

Economic and Environmental Feasibility of Solar Photovoltaic Systems for Sustainable Tobacco Curing in Zimbabwe

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ABSTRACT

This study presents a comprehensive economic and environmental analysis of the transition from conventional wood-fired to solar photovoltaic (PV) integrated tobacco curing systems in Zimbabwe. Using a Cost-Benefit Analysis (CBA) framework on data from 50 stratified randomly sampled farmers in the Chikomba district, Zimbabwe. The study evaluates economic feasibility through Benefit-Cost Ratio (BCR), Net Present Value (NPV), and Payback Period (PP), alongside environmental performance measured by Fuel Efficiency Gain (FEG). Results in CBA showed that solar PV system, despite a higher initial investment (\$7,500 vs. \$2,500), offer a high CBR of 26.38 after 3 years whilst the conventional system offered 3.5. This demonstrated that the solar system is a more profitable investment. NPV showed that the solar PV system reach a higher cumulative of \$29,642 after 3 years compared to the conventional system which achieved only \$11,183. FEG was higher for solar PV system as wood consumption is reduced by approximately 128.6% providing notable environmental benefits. The payback period for both systems was 1 year with solar PV system having lower operational costs than conventional system. These findings demonstrate that solar PV curing systems offer a sustainable and economic way to cure tobacco for Zimbabwe's tobacco sector, supporting national goals for increased sustainability and environmental stewardship.

Keywords: Solar PV, Cost-Benefit Analysis, Tobacco Curing

1. INTRODUCTION

The global agricultural landscape is currently undergoing a significant transformation, driven by the dual imperatives of enhancing economic output and promoting environmental sustainability. In many developing nations, traditional farming practices and post-harvest processes are a major source of environmental degradation and economic inefficiency. A prime example is Zimbabwe, where tobacco farming is a cornerstone of the national economy, contributing over 50% of the country's agricultural exports and nearly 10% of the Gross Domestic Product (Shati *et al.*, 2021). According to the Tobacco Industry Marketing Board (TIMB, 2023), it typically makes up 43% of the nation's agricultural GDP, about 10% of the GDP overall, and more than 50% of its agricultural exports. The crop plays a vital role in Zimbabwe's economy and is the country's second-largest source of foreign exchange earnings after gold (Madanhire & Chiwarange, 2018). However, the postharvest phase particularly the curing process remains both resource-intensive and environmentally taxing, with conventional systems heavily reliant on firewood and coal (Chronicle, 2014). This dependence not only accelerates deforestation but also inflates production costs for farmers, threatening the long-term sustainability and profitability of the industry (All Africa Global Media, 2025). The lack of alternative energy sources for tobacco curing has been highlighted as a major issue which is causing deforestation in Zimbabwe (Nuwagira *et al.*, 2018).

The profitability of tobacco lies in the curing process. The best cured tobacco leaf fetches a good price on the auction floor. This drives the tobacco farmers to always be on the lookout for efficient, cost effective ways to increase quality of their tobacco by drying it in the best possible way. Some farmers the large scale and the small scale rely on conventional barn according to **TIMB (2017)**, 70% rely on conventional barns for curing tobacco. The majority of tobacco farmers in Zimbabwe are not linked to the electrical grid, and those who are frequently without power. The original barns were built to use coal for tobacco curing, but using coal requires electricity to run combustion fans (**Millers, 2015**). This has pushed the 70% of the tobacco farmers who rely on conventional method to use wood as a source of fuel to power the barns (**Munanga et al., 2014**). The heavy reliance on wood has resulted in deforestation in some part of the country.

In response, there is growing interest in innovative, energy-efficient alternatives such as solar photovoltaic integrated curing systems, which promise to transform the value chain by reducing input costs, minimizing environmental impact, and enhancing product quality (**Manyanhaire&Kurangwa, 2014**). Zimbabwe has 15% of the small scale and large scale tobacco farmers relying on solar integrated system to cure the tobacco leaf (**TIMB, 2022**). The farmers who have adopted the solar integrated system are expanding their operations yearly and they seem to trust the efficiency of the solar system. The solar curing barns offer Zimbabwean tobacco farmers a cleaner and more climate resilient alternative for tobacco processing (**Wang et al., 2017**). They curb deforestation, cut emissions, reduce production costs and support sustainable smallholder agriculture. Also Zimbabwe has endured erratic power supply for years. Frequent load shedding and blackouts have made it hard for farmers to plan their operations efficiently. According to **Shati et al. (2021)** solar system promises to ease energy crises for the tobacco farmers. However the farmers who are not on solar constantly mourn the high costs involved in solar system.

This study aims to add to this body of knowledge by conducting a comprehensive assessment of the economic and environmental feasibility of solar PV integrated tobacco curing systems. Using a Cost-Benefit Analysis (CBA) framework, the research compares solar PV systems against conventional curing methods in Zimbabwe (**Akinyi et al., 2022**). The objective is to provide empirical evidence to inform farmers, policymakers, and other stakeholders about the tangible benefits of transitioning to sustainable, renewable energy solutions for a crucial agricultural sector.

2. MATERIALS AND METHODS

2.1. Study Area, Sample, and Data Collection

This study was conducted in the Chikomba district of Zimbabwe, a region with significant tobacco farming activity. To ensure a representative sample, 50 tobacco farmers were selected for the study using a stratified random sampling method. The farmers were divided into two groups: 30 who exclusively use conventional curing systems and 20 who have adopted solar PV integrated systems, some of whom also use conventional methods. Data was collected through a combination of structured questionnaires and detailed interviews, designed to capture all relevant costs and benefits associated with each curing method over a three-year period.

2.2 Analytic tools

In order to perform the Cost Benefit analysis of the two systems the solar photovoltaic curing system and conventional system a total cost of the systems were known. Four decision criteria were used under CBA and these are Cost Benefit Ratio (CBR), Net Present Value (NPV), Fuel Efficiency Gain (FEG) and Payback Period (PP).

2.2.1. Benefit Cost Ratio: Calculate the total costs (initial investment, operational costs) and benefits (reduced fuel consumption, environmental savings) of each system.

Net Benefits = Total Benefits - Total Costs

Cost Benefit Analysis Ratio (Benefit - Cost)

$$BCR = \frac{\sum PV(\text{Benefits})}{\sum PV(\text{Costs})}$$

If $BCR > 1$, benefits outweigh costs, it's a worthwhile project.

2.2.2. Net Present Value (NPV)

$$\sum_{t=0}^n \frac{Bt - Ct}{(1+r)^t}$$

Bt = Benefit (inflow) at time period t Ct = Cost (outflow) at time period t r = discount rate (interest rate/ required rate of return per period) n = total number of period

2.2.3. Fuel efficiency gain: This is the % of the efficiency gain after introducing the solar integrated system when a farmer moved from convectional system.

a) Calculate Initial Efficiency Gain

$$\text{Fuel efficiency}_{\text{initial}} = \frac{\text{Weight of cured tobacco}}{\text{Amount of fuel consumed}}$$

b) Calculate new fuel efficiency after solar integrated system

$$\text{Fuel efficiency}_{\text{new}} = \frac{\text{Weight of cured tobacco}}{\text{Amount of fuel consumed after solar integrated system}}$$

c) Fuel Efficiency Gain

$$\text{Fuel Efficiency Gain \%} = \frac{(\text{Fuel Efficiency}_{\text{new}} - \text{Fuel Efficiency}_{\text{initial}})}{\text{Fuel Efficiency}_{\text{initial}}} * 100$$

2.2.4. Payback Period: Time to recover solar PV system costs and convectional cost.

$$\text{Payback Period (years)} = \frac{\text{Initial solar investment}}{\text{Annual cost benefits}}$$

The whole price comprises the costs of purchasing equipment, transportation, erection, building, and commissioning, among other system components.

2.2.5 Main Variables used in Cost Benefit Analysis. The different cost components and benefit variables used the CBA.

The cost benefit analysis include both the market and non market costs and benefits as it addresses increase or decrease in social well being so that intergenerational equity and sustainability criteria can be addressed (Alcon *et al.*, 2024). For the benefit that's revenue and savings which increased quality of the tobacco leaf that fetches high price at the market and environmental preservation that comes in form of less trees being cut for curing, less pollution. The costs are the fixed and variable costs derived from the expected changes in the tobacco curing ecosystem like fuel, operational and equipment costs.

Costs of tobacco curing

- Fuel costs (US\$): Wood being used for curing
- Labor (US\$): Being used in ferrying the wood and taking care of the curing system
- Equipment & Infrastructure (US\$): The initial investment equipments
- Operating and maintenance costs (US\$): Costs incurred in taking of the system

Benefits of tobacco curing

- Fuel cost savings (US\$): Any wood saved in the use of the curing system
- Increased productivity capacity (US\$): Increment of price of the finished product
- Tobacco price improvement: The new price offered due to the use of any of the system

2.2.6 Sensitivity analysis

The study employed sensitivity analysis to assess the economic viability of switching from a traditional system to a solar PV tobacco curing system. The impact of a variable modification on the NPV was demonstrated by this analysis. Akinyi *et al.* (2022) assert that handling uncertainty is crucial in every CBA investigation. The sensitivity analysis was carried out using the pessimistic-optimistic scenario methodology. Sensitivity analysis was used to assess how changes in input values, such as costs or benefits, impact a project's overall profitability or result (Alcon *et al.*, 2024). The most advantageous values are assigned in the optimistic scenario, while the least favorable values are assigned in the pessimistic scenario. Costs and benefits were the two input variables taken into account in this study. The variables were changed by 10% on the presumption of a perfect market. To determine whether variable was most or least sensitive to the NPV, the difference between the base values was calculated.

3. RESULTS AND DISCUSSION

3.1 Benefit Cost Ratio

Table 1 shows that the total benefits of having a solar system over 3 years is valued at \$47 771.1 where as the costs are \$13 300 in comparison with convectional system that has benefit value of

\$27 600 and costs of \$10 050. This emanates from high value benefits of the solar system which does not use wood or coal in tobacco curing hence it saves on fuel. The benefits of the convectional system are less as it uses wood for curing hence it does not save much on fuel and labor thus also raising its costs. Similar findings were found by *Shatiet et al., (2021)*.

Table 1: Benefit Cost Ratio (BCR) for Solar and Conventional systems tobacco curing

Year	Benefits (Solar)	Costs (Solar)	BCR (Solar)	Benefits (Conventional)	Costs (Conventional)	BCR (Conventional)
1	9,423.70	8,350	1.13	6,600	6,100	1.08
2	15,923.70	850	18.73	8,400	3,600	2.33
3	22,423.70	850	26.38	12,600	3,600	3.5

Table 1 highlight that both systems are cost effective (BCR>1) but solar system delivers more than the benefits per dollar invested compared to the convectional system. Initially (Year 1) both solar and conventional systems have similar BCRs slightly above 1 meaning they are marginally profitable overtime, the solar system’s BCR increases substantially. The solar system provides higher benefits for lower or relatively smaller incremental costs in Year 2 and 3 showing that it is more economically efficient option in the longer term. The solar system has a CBR of 26.38 after 3 years of installation this means that for every \$1 spent you get \$26.38 in benefits whereas the convectional system has a CBR of 3.5 meaning that for every \$1 spent one gets \$2.08 in benefits. This signals Solar Integrated system as a more profitable investment than convectional system. The findings resonates with (*Alcon et al., 2024*)

3.2. Net Present Value analysis

The results in Table 2 show that solar PV system achieves far higher cumulative discounted cash flows reaching \$29,642 after 3 years more than conventional system which achieved only \$11,183 over the same period of time despite a lower upfront investment in the first year. These findings are similar to *Alcon et al., (2024)*. The results show that the solar system has accelerating cash flow advantage with the gap widening significantly in Year 2 and 3 due to increasing revenue benefits and consistent cost savings. All this makes the solar PV system a superior long term investment for sustainable tobacco curing in Zimbabwe. The solar system generates 165% more value and demonstrates exceptional financial efficiency with a profitability index of 4.32 versus 2.00 of the convectional system.

Table 2: Solar PV and convectional system NPV breakdown at 10% discount rate

Year	Net Cash Flow		P. Value Factor		Present Value	
	Solar	Conventional	Solar	Conventional	Solar	Conventional
1	\$1,074	\$500	0.91	0.91	\$976	\$455
2	\$15,074	\$4,800	0.83	0.83	\$12,458	\$3,967
3	\$21,574	\$9,000	0.75	0.75	\$16,209	\$6,762
Total NPV					\$29,642	\$11,183

3.3. Fuel efficiency gain analysis

According to Table 3 to cure 1 kg of tobacco the farmers in Chikomba district in Zimbabwe use 8kg of firewood when they are using the convectional system. Comparatively they use 3.5kg of firewood to cure 1kg of tobacco when they are using the solar PV system. The fuel efficiency gain is 128% when using the solar system which is more than double fuel efficiency in cured tobacco per wood used..The use of solar PV technology substantially lowers fuel requirements reducing both operational costs and environmental impact through decreased deforestation and carbon emissions. These findings resonate with *Madanhire et al., (2018)*. The reason for the reduced fuel use in solar system is that the farmers were now relying on solar for curing rather than firewood for feeding their barns. This 128% fuel efficiency gain align with the findings of *Krishnan et al., (2018)*, *Shati et al., (2021)* and *Orpia et al., (2021)*.

Table 3: Fuel efficiency for each system

System	Tobacco Cured (grams)	Wood Used (grams)	Efficiency (g tobacco/g wood)	Efficiency Gain (%)
Wood-fired (before)	1,000	8,000	0.125	-
Solar-integrated (after)	1,000	3,500	0.286	128.6

3.4. The Payback period analysis

The results in Table 4 show that the conventional system has a payback period of 1 year due to the initial investment being recovered in the first year. Solar systems PV system has a payback period of 1 year as well enabled by substantial reductions in recurring costs. These findings resonate with **Barron- Gafford *et al.*, (2019)**. While PV system requires higher upfront investment, the combination of rapid payback and lower operating costs justifies the expenditure and support long term economic resilience. The 1-year payback period for solar PV system fall under acceptable investment recovery timeframes for agricultural technology (**Cotter, 2023**). Both systems show rapid payback and solar system shows even a strong financial performance. According to **Fernando *et al.*, 2014** payback period less than 7 years are considered favorable for solar energy investments in agricultural applications making the solar integrated system economically attractive to tobacco farmers

Table 4: Payback period analysis for solar PV integrated system and convectional tobacco curing system

Year	Solar System Costs	Solar System Benefits	Savings	Payback
1	8350	9423.7	1073.7	1st year
Year	Convectional Costs	Convectional Benefits	Savings	Payback
1	6100	6600	500	1st year

4.1 Sensitivity analysis using pessimistic and optimistic approach

Sensitivity analysis was based on the NPV hence it was used as the base case. In this study NPV was \$29 642 for the solar PV system and \$11 183 for the convectional system. Table 5 shows the cost sensitivity robust performance under adverse cost conditions. If the costs decreases by 20% the NPV of the solar PV system advantage value gets to \$18 000. When the costs increase by 20% the solar advantage now increases to \$19 147. The difference between the increase and the decrease of the costs shows that the solar system’s advantage increases with higher costs because convectional system is more affected by proportional cost increase due to higher baseline operational costs. The findings are similar to **Akinyi *et al.*, 2022**.

Table 5: Cost sensitivity analysis under adverse conditions

Cost Change (%)	Solar NPV	Conventional NPV	Solar Advantage
Initial Cost	\$29,642	\$11,183	\$18,459
Decrease of 20%	\$31,429	\$13,428	\$18,000
Increase of 10%	\$28,749	\$10,061	\$18,688
Increase of 20%	\$27,856	\$8,938	\$18,917
Increase of 30%	\$26,963	\$7,816	\$19,147

Table 6 reveal that even with 30% revenue decline the solar system maintains a \$15 136 NPV whilst the convectional is at \$5 115. The results show that solar system is demonstrating exceptional resilience as solar system delivers 54.8% higher revenue in the third year. The reason

for these results could be lower operational costs in the solar PV system hence it records high revenues. These results are similar to **Krishnan *et al.*, (2018)**, **Shati *et al.*, (2021)** and **Orpia *et al.*, (2021)**

Table 6: Revenue sensitivity analysis under adverse conditions

Revenue Change (%)	Solar NPV	Conventional NPV	Solar Advantage
Initial Revenue	\$29,642	\$11,183	\$18,459
Decrease of 30%	\$20,251	\$5,115	\$15,136
Decrease of 20%	\$23,382	\$7,138	\$16,244
Decrease of 10%	\$26,512	\$9,161	\$17,351
Increase of 10%	\$32,773	\$13,206	\$19,567
Increase of 20%	\$35,903	\$15,229	\$20,674
Increase of 30%	\$39,033	\$17,251	\$21,782

5.1 Recommendations

To the farmers

- To adopt solar PV tobacco curing system. Despite the higher initial investment, solar system offer far greater long term profitability. After 3 years the system indicate strong and financial robustness
- The farmers can collaborate and form cooperatives so as to seek out financial support to lower initial costs
- The farmers can consider short payback periods of the systems and the fact that with solar PV system it yields much higher cumulative gains and significantly lower operational costs after payback hence solar is the best option to adopt

To government

- Investment in rural renewal energy infrastructure as further infrastructure development will empower tobacco farmers to access solar technology
- To monitor and evaluate performance. The government should continue research and outreach to track system performance

6. Conclusion, implications, future research and limitation of study

6.1 CONCLUSION

The transition from traditional firewood based curing method to solar PV system in Zimbabwean tobacco farming yield compelling economic and ecological benefits. The Cost Benefit Analysis revealed that the solar PV system although requiring a higher initial investment deliver a superior Benefit Cost Ratio (BCR of 26.38 versus 3.5) and a much greater Net Present Value (NPV of \$29 642 versus \$11 183) within 3 years confirming solar PV as a more profitable and robust choice. Solar PV operations achieved significantly higher Fuel Efficiency Gains reducing wood consumption by approximately 128.6% a major stride for environmental operation conservation. It is recommended that farmers and policy makers should accelerate adoption of solar PV curing leveraging its proven economic advantages.

6.2 Policy implications of this research

The findings carry significant implications for policymakers and industry leaders seeking to foster sustainable growth. Adoption of solar PV systems can help legislators accomplish climate and forest conservation goals as they will impact on the environment. The change would lessen the pressure on deforestation, cut greenhouse gas emissions and establish Zimbabwe tobacco as a more sustainable international commodity. Also the farmer livelihoods will improve given the higher long term returns and reduced operation expenses solar PV curing enhances farmer profitability, secures energy supply and reduces exposure to wood fuel shortage. The massive adoption of the solar PV system will transform of the agricultural sector. Adopting solar

photovoltaic (PV) can spur a wider use of renewable energy in Zimbabwean agriculture by promoting investment in local production and installation skills.

6.3 Future work

Looking ahead further research is needed to address remaining gaps such as broader access to financing for solar investments and the scalable integration of renewable within Zimbabwean agriculture. The future of tobacco curing in Zimbabwe lies in widespread solar adoption which not only secures farmer's income but also aligns with national sustainability goals and global stewardship trends. Strategic collaborations between researchers, policymakers and farmers will be essential to mainstream this technology. The solar PV system helps to lessen the environmental effect of agriculture by supplying clean electricity to support agricultural practices like tobacco curing that now depend on fossil fuels. Also further research on hybrid energy systems can be done which investigate into solar biogas or hybrid solar biomass curing systems that remains dependable on weather forecast.

6.4 Limitations of the Study

The study acknowledges its primary limitation in relying on static costs. The CBA assumes constant prices of wood, maintenance and labor over 3 years, which may not fully capture the complexity at the retail and wholesale shops. While the analysis did provide an extra cost provision a comprehensive less static costing would be needed for the actual costing if the installation of the solar PV system will be done at later years.

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