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DESIGN OF A PROTOTYPE SOLAR THERMAL TOBACCO CURING BARN

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Abstract
need to move away from using firewood for tobacco curing. It became necessary to develop alternative renewable energy systems. Prototyping takes precedence before introducing the renewable energy tobacco curing system for use by farmers. The initiative is to design a prototype tobacco curing barn for use with solar thermal collector tobacco curing energy systems. The design accommodates dimensions of maximum cross-section of a tobacco leaf at 68 centimetres long and 40 centimetres wide. Prototype roof rail sustains tobacco mass of 100 kilogrammes. Barn mobility is enabled by mounting 4 roller wheels sustaining a gross weight of 500 kilogrammes. A barn handle is at one narrow side. The paper explains a detailed design process and sketches of the prototype tobacco curing barn as well as presents a lifecycle costing of the project's investment in Zimbabwe.

Keywords: Barn, collector, design, modularity, prototype

1. INTRODUCTION

In July 2020, a survey was conducted on small-scale tobacco farmers in Zimbabwe. The results show that tobacco producers are ready to fully support the implementation of sustainable renewable energy systems for tobacco processing on farms. Opinions between farmers and engineers were unanimous on this issue. The conclusions drawn from this survey initiated the design of a prototype tobacco-curing barn as a control volume for the transfer of matter and energy during the tobacco-curing process. Most solar dryers are designed and manufactured for dehydration and heating of food crops. Such heat generation and transfer activities occur at relatively low temperatures. Liquid solar panels are used for medium and high temperature solar heaters. The current design is especially for tobacco curing heat treatment, which is a low to medium temperature activity. Expanding use of the developed technology into developing countries will make the research breakthrough into use of solar collectors in tobacco treatment sustainable. Renewable energy technology produces marketable energy by converting natural phenomena into usable energy, but most renewable energy sources are intermittent, with technical and economic regional variations. The problem is difficult but it can be solved (Kalogirou, 2004).

The unified design approach does not apply to the dimensions of solar-assisted crop dryers. Variables included in the design process are the load, climate and economic data. Lack of sufficient knowledge and information about these variables has led rural producers in developing countries to use traditional energy sources and deprive themselves of suitable techniques for their improvement (Santos et al., 2004). When planning and designing a solar dryer with forced convection, Komolafe and Waheed (2014) integrated it with a heat storage material. The basic design parameters considered were aggregated information about the application of the equipment, performance assumptions, and analysis of information about various produce. Important variables considered in the plan were the amount of water removed from the agricultural product, the capacity of the dryer representing a unit batch of drying, the local availability of building materials for drying chambers and trays. Also considered was the amount of raw products loaded and unloaded, the amount of daily solar radiation and the amount of energy and dry air absorbed by the dryer per day. Dryer dimensions were derived by measuring a certain amount of moist product dried to storage moisture content. Fujiwara (1983) showed that the number of collectors is related to performance parameters and operating environment. Figure 1 is a flow chart of the design process for sizing a solar-assisted crop drying system and assessing the combination of solar collector area and auxiliary energy requirements for the load (Santos et al., 2004).

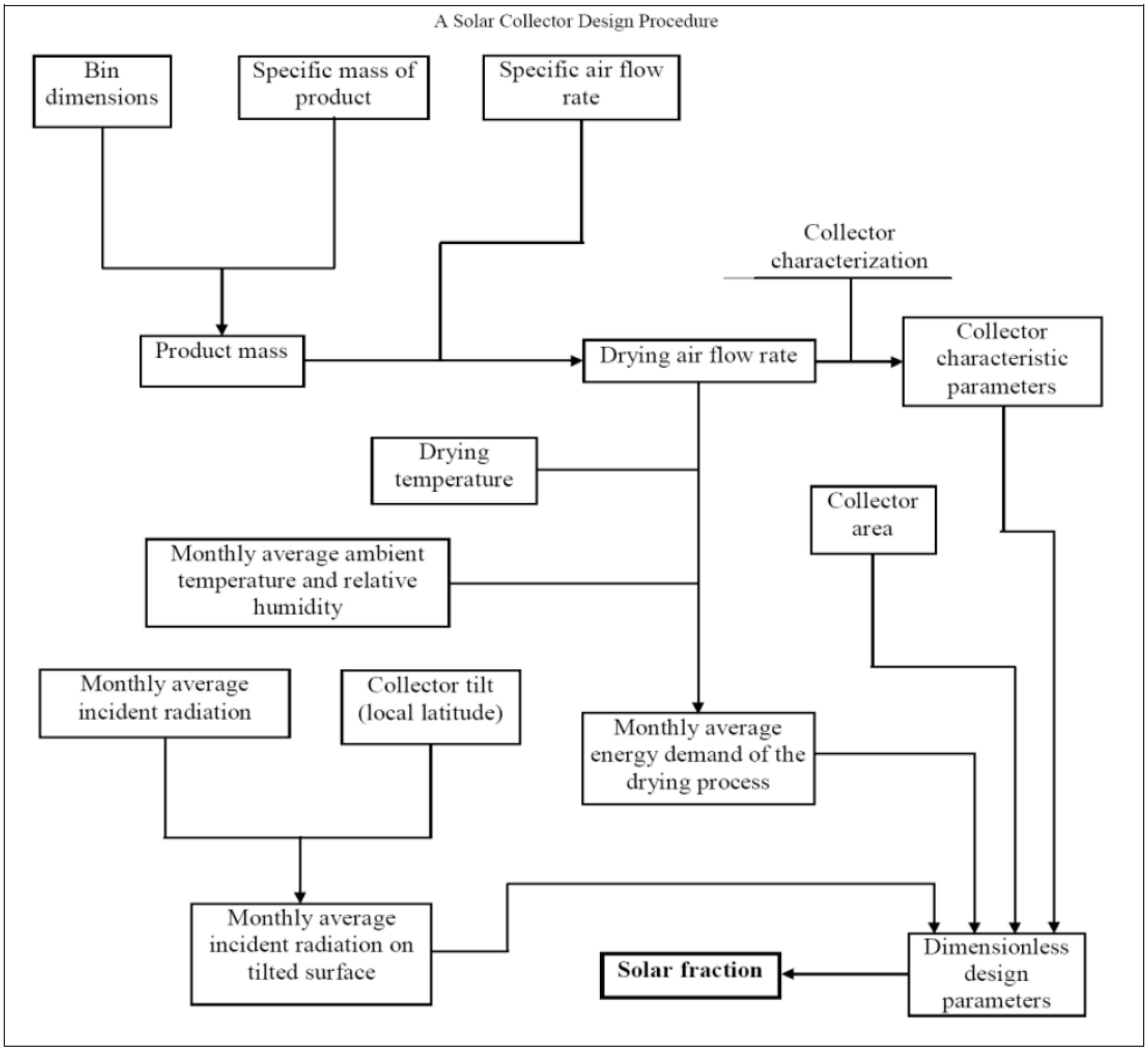

Fig.1 Crop drying design parameters (Santos et al, 2004).

The prototype barn is designed to cure tobacco. The undried mass of the product is 100 kg per batch and the flow of dry air to the collector is 40 kg per hour. Drying begins at 35°C temperature and 85% humidity respectively. It then slowly rises from 35°C to 60°C, while at the same time reducing relative humidity from 85% to about 35%. Temperature gradually rises from 60°C to the drying stage of tobacco stalks at 70°C, after which the relative humidity drops to about 18%. The average energy required to cure 100 kilograms of tobacco is 300 mega joules. The northward inclination of the collector is equal to the local latitude 20° south of the equator. The collector area should be 2m x 1m, or 2m². As shown in Table 1, the width and height dimensions of the stall should correspond to the maximum length and width of tobacco leaves of 62.85 cm and 35.93 cm, respectively. Ekechukwu (1999) states that the amount of water present in a material is expressed either wet-based or dry-based, in decimal or as a percentage. The moisture content on the dry basis is the weight of moisture present in the product per unit weight of dry matter in the product and represented as:

$$M_{\mathrm{db}} = \frac{W_{\mathrm{o}} - W_{\mathrm{d}}}{W_{\mathrm{d}}}$$

Table 1: Maximum and average dimensions of tobacco leaves (Wolf and Gross, 1937).

Leaf dimensions and areas of low-topped plants							
Leaf No.	Length cm	Width cm	Area cm^2	Length/Width	Thickness μ	Transection area of midrib cm^2	Transection area of vascular axis cm^2
1	52.6	29.6	982.68	1.777	359	0.663	0.063
2	60.2	33.0	1 269.27	1.827	351	0.823	0.076
3	59.1	32.6	1206.10	1.812	306	0.813	0.087
4	61.8	35.3	1368.40	1.758	294	0.953	0.108
5	62.3	35.9	1 424.56	1.745	299	1.024	0.097
6	65.3	36.5	1 523.56	1.794	299	1.094	0.122
7	68.8	38.3	1 628.41	1.803	311	1.157	0.143
8	67.0	39.6	1 658.36	1.705	301	1.269	0.139
9	68.6	42.6	1 844.45	1.608	407	1.378	0.178
Average	62.85	35.93	1 433.97	1.759	325	1.106	0.1126

Table 2 Expected Energy and Mass Transfer During Tobacco Curing Process for Prototype

Item	Sri Lankan Barn (Jayasighe and Namal, 2010)	Prototype Tobacco Curing Barn (University of Zimbabwe)
Green leaf weight	3 500kg	100kg
Cured leaf weight	525kg	15kg
Removed moisture	2 975kg	85kg
Moisture removing heat	7 810MJ	225MJ
Barn heat output	49 239MJ	300MJ
Barn efficiency	16 percent	75 percent

And expressed as a percentage, Mdb = Mdb X 100 (Ekechukwu, 1999). Wet-based moisture content is the weight of moisture present in a product per unit weight of undried material and is expressed as:

$$M_{\mathrm{wb}} = \frac{W_{\mathrm{o}} - W_{\mathrm{d}}}{W_{\mathrm{o}}}$$

Expressed as a percentage, Mwb = Mwb x 100. In both cases, Wo is the starting weight of the undried product measured in kilograms, Wd is the weight of the dried product in kilograms, Mdb is the mass of the dried product, and Mwb is the mass of the undried product (Ekechukwu, 1999). A tobacco mass that is dried at any given time is 100 kilograms. The weight of the dried final product is 15 kg after the tobacco drying process after 85 kg of water loss. Table 2 shows the expected energy and mass transfer within the control volume prototype during the tobacco curing process.

Parameter measurements for Sri Lankan tobacco barn tested in 2010 are 35 times higher than prototyped tobacco barn. Table 2 shows that use of solar thermal energy together with environmentally friendly auxiliary energy systems can significantly improve the efficiency from 16% to 75%. In the case of fossil fuels, it takes 1,630 MJ of heat to cure 100 kilograms of tobacco, but the forecast uses only 300 MJ, which saves 1,330 MJ of energy. Tobacco prototype saves fuel. Fuel saver means designing a system without heat storage and solar heat is supplied directly to the proper tobacco curing process. The maximum rate at which the solar system supplies energy must not be significantly higher than the rate at which the process consumes the energy produced (Kalogirou, 2004). The system is not cost effective in intermittent, cloudy weather and at night, so the design includes an auxiliary electric heat source mounted on a removable oven.

2. METHODOLOGY: RENEWABLE ENERGY-POWERED TOBACCO CURING SYSTEM DESIGN

Acquisition phase includes various phases of design, development, procurement, construction, or production and implementation (Nicholas, 1990). The design of the tobacco barn was after a visit to the research station of the Tobacco Research Board in Harare in January 2020. The purpose was to establish the composition and operation of the barn. The barn architecture uses ArchiCAD 21 design software. Smirnov (2015) describes ArchiCAD's behavioral characteristics as a complex tool for complete project creation, as it allows you to combine external and internal designs into a single image. ArchiCAD can create all the drawings, specifications and other structural lists needed by engineers. According to a survey by Smirnov (2015), it is used by 30% of architects and accounts for the majority, as shown in Figure 2.

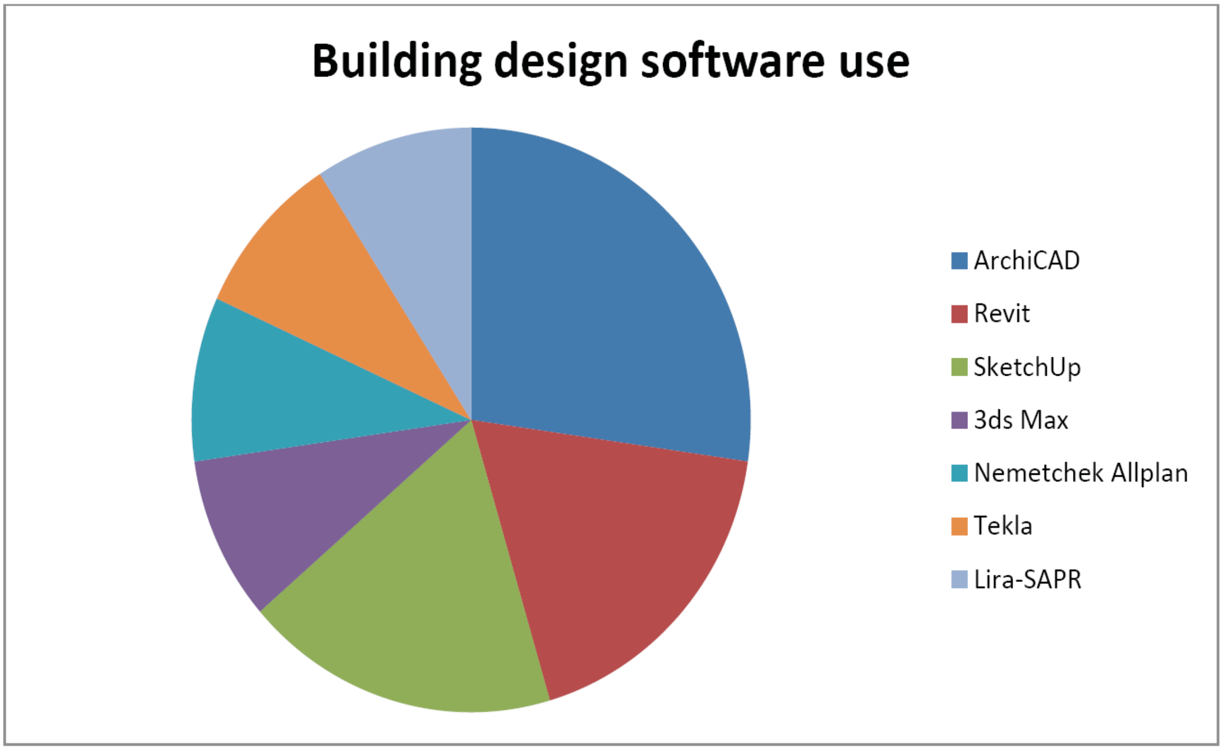

Fig. 2 Comparison of architectural design software use (Smirnov, 2015).

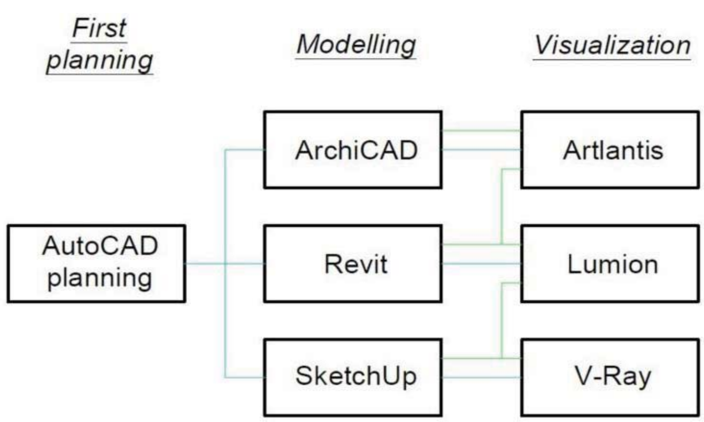

Fig 3 Scheme of software interaction (Smirnov, 2015)

Fig. 4 Tobacco barn prototype

Smirnov (2015) argues that ArchiCAD's concept is for users to create three-dimensional (3D) model buildings using tools that have real similarities such as walls, pillars, doors, and windows. Upon completion, the program will be able to extract various information from the project such as floor plans, façade, sections and so on. The main advantage of ArchiCAD is the interaction between all parts of the project. This technology allows you to work with various individual drawings throughout the project (Smirnov, 2015). Figure 3 shows the interoperability of ArchiCAD with other software, including importing documents from AutoCAD plans, designing or modeling in ArchiCAD, and exporting to Artlantis (Smirnov, 2015).

2.1 BARN STRUCTURE

The standard guidelines recommended by the Brace Institute for the design and construction of dryers are the length to be at least 3 times the width of the cabinet to minimize shading. Also, the optimum tilt angle is a function of the latitude (Ekechukwu and Norton, 1999). In addition, proper spacing between crop is required to ensure adequate levels of air circulation under, above, and around the product. The choice of material depends on its availability and the degree of drying capacity required (Ekechukwu et al., 1999). The tobacco barn prototype takes into account Brace recommendations for developing an acceptable product. The design also accommodates similarities and is an exact replica of the actual barn in all dimensions. If all the linear length scales of one object are a fixed ratio of all the corresponding length scales of the second object, then the two objects are said to be geometrically similar (McDonough, 2009). Two geometrically similar objects are also called dynamically similar if the forces acting on the two objects at the corresponding points are in the same ratio everywhere. Geometrical similarity is needed to account for the dynamic similarity of the design and the airflow system as well (McDonough, 2009). The prototype is a replica of the barn measured at the Zimbabwe Tobacco Research Board Centre at a dimensional ratio of 1: 5. The design of the prototype tobacco barn took into account both the recommendations of the Brace Institute and the geometric and dynamic similarities. Figure 4 is the configuration of the prototype barn.

Komolafe and Waheed (2018) used eco-friendly materials in the area to build a solar dryer. These materials included plywood, corrugated aluminium sheets, copper tubing, angle steel, plexiglass, mild steel, stainless steel, and an axial fan (Komolafe and Waheed, 2018). Barn building material are recycled iron plates, hardened cast iron, flat iron bars, round iron bars, angle steel, and structural steel. Barn dimensions are 2m x 0.8m x 1.2m high on the side facing the sun and 1.5m high on the front door side. Since the height difference between the door side and the side facing the sun is 0.3 meters, the pitch angle of the barn roof must achieve 20.6°, $\tan \theta = (0.3 / 0.8) = 3/8$. The University of Zimbabwe test site is located in Harare and its geographical location is 17° 49` 29" south and 31° 3` 11" east.

The expected tilt angle is 2 degrees greater than 18-degrees south latitude, allowing solar collectors to capture more energy during the Zimbabwean tobacco maturity winter season. Kalogirou (2003) states that collectors are directed directly to the equator, south in the northern hemisphere and north in the southern hemisphere. The optimum tilt angle for the collector corresponds to the latitude of the location with an angle deviation of 10° to 15° depending on the application (Kalogirou, 2018). A suitable barn roof tilt angle is 20.6°.

2.2 TOBACCO BARN FLOOR AND VIEW

Figure 5 shows the barn floor plan and view. There is a 0.3m cubic box oven on the back facing the sun. A 0.2m diameter opening from the oven through the barn wall connects the tobacco barn heat exchanger to the solar heat collector energy system. The 0.2m diameter heat exchanger pipe is divided into two parallel pipes with a diameter of 0.1 m at a distance of 0.4m from the adjacent wall on the furnace side. They run parallel along the barn floor before merging into a 0.2m diameter heat exchanger pipe at a distance of 0.4 meters before reaching the solar chimney on the eastern wall. Solar chimneys and smoke exhaust chimneys are installed side by side in the prototype barn (Madhlopa and Ngwalo, 2009). The barn floor has a floor support consisting of four cylindrical sturdy legs with a diameter of 0.1 meters, located 0.2 meters from each set of adjacent walls. The trolley wheels, which carry a load of 5400 kg, are bolted to the barn floor to support the entire barn structure and make it easier to move as a laboratory equipment.

The front of the prototype is a barn door 2 meters long and 1.5 meters high. It is attached to one end of the barn in a set of three hinges. There is a door lock system on the other side. The barn door handle is mounted near the locking system. The front or door side is always further with respect to the sun so that the barn roof collector can tilt towards the sun. Sauliner (1976), Ekechukwu et al. (1999) designed a multi-stack mixed mode dryer that is loaded and unloaded through a wooden rear access door. The current design allows crops to be loaded and unloaded from the front of the prototype barn, which is 2 meters long and 1.5 meters high.

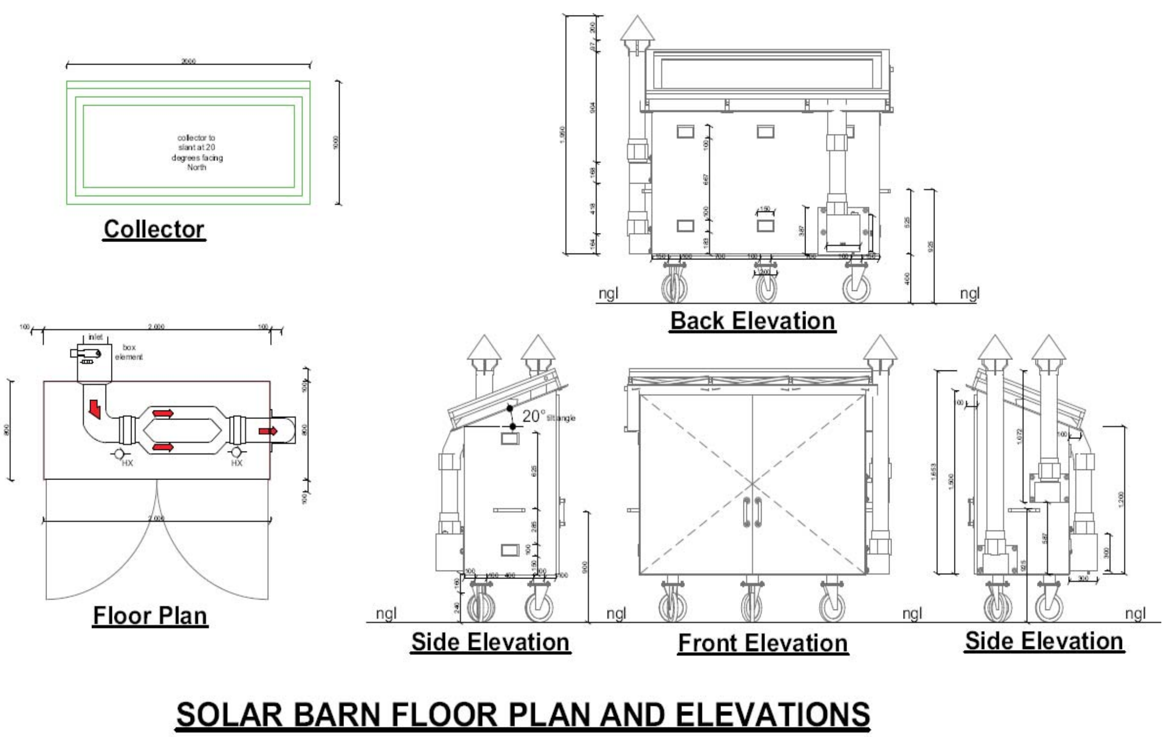

Fig. 5 Floor plan and view of the barn prototype

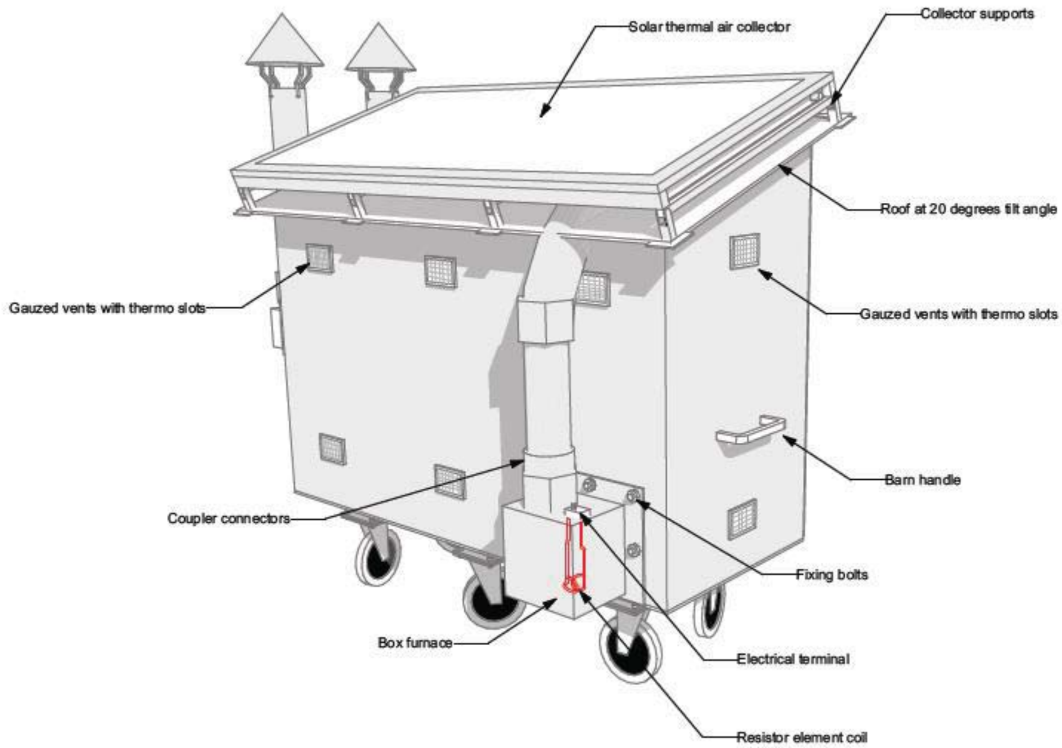

Fig. 6 Barn heating and chimney sides

2.3 TOBACCO BARN PROTOTYPE REAR WALL OR OVEN SIDE

The barn prototype rear wall or oven side is 2 meters long and 1.2 meters high. The height difference between the front and back is 30 centimetres, and the width of the barn is 0.8 meters, so the tilt angle is 20.6 degrees. On the back of the prototype there is an opening that connects the solar collector to the heat exchanger. There is also a set of four fixing screws to facilitate the assembly of the removable 30 x 30 cm oven. A 15 x 10 cm vent with doors will be installed in the selected location and will be located 10 cm above the floor and 10 cm below the roof. There are 6 ventilation slots on the back and 4 more ventilation slots on the other side. These make it possible to carry out certain prescribed experimental procedures such as promote natural convection for the flow of air into and out of the barn. The back or furnace side is always facing the sun so that the solar collector can capture the solar energy and convert it into usable heat energy.

2.4 PROTOTYPE TOBACCO BARN CHIMNEYS SIDE

The chimney side is the width of the tobacco barn. The dimensions are 0.8 meters wide, 1.5 meters high at the front and 1.2 meters high at the rear. The slope from front to back will be smooth. The chimney side is shown in the eastern elevation in Figure 5. The two chimneys are removable, allowing the main barn to be modularized and passed through a limited dimensional entrance. They are attached to the barn with four fixing screws per chimney. Solar chimneys dissipate solar air residues as waste heat. This eliminates the smoke emissions observed in traditional chimneys and reduces environmental pollution. The flue chimney and smoke vents are used to remove flue gas from curing tobacco and expel humidified air.

2.5 BARN HANDLE SIDE

The handle side can be clearly seen in Figure 6 in the foreground. It is also a broadside with the same dimensions as the chimney side. On this side there is a handle to operate the prototype if any movement is required. along with the chimney side, it secures the barn roof with a 20.6° tilt angle.

2.6 BARN ROOF

The barn roof will be 2 meters long and 1.1 meters wide to compensate for overlap and barn pitch. In the sloping state, the roof has a solar collector frame on top at 20.6°to the horizontal. Kalogirou (2004) argues that existing buildings are generally not designed or arranged to accommodate collector arrays, and that structures that support collector arrays often need to be added to existing structures for a fee. The new building can also be easily designed with little or no additional cost to allow the installation and access of collectors. Prototype tobacco roof slope takes into account the aforementioned shortcomings of the past, as well as the current and future design requirements of the building related to the correct roof slope to facilitate the installation of solar panels. The roof has a centrally soldered tobacco rack that runs horizontally along the barn. The rack has got five hooks, each holding and drying a bunch of 20 kilograms of green tobacco leaves. The barn roof also has three slots for temperature measurement, as shown in Figures 4 and 6.

2.7 BARN PAINTING AND INSULATION

Hassan and Khan (2016) states that insulation is used in the construction industry to reduce heat loss or increase from the exterior envelope (exterior walls, windows, roofs, foundations, etc.). Insulation provides thermal comfort inside by keeping the temperature at the right level. To save heating or cooling energy, insulation, also known as delayed or cold insulation, is used in pipes, tanks, boilers, and other industrial equipment. Insulation is usually mineral wool for hot insulation. Hassan et al. (2016) explain that R value refers to the ability of insulation to withstand the flow of heat. The R-value can vary depending on the direction of heat flow through the product, and the higher the insulation of the R-value, the better the results in terms of thermal performance (Hassan et al., 2016). The entire prototype is insulated with heat insulating paint. The interior of the tobacco barn is painted with a reflective, heat-resistant paint of orange or yellow. The exterior is painted grey.

Table 3. R-values for various materials (washington.edu, 2020)

Materials	Thickness (mm)	R-value
Expanded Polystyrene	25.4	5.00
Polyurethane Foam (Formed on site)	25.4	6.25
Polyisocyanurate (Foil Faced)	25.4	7.20

Table 3 shows the R-values for some selected insulation materials. From the table, polyisocyanurates are the ideal choice, but polyurethane foam is the best choice as it can be sprayed inside the barn walls. Paints with a high polyurethane content in their chemical composition are also suitable for stable insulation.

2.8 BARN MODULARITY AND MOBILITY

Modularity stems from product decisions on modules and components. This allows for product diversity through the use of standardized modules for assembling different products (Koren, 2010). The tobacco barn prototype consists of four modules: a barn mainframe, a removable oven, a removable solar chimney, and a removable flue chimney. Standardized modules can be used in different product combinations to create product diversity (Koren, 2010). Prototype can use different ovens by varying the width dimensions to accommodate different auxiliary heat sources for drying systems such as liquefied petroleum gas, electricity (PV or conventional), and biogas. The same applies to solar chimney and flue exhaust chimney, which vary in width and height depending on structural requirements. Modularity allows the prototype mainframe to pass height and width limits without obstacles. Koren (2010) states that the interface between modules is simple and can be mechanical, hydraulic, electrical, informational and control signals. In the tobacco barn prototype, the interface is a mechanical set of four screws per removable component that facilitates the binding of the gadget to the prototype adding a sealant to prevent air leaks from the interface's contact surfaces.

In contrast to the previous static prototype of the barns and dryers in the literature, the current structure has got one of the narrow sides using a pull handle and 4 wheels underneath the structure. This mobile prototype is mobile and easy to use. With the flexibility and minimal effort, you can easily switch to an exhibition for experimental demonstrations. However, its weakness could be the stability of the wheels on slippery ground. This is facilitated by the fact that the 2 chimneys side wheels are fixed with no degree of freedom and only the 2 handle side wheels have 3 three degrees of freedom to go straight, turn left or turn right. Fixed wheels give stability and free wheels ensure mobility. You can also improve statics by adding grooved wedges in the same position on each wheel. The wedge has a rough surface that contacts the ground and acts as a friction lining.

2.9 LIFE CYCLE COSTS AND RECOMMENDATIONS

Kalogirou (2004) cites that no study of the solar system is complete without an economic analysis. Economic analysis of solar energy systems is performed to determine the lowest cost to meet energy needs when considering solar and non-polar alternatives (Kalogirou, 2004). Table 4 provides project cost estimates for the current design and the nomenclature of materials required to build the prototype tobacco shed. To preserve the environment through efficient use of resources and lower costs, 12 m² of sheet metal and other ancillary items valued at USD 996 were salvaged and reused. This reduces the financial requirements of the project from USD 3 214 to USD2 218. Taking advantage of the flexible payment of labour due to its gradual introduction during the five-month manufacturing period from September 2021 to January 2022, the sourcing is done in a similar manner and is expected to benefit from good deals and discounts as well as making the best buys. quality and price advantages by attracting cheaper suppliers, the implementation of the project is achievable. Full project cost recovery is expected when an order with five actual customer installations is placed with the installation cost of $7 200 and the realized profit of $ 1 200 per customer.

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Table 4 bill of materials for tobacco barn construction project implementation

Materials Required	Quantity	Unit Cost US$	Total Cost Estimate US$	Salvaged, Available and Reusable	Financial Savings in US$
1. 3mm-thick cast iron and mild steel metal sheets: Base/Floor = 2m² Front/Door = 3m² Back/Oven = 3m² 2 sides = 3m² Roof = 3m² Total = 14m²	14m²	$60/m²	$840	12m²	$720
2. 2mm-thick angle iron bar	2 bars × 6m	$20/bar	$40	1 bar	$20
3. 3mm-thick and 2cm wide flat iron bar	4 bars × 6m	$20/bar	$80	Nil	$0
4. 2cm square tube	1 tube × 6m	$20/tube	$20	Nil	$0
5. Galvanised piping + chimney system and blower fan	1 system	$400	$400	Nil	$0
6. Furnace material	½m²	$20/m²	$10	Nil	$0
7. Auxiliary resistor element system	1 pair	$15	$15	1 pair	$15
8. Barn and door handles	2 units	$15	$30	Nil	$0
9. Roller wheels	4 wheels	$50/wheel	$200	Nil	$0
10. 12mm bolts, nuts, rivets, locknuts and washers	60	$3	$180	Nil	$0
11. Door lock system	1 unit	$40	$40	Nil	$0
12. Barn exterior paint and varnish	1 unit	$100	$100	Nil	$0
13. Barn interior heat resistant spray paint	17 × 300ml	$100	$100	Nil	$0
14. Transport charges	5 trips	$30	$150	Nil	$0
15. Sealants +lubricants	Assorted	$80	$80	Nil	$0
16. Fire extinguishers, reflectors and 7cm pipes × 10m	Sundry	$150	$150	Nil	$0
17. Sub-sub-total			$2 435		$755
18. welding material @10% of sub-sub-total			$243.5		$75.5
19. sub-total			$2 678.5		$830.5
20. labour @20% of sub-total			$535.7		$166.1
21. Grand total of the project			**3 214.2**		**996.6**

3. RECOMMENDATIONS

A prototype tobacco curing barn was designed. It had advantages of ideal barn roof inclination to accommodate solar collector mounting, easier mobility and also modularity. Also the project life cycle costing (LCC) was conducted and presented. It revealed that the project implementation is feasible and justifiable irrespective of existing constraints. With the all the above mentioned advantages and subject to systematically addressing constraints and shortcomings, the barn design is recommended to be considered for the subsequent stage of fabrication. This will facilitate tobacco curing experiments to take place. Fabrication will be done according to the laid out specifications. Any modifications will be noted and reasons for such cited in writing. System acquisition for the thermal air collector, air blower fan and thermal equipment will occur in tandem with barn construction.

A prototype of a tobacco curing barn was designed. It has the advantage of an ideal roof slope for mounting a solar collector, is easier to move and is also modular. In addition, Project Life Cycle Costs (LCCs) were conducted and presented. It shows that the implementation of the project is feasible and justifiable regardless of the existing limitations. With all the advantages mentioned above and able to systematically address the limitations and shortcomings, it is recommended to consider the design of the barn for the next stage of construction. This will make it easier to perform tobacco healing experiences. Manufacturing will be carried out according to established specifications. Any modification will be noted and the reasons given in writing. The acquisition of the air collector system, the blower and the thermal unit will be done in parallel with the construction of the barn.

4. CONCLUSION

The design of the tobacco dryer prototype was completed in August 2020 as planned. The design process takes into account the nature of the crop to be treated, the geographical location of the project and the resources available locally. The potential limitations of barn immobility were addressed through portability and modularity, two key elements of the design. The construction of the barn is recommended as the next step in the research. Funding for the manufacture of prototypes, the acquisition of collectors, the purchase of electrical equipment and accessories, as well as the assembly and subsequent testing of the system in the final phase of the project are underway from September 2021 to April 2022.

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