, and E_d is the negative externality of using diesel fuel such as the cost of GHG emissions and health costs of air pollutants from diesel combustion. On the other hand, C_{SPIS} is the annual operations and maintenance cost of SPIS and I_{SPIS} is the investment cost for SPIS. Using the NPV rule, the farmer's strategy is characterized by the decision to invest in SPIS now when NPV is positive, otherwise, continue using the diesel irrigation system as shown in Equation 2. Note that when diesel prices are low, it is more costly to invest in SPIS due to its high investment cost, hence, NPV<0.

$$\begin{aligned} &NPV \geq 0 \quad \text{invest} \\ &NPV < 0 \quad \text{postpone} \end{aligned} \tag{2}$$

Another economic tool is the Internal Rate of Return (IRR), which is the maximum interest rate or discount rate at which the project benefits equal to the investment [23]. From Equation 1, the IRR for SPIS can be calculated using Equation 3, where $= \frac{1}{1+IRR}$.

$$NPV = \sum_{t=1}^{T_{SPIS}} \rho^t \left(S_t - C_t\right) - I_{SPIS} = 0 \tag{3}$$

Moreover, the payback period (PBP) is the amount of time needed to recover the cost of the initial investment in SPIS [8]. The PBP can be calculated using Equation 4.

$$PBP = \frac{I_{SPIS}}{S_t - C_t} \tag{4}$$

Considering the uncertainty in diesel fuel prices, another option for the farmer is to defer or postpone the investment in SPIS. In line with previous studies, we assume that diesel prices are stochastic and follow a Geometric Brownian Motion (GBM) [14, 16, 24]. GBM is a continuous-time stochastic process in which the logarithm of the randomly changing quantity results in a Brownian motion with drift [25]. For diesel prices, GBM can be represented in Equation 5.

$$dP_{d,t} = \mu_d P_{d,t} dt + \sigma_d P_{d,t} dW_t \tag{5}$$

where μ_d and σ_d^2 are percentage drift and percentage volatility of diesel prices and W_t is a Wiener process or Brownian motion equal to $\varepsilon\sqrt{dt}$ such that $\varepsilon \sim N(0,1)$. Using Ito's formula, this can be solved to estimate the future prices of diesel as shown in Equation 6.

$$P_{d,t+1} = P_{d,t} \exp\left[\left(\mu_d - \frac{\sigma_d^2}{2}\right)\Delta t + \sigma_d \sqrt{\Delta t}\,\varepsilon_t\right] \tag{6}$$

From Equation 6, price paths for diesel can be generated from the current price and incorporated in Equation 1 to calculate the NPV. Using Monte Carlo simulations, the expected net present value, $\mathbb{E}\{NPV\}$, for adopting SPIS can be estimated using Equation 7. This process repeats the NPV calculations in (J) multiple times under stochastic prices of diesel then, calculating the average NPV from all the iterations.

$$\mathbb{E}\left\{NPV_j | P_{d,0}\right\} = \frac{1}{J}\sum_{j=1}^{J} NPV_j \approx \mathbb{E}\left\{NPV | P_{d,0}\right\} \tag{7}$$

The farmer's problem is to maximize the value of adopting SPIS or continuing diesel irrigation system as described in Equation 8.

$$V_t = \max\left\{\mathbb{E}\{NPV\},\ \mathbb{E}\left\{\sum\nolimits_{0\leq t\leq\tau} \rho^t\left(-S_t\right)\right\} | P_{d,t}\right\} \tag{8}$$

where V_t is the option value, which is the maximized value of either investing in SPIS with $\mathbb{E}\{NPV\}$ or continuing diesel irrigation with a cost of $\mathbb{E}\left\{\sum\nolimits_{0\leq t\leq\tau} \rho^t(-S_t)\right\}$ from time $t=0$ to optimal timing of investment $t=\tau$. Note that while $\mathbb{E}\left\{\sum\nolimits_{0\leq t\leq\tau} \rho^t(-S_t)\right\}$ is negative, there are initial prices of diesel $P_{d,0}$ where it is still more optimal to use diesel irrigation due to the high investment cost of SPIS (I_{SPIS}). Hence, the optimal timing of investment is characterized by the minimum period where shifting to SPIS is maximized as shown in Equation 9.

$$\tau^* = \min\left\{\tau | V_{t+1} = V_t\right\} \tag{9}$$

Finally, the optimal investment strategy using ROA is characterized by a decision to invest immediately in SPIS and postpone or delay the investment as shown in Equation 10.

$$\begin{cases} V_{\tau^*}\left(P_{d,t}\right) \leq V_0\left(P_{d,0}\right) & \text{invest} \\ V_{\tau^*}\left(P_{d,t}\right) > V_0\left(P_{d,0}\right) & \text{postpone} \end{cases} \tag{10}$$

C. Data and Scenarios

This study applies the proposed ROA model for shifting irrigation technology from diesel to SPIS using the case of small farmers from the Philippines. Among the reasons for choosing the case of the Philippines are (a) it is an agricultural country with 24.5% of the economy based on agriculture, hunting, forestry, and fishing [26]; (b) irrigated agricultural land covers 61.39% of the total irrigable area provided by the National Irrigation System (44.97%), communal irrigation system (35.27%), private irrigation system (10.30%), and other national government agencies (9.4%) [27]; (c) the remaining non-irrigated land is mostly owned by small-scale farmers and is rain-fed, which are vulnerable to climate hazards [5]; and (d) diesel prices are highly volatile as the country is too dependent on imported fossil fuels, yet has a huge potential for renewable energy generation [28].

The data from this study were gathered from both primary and secondary sources. Diesel consumption was surveyed from small-scale farmers who were using diesel irrigation systems. The current price of diesel was taken from the Department of Energy, historical prices of diesel were gathered from the Energy Information Agency, investment parameters were taken from the National Economic Development Authority (NEDA), and the technology parameters were taken from the literature. The summary of data used in this study is presented in Table I.

TABLE I
LIST OF VARIABLES AND ESTIMATED PARAMETERS FOR THE PROJECT VALUATION

Parameter	Symbol	Unit	Value
Initial price of diesel	$P_{d,0}$	USD/L	1.09
Average annual diesel consumption	Q_d	L/ha/yr	74.55
Average annual operations and maintenance costs for diesel	C_d	USD/ha/yr	475
Externality cost of using diesel	E_d	USD/ha/yr	231
Average annual cost savings	S_t	USD/ha/yr	556
Average annual operations and maintenance costs for SPIS	C_{SPIS}	USD/ha/yr	140
Investment cost for SPIS	I_{SPIS}	USD	2100
Percentage drift of diesel prices	μ_d	%	0.0386
Percentage volatility of diesel prices	σ_d^2	%	0.0296
Valuation period for SPIS	T_{SPIS}	years	10
Discount rate	r	%	10
Decision period for SPIS	τ	years	10
Monte Carlo simulations	J	times	10,000

The investment cost for SPIS is USD 2100, which covers the costs of the pump and controller, solar PV panel, accessories, grounding, PV cables, and the cost of mounting such as materials (pipe, concrete, accessories) and labor costs (excavation of foundation, concreting, steal works) [5]. The SPIS technology can be utilized to irrigate 2-3 hectares of rice farms with 9 m^3/hr water output [5]. The average annual operations and maintenance cost for SPIS is USD 140. The benefits of shifting to SPIS include the energy cost savings and externality costs of using diesel. The average annual operation and maintenance for using diesel is USD 475. The average annual diesel consumption of the selected small-scale farmers is 74.55 L. Based on this value, the calculated annual cost savings for shifting to SPIS without externalities is USD 556. On the other hand, the costs of negative externalities are calculated based on the emission factors of GHG, carbon monoxide, nitrous oxides, sulfur oxides, particulate matter, and volatile organic compounds for diesel combustion [29] and the health costs of these emissions [30, 31]. The calculated annual cost of negative externalities is USD 213, which is added to the annual cost savings of shifting to SPIS with a total of USD 787.26. The NPV calculation covers a

10-year valuation period at a 10% discount rate.

To calculate the stochastic prices of diesel, 10-year historical data were used to run the Augmented Dickey-Fuller unit root test for the stochastic process. The test result confirmed that $P_{d,t}$ follow GBM with $\mu_d = 0.0386$ and $\sigma_d = 0.0296$. These parameters are then used to generate stochastic prices of diesel, as described in Equation 6. A sample simulation of price paths is shown in Figure 2.

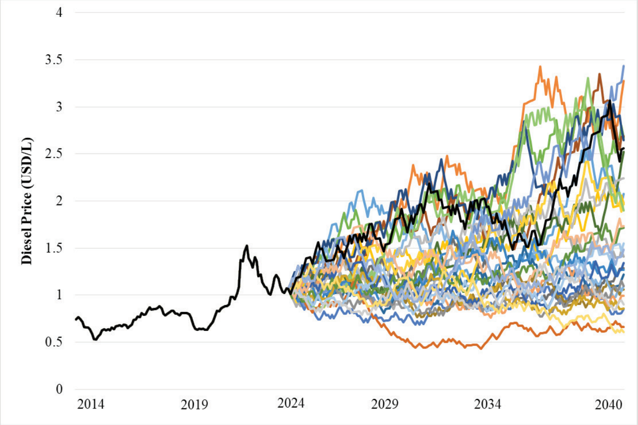

Fig. 2. Historical Diesel Prices (2014–2024) and Diesel Price Paths (2024–2040) based on Geometric Brownian Motion. (Note: curves from 2024 onwards are authors' simulations)

Given these price paths, the real options value is calculated annually by maximizing the value of either continuing the use of diesel-powered irrigation or shifting to SPIS from the initial price of diesel at $P_{d,0} = 0$ to USD 1.5/L. Then, the optimization process is repeated until the decision period $t = \tau$, which is set at 10 years. This is the period given to the investor whether to reject the project, invest immediately, or postpone the implementation of the project until its expiration date in the 10th year. The optimization results were tested for the impacts of decreasing solar PV systems (10%, 20%, and 30%), multiple utilization (additional 10%, 20%, and 30% benefits), and cost-sharing among farmers (5%, 10%, 20% reduction). Lastly, the GHG emissions and health costs of using diesel are incorporated in Equation 1 as the negative externalities of using diesel fuel.

III. RESULTS AND DISCUSSION

A. Cost Benefit Analysis of SPIS

The result of the cost-benefit analysis of shifting to SPIS from diesel-powered irrigation is presented in Table II. Based on the survey of small-scale farmers who own till 1 hectare or less rice farms, the average annual cost savings from diesel fuel and other operations and maintenance costs of using diesel-powered irrigation systems is USD 556.26 per hectare. This amount can be used to offset the high investment cost of SPIS or invest in other technologies or systems that promote sustainable farming [5]. Considering the valuation period of 10 years at a 10% discount rate, the NPV of shifting to SPIS is USD 229.68 per hectare. This implies that SPIS is economically viable and can generate USD 229.68/ha additional value by shifting to SPIS.

TABLE II
RESULT OF COST BENEFIT ANALYSIS OF SHIFTING TO SPIS FROM DIESEL IRRIGATION

Economic Indicators	Unit	Value
Annual cost savings	USD/ha/yr	556.26
Net present value	USD/ha	229.68
Internal rate of return	%	12.49
Payback period	Years	5.58

In terms of economic efficiency, the project has an IRR of 12.49%, which implies that the project generates 12.49% returns relative to the initial investment. This value also indicates that the project is feasible as it is greater than the hurdle rate set by the NEDA at 10%. Moreover, PBP shows that the investment in SPIS can be recovered in 5.58 years. While this seems long from the perspective of small-scale farmers, it should be noted that PBP is based on the cost savings from shifting to SPIS and that solar PV is exclusively utilized for irrigation purposes only. Since the technology is mobile and the system is only utilized mostly during the early stage of rice production during non-rainy season, solar PV panels can also be utilized for other purposes such as generating electricity for household use. These results support previous claims that small SPIS are profitable with 20% IRR for investment while large SPIS are moderately profitable at 10% IRR but can be improved by introducing additional uses of solar energy [32]. Meanwhile, it should be noted that these results are solely based on the cost savings from using diesel fuel. This study also considers the negative externalities of using diesel, which will be discussed in the last subsection.

B. Real Options Valuation

Considering the uncertainties in diesel prices, this study extends the cost-benefit analysis by applying real options valuation or ROA. The results of the valuation in the BAU scenario are summarized in Table III and presented in Figure 3.

From the figure, the blue curve represents the calculated option values at t=0 for every initial diesel price from zero to USD 1.5 per liter. Each point on the curve represents the maximized value of either shifting to SPIS or continuing the diesel-powered irrigation. It can be noticed that there are negative values on the curve showing that, at these diesel prices, cost savings can still not offset the high investment cost of SPIS. Meanwhile, option values are positive at initial diesel prices above USD 0.6058/L. This means that the optimal (minimum) price of diesel to make the investment in SPIS feasible is USD 0.6068/L. Hence, at USD 1.09/L current price of diesel, the option value is positive and investment in SPIS is feasible, which also supports the claim in the cost-benefit analysis in the previous section.

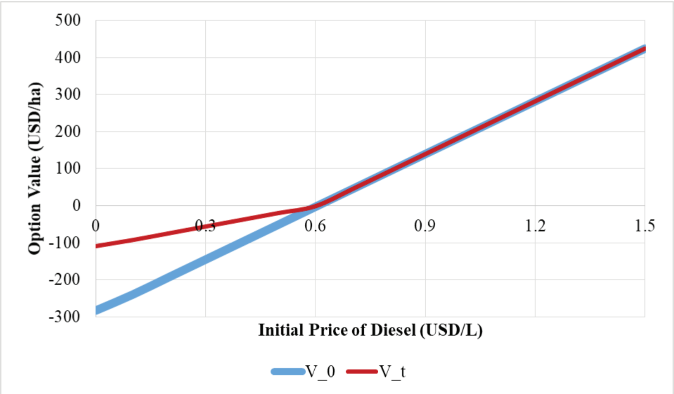

Fig. 3. Option values of shifting to SPIS in the Business-as-usual scenario

TABLE III
OPTION VALUES AT INITIAL AND TERMINAL DECISION PERIODS AND THE VALUE OF WAITING AT DIFFERENT PRICES OF DIESEL (IN USD/HA)

P_d,0	V_0	V_t	V_waiting
0	-283	-109	174
0.1	-240	-92.5	147
0.2	-192	-74.2	118
0.3	-145	-55.9	89.1
0.4	-97.6	-37.6	60
0.5	-50.2	-19.3	30.8
0.6	-2.75	-1.06	1.69
0.7	44.7	44.7	0
0.8	92.1	92.1	0
0.9	140	140	0
1	187	187	0

Note: P_d – initial price of diesel, V_0 – option value at the initial period, V_t – option value at the terminal period, V_ waiting – value of waiting

On the other hand, the red curve represents the calculated option values at the terminal decision-making period (10 years) for every initial diesel price. Meanwhile, the distance between the curves represents the value of waiting to invest in SPIS. For instance, at a diesel price of USD 0.3/L, the option value in the initial period is USD -145/ha and USD -56/ha in the terminal period. This means that, at this diesel price, the value of waiting to invest is USD 89/L. It is also shown in Table 3 that the values of waiting are positive from initial diesel prices of 0 to USD 0.6/L. This explains the motivation of farmers to postpone the investment in SPIS as running irrigation using diesel is relatively cheaper than shifting to SPIS, and the cost savings cannot offset the high investment cost of SPIS. However, at the current diesel price of USD 1.09/L, the value of the option to wait is equal to zero, which implies a more optimal decision to invest immediately as postponing the investment incurs no additional value to the project. These managerial flexibilities in the decision-making process highlight the advantage of using ROA over the "now-or-never" decision rule using traditional economic valuation tools such as the NPV and IRR [16, 18].

C. *Technology Learning Scenarios*

To test the robustness of the results, this study presents three investment cases including technology learning, cost-sharing, multiple utilization of SPIS, and negative externalities of diesel.

In technology learning, four scenarios are considered: business-as-usual (BAU), stated policies scenario (STEPS), announced pledges scenario (APS), and the net-zero emission scenario (NZS). In STEPS, the global solar capacity of 220 GW is expected to double by 2030; the planned boost in the manufacturing capacity if fully realized, appears able to meet many of the deployment milestones in the APS; and further milestones in the case of solar and batteries provide what is required in the net-zero emissions by 2050 in NZS [33]. Following Wright's Law, technologies get cheaper at a consistent rate as the cumulative production of that technology increases. In the case of solar PV, the average learning rate is 20.2%. As a classic case of learning by doing, the price of technology declines when more of that technology is produced, increasing production gives the engineers the chance to learn how to improve the process, and more deployed technology satisfies the increasing demand leading to falling prices, and the technology becomes cost-effective [34]. Considering the different climate target scenarios, this study assumes that the learning rate within ten years of waiting to invest is 20%, 30%, and 40% for the STEPS, APS, and NZS scenarios. The results of real options valuation for shifting to SPIS at different technology learning are presented in Table IV and Figure 4.

TABLE IV
OPTION VALUES AT THE INITIAL AND TERMINAL PERIODS FOR DIFFERENT CLIMATE SCENARIOS

P_d,0	V_0	V_BAU	V_STEPS	V_APS	V_NZS
0	-283	-109	53	134	215
0.1	-240	-92	69	150	231
0.2	-192	-74	88	169	250
0.3	-145	-56	106	187	268
0.4	-98	-38	124	205	286
0.5	-50	-19	143	224	305
0.6	-3	-1	161	242	323
0.7	45	45	179	260	341
0.8	92	92	197	278	359
0.9	140	140	216	297	378
1	187	187	234	315	396

Note: P_d – initial price of diesel, V_0 – option value at the initial period in business-as-usual scenario, V_BAU – option value at the terminal period in business-as-usual scenario, V_STEP – option value at the terminal period in stated policies scenario, V_APS – option value at the terminal period in announced pledges scenario, V_NZS – option value at the terminal period in net-zero scenario

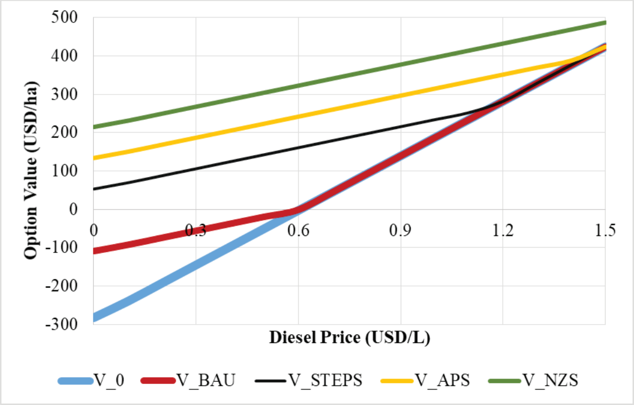

Fig. 4. Option values for shifting to SPIS at various learning rates based on climate target scenarios (BAU: business-as-usual, STEPS: stated policies scenario, APS: announced pledges scenario, NZS: net-zero emission scenario)

It can be observed that the option values at the terminal period (V_t) increased from the BAU scenario to other climate target scenarios. Compared with the BAU result, the option value in the STEPS scenario at the current diesel price (USD 1.09/L) is USD 230/ha at the initial period and USD 250/ha at the terminal period. This means that it is more optimal to postpone the investment with a value of waiting equal to USD 20/ha. In the APS and NZS, the option values at the terminal period are USD 331/ha and USD 412/ha, which result in the values of waiting equal to USD 102/ha and USD 183/ha, respectively. This implies that more stringent climate targets result in higher demand and lower prices for cleaner sources of energy like solar PV [35, 36]. On the contrary, small-scale farmers tend to wait or defer their shift of technology from diesel to SPIS until the period when solar PV is relatively cheaper than its current prices. These support previous claims on the application of real options that, while investment in solar PV is already profitable, investors can defer investment to obtain a more optimal investment value [14, 37].

D. *Cost-Sharing Scenarios*

In the case of cost-sharing, the researchers present three scenarios, where SPIS is shared by small-scale farmers. The BAU scenario is the baseline, 2S is shared by two, and 3S is shared by three small-scale farmers. In 2S and 3S scenarios, the researchers assume that the investment cost as well as operations and maintenance costs are equally shared among the farmers. Since the utilization rate is increased, the researchers assume that the capacity of the SPIS is also increased by 50% and eventually the associated costs. The results of the option valuation are shown in Table V and Figure 5.

TABLE V
OPTION VALUES AT THE INITIAL AND TERMINAL PERIODS FOR DIFFERENT COST SHARING SCENARIOS

P_d,0	V_0 (BAU)	V_t (BAU)	V_0 (2S)	V_t (2S)	V_0 (3S)	V_t (3S)
0	-283	-109	519	519	1320	1320
0.1	-240	-92.5	562	562	1363	1363
0.2	-192	-74.2	609	609	1411	1411
0.3	-145	-55.9	656	656	1458	1458
0.4	-97.6	-37.6	704	704	1505	1505
0.5	-50.2	-19.3	751	751	1553	1553
0.6	-2.75	-1.06	799	799	1600	1600
0.7	44.7	44.7	846	846	1648	1648
0.8	92.1	92.1	894	894	1695	1695

0.9	140	140	941	941	1743	1743
1	187	187	988	988	1790	1790

Note: P_d – initial price of diesel, V_0 – option value at the initial period, V_t – option value at the terminal period, BAU – business-as-usual, 2S – SPIS shared by 2 small-scale farmers, 3S – SPIS shared by 3 small-scale farmers

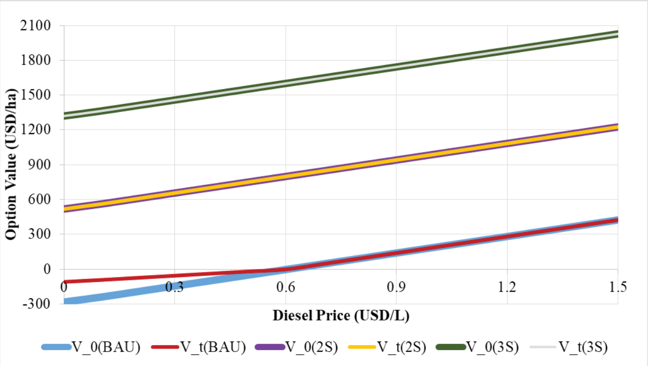

Fig. 5. Option values for shifting to SPIS at various cost-sharing scenarios (BAU: business-as-usual, 2S: shared by two farmers, 3S: shared by three farmers)

Compared with the BAU scenario, it can be observed that the option values for the 2S and 3S scenarios are all positive. This implies that even if the fuel cost is almost free, the operations and maintenance cost for diesel irrigation can already compensate for the costs of shifting to SPIS as these are shared among small-scale farmers. Another point of discussion is the significant shift of the curves upwards, which indicates that the option values for shifting to SPIS increase when the costs are shared among farmers. For instance, at the current diesel price of USD 1.09/L, the option values increase from USD 230/ha in the BAU scenario to USD 1031/ha in the 2S scenario and USD 1833/ha in the 3S scenario. These findings support the previous claim that the promotion of SPIS should also focus on the communal approach by sharing the upfront costs of SPIS thereby encouraging the technology adoption and upscaling [38]. Moreover, the option value curves for 2S and 3S are the same for the initial period (V_0) and the terminal period (V_t). These indicate that the value of waiting is equal to zero, hence, it is more optimal to invest now than postpone the investment when the cost of SPIS is shared among small-scale farmers. These also provide implications to encourage small-scale farmers to cost-share to make the SPIS more attractive than to continue using diesel-powered irrigation systems.

E. *Multiple Utilization Scenarios*

Since SPIS will only be utilized during the early months of cropping season and only during non-rainy seasons, the researchers can assume that the solar PV of SPIS can be tapped to generate renewable electricity for households. Considering the three months rainy season in the case country, this study presents multiple utilization scenarios namely, BAU: business-as-usual, 1U: one-month household utilization, 2U: two-months household utilization, and 3U: three-months utilization of solar PV for household use. For the 1U scenario, this study assumes that the solar panels have a capacity of 2.273 kW and can be utilized for six hours during the day with a 20% efficiency during rainy seasons. The current average electricity rate in the case country for household consumption is 57.38 cents/kWh. Hence, the value of cost savings for electricity consumption is added to the cost savings of using diesel irrigation. These values are equal to USD 46.95/ha/yr, USD 93.91/ha/yr, and USD 140.86/ha/yr for scenarios 1U, 2U, and 3U. The results of the options valuation are presented in Table VI and Figure 6.

TABLE VI
OPTION VALUES AT THE INITIAL AND TERMINAL PERIODS FOR DIFFERENT COST SHARING SCENARIOS

P_d,0	V_0 (BAU)	V_t (BAU)	V_0 (1U)	V_t (1U)	V_0 (2U)	V_t (2U)	V_0 (3U)	V_t (3U)
0	-283	-109	6	6	294	294	583	583
0.1	-240	-92	49	49	337	337	626	626
0.2	-192	-74	96	96	385	385	673	673
0.3	-145	-56	143	143	432	432	720	720
0.4	-98	-38	191	191	479	479	768	768
0.5	-50	-19	238	238	527	527	815	815
0.6	-3	-1	286	286	574	574	863	863
0.7	45	45	333	333	622	622	910	910
0.8	92	92	381	381	669	669	958	958

0.9	140	140	428	428	717	717	1005	1005
1	187	187	475	475	764	764	1053	1053

Note: P_d – initial price of diesel, V_0 – option value at the initial period, V_t – option value at the terminal period, BAU – business-as-usual, 1U – one-month household utilization, 2U –2-months household utilization, and 3U –3-months utilization of solar PV for household use

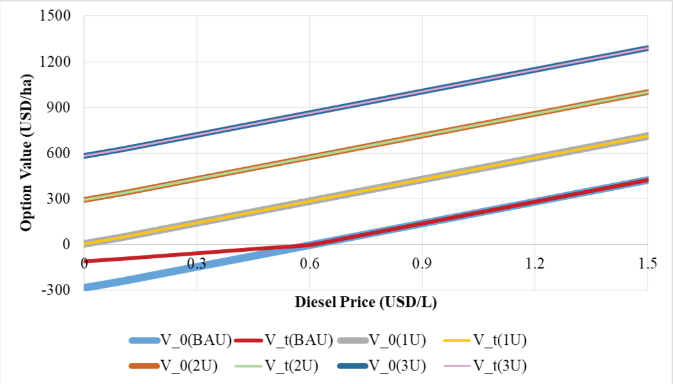

Fig. 6. Option values for shifting to SPIS at various multiple sharing scenarios (BAU: business-as-usual, 1U: one month, 2S: two months, 3S: three months utilization of solar PV for household use)

Similar to the cost-sharing scenarios, the option values for multiple-sharing scenarios are positive. This implies that the high investment cost as well as other operations and maintenance costs of SPIS can be compensated by the cost savings from diesel irrigation plus the value of electricity generated from the solar PV for household use. It can also be noticed that the curves significantly shift upwards, which indicates that the option values for shifting to SPIS increase with additional utilization of solar PV. For instance, at the current diesel price (USD 1.09/L), the option values increase from USD 230/ha in the BAU scenario to USD 518/ha in the 1U scenario, USD 518/ha in the 2U scenario, and USD 1095/ha in the 3U scenario. These results support the previous claim that while SPIS is already an economically viable option over diesel-powered irrigation, its feasibility can still be improved by introducing additional uses of solar energy such as household electricity generation [8, 32]. Furthermore, the option value curves for 1U, 2U, and 3U are the same for the initial period (V_0) and the terminal period (V_t), which indicates that the value of waiting is equal to zero. These imply that an optimal decision to invest immediately as postponement incurs no additional value to the project. These also provide implications to encourage small-scale farmers to utilize the solar PV of SPIS for other purposes such as household electricity consumption to make the SPIS more attractive than to continue using diesel-powered irrigation systems.

Finally, the findings in most real options literature that waiting or postponing the investment is a more optimal decision until the uncertainties are reduced and maximum benefits are obtained [14, 39-41]. On the contrary, in this study, the researchers showed that there are investment scenarios where it is more optimal to invest immediately as postponing the investment does not provide additional value to the project such as the cases of cost-sharing and multiple utilization scenarios.

F. *Externality Cost Scenario*

To further increase the attractiveness of shifting to SPIS, this study considers the negative externality of using a diesel irrigation system. This includes the GHG emissions as well as the health costs of air pollutants from diesel combustion. Among the air pollutants considered are carbon monoxide, nitrous oxides, sulfur oxides, particulate matter, and volatile organic compounds. Studies show that long and short-term exposures to these air pollutants have a different toxicological impact on humans including respiratory and cardiovascular diseases, and long-term chronic diseases [42, 43]. Replacing diesel with SPIS avoids these air pollutants from diesel combustion, thereby reducing the associated health risks and costs to farmers and the nearby communities. Moreover, shifting to SPIS also reduces the emissions of GHGs such as carbon dioxide and nitrous oxide, which absorb heat from the atmosphere and contribute to climate change [44]. Based on the average annual diesel consumption of small-scale farmers, the costs of these externalities are added to the annual cost savings from shifting to SPIS. Table VII presents the results of the CBA with and without these externalities.

TABLE VII
COMPARISON OF COST BENEFIT ANALYSIS WITH AND WITHOUT NEGATIVE EXTERNALITIES

Economic Indicators	Unit	Without Externality	With Externality
Annual cost savings	USD/ha/yr	556.26	787.26
Net present value	USD/ha	229.68	1649.11
Internal rate of return	%	12.49	26.22%
Payback period	Years	5.58	3.46

As shown in table V, the annual cost saving increased from USD 556 to USD 787 representing the negative externalities that are valued at USD 231/ha/yr. Consequently, this increases the NPV from USD 230/ha to USD 1649/ha, representing a significant increase in the added value of the investment. The economic efficiency of shifting to SPIS also increases from 12.49% IRR without externalities to 26.22% IRR with externalities, implying that the project generates 26.22% returns relative to the initial investment. Furthermore, the PBP reduces from 5.58 years to 3.46 years, making the shifting of technologies to SPIS more attractive than continuing diesel-powered irrigation systems. Meanwhile, these values are then integrated in the real option valuation which are shown in Table VIII and Figure 7.

TABLE VIII
OPTION VALUES AT THE INITIAL AND TERMINAL PERIODS FOR DIFFERENT CLIMATE SCENARIOS

P_d,0	V_0_BAU	V_t_BAU	V_0_E	V_t_E
0	-283	-109	1137	1137
0.1	-240	-92.5	1180	1180
0.2	-192	-74.2	1227	1227
0.3	-145	-55.9	1274	1274
0.4	-97.6	-37.6	1322	1322
0.5	-50.2	-19.3	1369	1369
0.6	-2.75	-1.06	1417	1417
0.7	44.7	44.7	1464	1464
0.8	92.1	92.1	1512	1512
0.9	140	140	1559	1559
1	187	187	1606	1606

Note: P_d – initial price of diesel, V_0_BAU – option value at the initial period in a business-as-usual scenario, V_t_BAU – option value at the terminal period in a business-as-usual scenario, V_0_E – option value at the initial period in the externality scenario, V_t_E – option value at the terminal period in the externality scenario

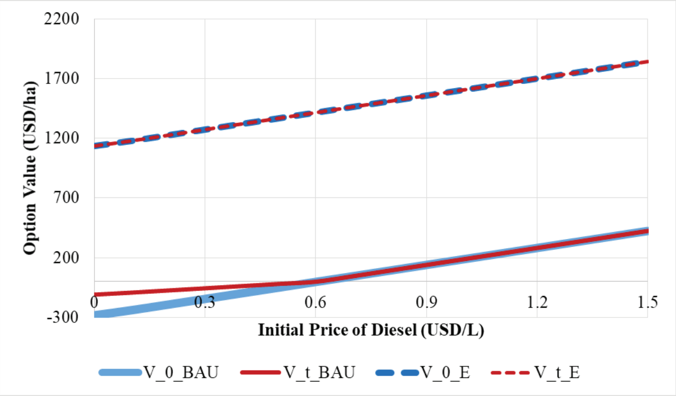

Fig. 7. Option values for shifting to SPIS integrating the negative externalities of using diesel fuel (BAU: business-as-usual without negative externality, E: with negative externality)

Results show that the option values significantly increase from the BAU scenario without negative externalities to the externality scenario. For instance, at the current price of diesel (USD 1.09/L), option values increase by 760% from USD 187/ha to USD 1606/ha. Compared with the BAU scenario, it can be observed that both V_0 and V_t in the externality scenario are the same. This implies an optimal decision to invest immediately in SPIS as postponing the investment does not give any additional value to the project. This result supports previous claims that incorporating the negative externalities of fossil fuel combustion makes alternative renewable energy technologies more attractive than continuing fossil-based technologies [16, 18].

IV. CONCLUSION

This study highlights the potential of SPIS to promote sustainable agricultural production while contributing to environmental conservation by reducing reliance on fossil fuels and mitigating greenhouse gas emissions. While the economic viability of SPIS has been extensively discussed in the literature, this study considered the uncertainty and the managerial flexibility in making investment decisions for the SPIS. Applying the cost-benefit analysis and real options approach, this study evaluated the relative attractiveness of shifting technologies from diesel-powered irrigation to SPIS under diesel price uncertainty.

Cost-benefit analysis results showed that shifting to SPIS is economically viable with USD 556.26/ha annual cost savings, USD 229.68/ha net present value, 12.49% internal rate of return, and a 5.58-year payback period. Contrary to most real options literature, the real options valuation found that at the current price of diesel, it is more optimal to invest in SPIS immediately as waiting or postponing does not give additional value to the project. These results are further favored by technology learning, cost sharing among small-scale farmers, multiple utilization of solar PV such as electricity generation for household consumption, and negative externality of using diesel in terms of GHG emissions and health costs from fuel combustion. These findings provide several recommendations to further improve the adoption and upscaling of SPIS:

- Providing strategic incentives, supporting policies, and innovative financing mechanisms to incentivize the widespread adoption of SPIS, particularly to cover the high upfront cost of SPIS from the perspective of small-scale farmers;
- In addition to national efforts, farmer cooperatives or local government units may seek other sources of financing support from non-governmental organizations as well as international funding sources;
- Implementing efforts to achieve more stringent climate targets will decrease the cost of SPIS, making it more attractive and affordable to small-scale farmers;
- Encouraging small-scale farmers to share the technology, thereby, reducing the investment as well as operations and maintenance costs;
- Utilization of solar PV for other purposes such as electricity generation for households, particularly in rainy seasons and the latter part of the cropping season when water is abundant and irrigation is not much needed;
- Information, education, and communication of the environmental benefits of using SPIS as well as the savings from health costs of using diesel-powered irrigation systems.

Yet, the study has several limitations that can be bases for further investigation. First, the study only took the perspective of small-scale farmers. For the upscaling and widespread adoption of the technology, future studies should also consider medium- to large-scale farmers to better capture the decision-making mechanisms from various perspectives. In the real options valuation, only the diesel prices were used. Uncertainties in social acceptance, electricity rates for multiple utilization, and externalities for using fossil fuels may also be included. Lastly, this study applied the real options to defer/postpone investment. Future real options valuation may consider the option to expand/upscale SPIS, the option to switch between irrigation and electricity generation for households, and the option to abandon when governments provide irrigation systems to agricultural lands. Albeit these limitations, the real options framework proposed in this study could be a good benchmark for further analysis empowering small-scale farmers to harness the potential of renewable energy, thereby fostering a more sustainable and resilient agricultural sector for generations to come.

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