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Conservation of Agricultural Products in Sub-Saharan Zone by Ecological Off-grid Cold Room, Case of Senegal

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Abstract

In this article, we have studied and dimensioned a solar cold room for the preservation of potatoes in sub-Saharan areas. The conservation of post-harvest agricultural products is a major issue in this part of Africa, hence the need to focus our research on off-grid refrigeration installations. In this work, we focused on the use of local materials such as agricultural residues and terracotta for the construction of solar cold rooms. This cold room manufactured in this way has an advantage from an economic point of view because it is less expensive to implement. Its implementation does not require too much qualified labor, which also contributes to saving money for our farmers. The cold room presented in this way is of paramount importance from an ecological point of view, as its operation has no impact on the environment. The proposed solution involves the design and implementation of an off-grid cold room powered by ecological sources, such as solar energy. This system aims to provide reliable and sustainable storage for perishable goods, thereby extending their shelf life and reducing losses. Key considerations include adapting the cold room design to local environmental conditions, integrating renewable energy sources for uninterrupted operation, and optimizing cooling technologies suited for the Sub-Saharan climate. Through a case study focused on Senegal, this research evaluates the feasibility and effectiveness of the ecological off-grid cold room in preserving agricultural products. It examines technical aspects such as temperature control, humidity regulation, and energy efficiency, as well as economic factors including cost-effectiveness and scalability. However, alongside this catastrophic humanitarian record, the Food and Agriculture Organization of the United Nations (FAO) notes that around a third of the food produced each year in the world for human consumption is lost or wasted—; that is, i.e. 1.3 billion tonnestons out of the 4 billion foods produced globally. Alone, saving a quarter of the food lost or wasted globally would be enough to feed the 820 million hungry people in the world.

Keywords: Cold room, Typha, terracotta, green energy

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INTRODUCTION

The earth is today populated by more than seven billion human beings (7,713,720,150), nearly a ninth of whom suffer from hunger. The majority of these 821 million people affected live in a developing country. The security of the food supply for the world population therefore represents a major challenge. This is further complicated by climate change, conflicts that are becoming permanent, and demographic growth [1].

Food losses in sub-Saharan Africa amount to $4 billion per year. Looking at Africa as a whole, we see that the vast majority of food losses occur between harvest and point of sale, as food wastage by consumers after purchase is very low. This means that even before the food reaches consumers, significant losses are recorded, both in quantity and quality [2]. Reducing food losses and waste is essential to mitigate climate change, reduce greenhouse gas emissions, and use our natural resources more efficiently. Faced with this unprecedented problem, what could be the unique solution to minimize these losses of food? agricultural products and could also be less expensive and accessible to local producers who are isolated from the electricity network? Thus, to make a contribution to this problem, the theme "design of a positive solar photovoltaic cold room using local materials (the clay and Typha) for the conservation of agricultural products (case of potatoes)" was submitted to us. The objective of our work is to set up a cold room better appreciated by local producers while respecting the environment to contribute to the reduction of food loss.

The causes of deterioration of perishable products are as follows:

- In the majority of cases, food spoilage is caused by complex chemical changes that occur within food products after harvesting or slaughter.
- These changes are caused either: by internal agents or by agents external to the product.
- Internal agents are the natural enzymes that exist in all organic materials. External agents are microorganisms that grow in or on the surface of food products. The main microorganisms that act on food products are as follows: bacteria, yeasts, and molds.
- Although each of these agents can destroy food products, most of the time natural enzymes and microorganisms combine efforts in destroying food. To preserve the products, it will be necessary to stop or at least reduce the activity of each of these agents [3].
- Fruits and vegetables, on the other hand, are as alive after harvest and distribution as they were when they were growing. The fact that they are alive requires different methods of conservation [4].

COLD PRESERVATION TECHNIQUES

Cold is a food preservation technique that stops or slows down cellular activity, enzymatic reactions, and the development of microorganisms. It thus extends the life of fresh, plant, and animal products by limiting their spoilage. Cold does not destroy toxins or microorganisms that may be contained in food. The majority of microorganisms present can therefore resume their activity upon return to a favorable temperature. There are three processes that use this technique: refrigeration, freezing, and fast freezing [5].

Refrigeration

Refrigeration corresponds to preservation by positive cold for a limited period since refrigerated products benefit from a use-by date. Generally, the refrigeration temperature is around 0°C to 4°C. There are three fundamental rules to respect when applying cold:

1. Refrigeration should be applied to healthy foods initially.
2. Cooling should be done as soon as possible.
3. Refrigeration must be continuous throughout the distribution chain: the cold chain must not be interrupted [5].

The storage conditions for these products are given by food groups according to their sensitivity to cold.

Freezing

Freezing maintains the core temperature of the food down to -18°C. This process causes the water contained in food to crystallize into ice. We then witness a significant reduction in available water, or a drop in water activity. Freezing allows food to be preserved for a longer period than refrigeration [5].

Fast Freezing

It is a technique that allows food to be exposed to temperatures lower than freezing. This involves sudden cooling (–35°C/–196°C) then freezing at –15°C/–18°C. This technique allows the formation of numerous small ice crystals that do not damage the food [5].

DIFFERENT METHODS OF PRESERVING POTATOES

Storage of Small Quantities in the Short and Medium Term in the Fields

Depending on the quantities of tubers harvested, the desired shelf life, and economic possibilities, several strategies are available to potato producers. This is why some producers use traditional methods to keep their crops in the fields for a few days before they are sent to storage facilities (Figure 1).

Medium-term Storage of Large Quantities

At these two structures, the boxes used contain a maximum of 25 kg of potato tubers, and the storage period can range from 3 months in the first case to 5 months for the second (Figure 2).

Long-term Storage of Large Quantities

In the latter case, it is a refrigerated structure or cold room, and the “pallet boxes” on the right each contain between 600 kg and 1000 kg. The storage period exceeds seven (7) months, and the temperature is between 3°C and 5°C (Figure 3).

STUDY AND SIZING OF THE SOLAR COLD ROOM

For a period of eight months of potato storage, we have adapted an internal temperature of 6°C and a relative humidity of 90% for our cold room. The storage capacity of our cold room is estimated at 500 kg with a daily entry of 100 kg of potatoes. The operating time of the system is set at 14 h, and the location has the following weather conditions:

- Maximum outdoor temperature 28°C
- Humidity 85%.

Figure 1. Potato storage, (a) a few days in the field; (b) 1 to 2 months in the field.

Figure 2. Potato storage, (a) an airy warehouse; (b) an underground warehouse (cellar).

Figure 3. Long-term storage of potatoes.

As insulation, we used a local material, which is Typha, and a terracotta envelope. Figure 4 shows some characteristics of certain insulation used in the construction of cold rooms. In the heat balance, wall insulation is of high relative importance. Case of long-term storage chambers. Orders of magnitude to be achieved for the thermal transmittance coefficients are as follows:

- 0.350 to 0.263 W/m²K in refrigerated storage,
- 0.263 to 0.162 W/m²K in frozen storage.

For hygienic reasons, condensation should not form. This is why it is necessary to provide sufficient insulation and correctly placed. Finally, the optimum annual gains following better insulation will be achieved by taking into account costs related to consumption (decrease), investment in insulation (increase), and the refrigeration machine (decrease) [6]. Thus, we present in Figure 4 the order of magnitude of the prices of insulators according to their conductivity (Figure 4). The constitution of the walls of the cold room is thus represented (Figure 5).

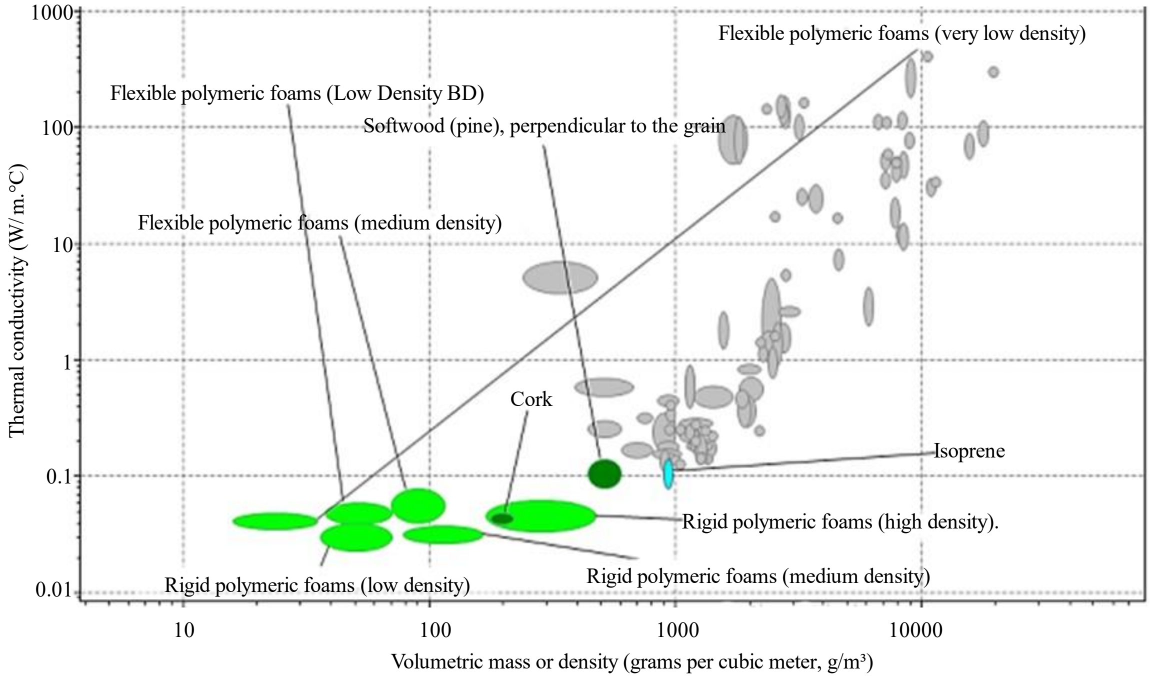

Figure 4. Thermal conductivity of some insulators as a function of density.

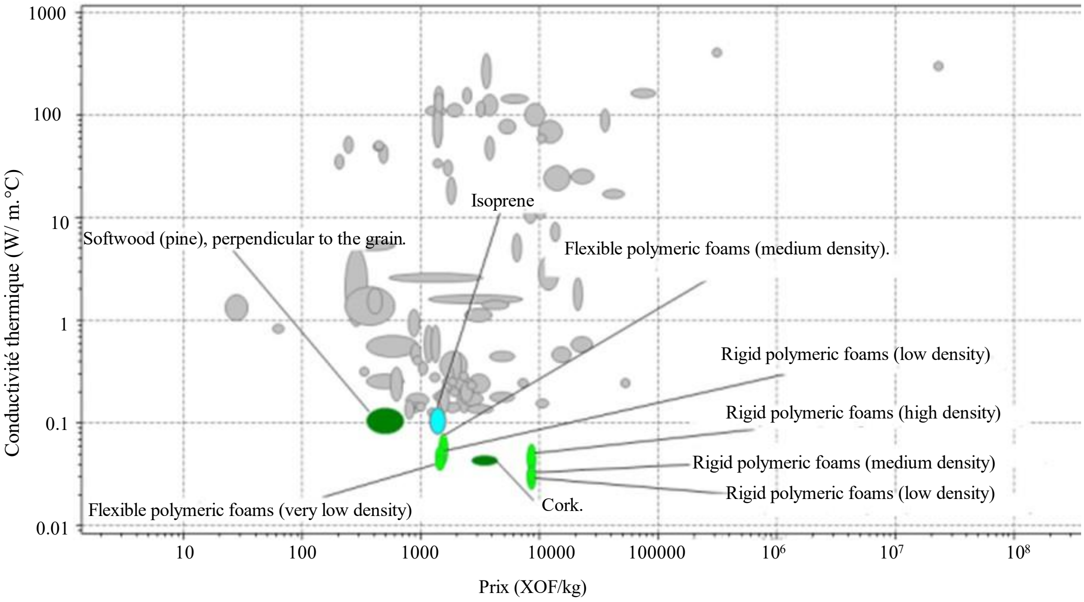

Figure 5. Price of insulators based on their conductivity.

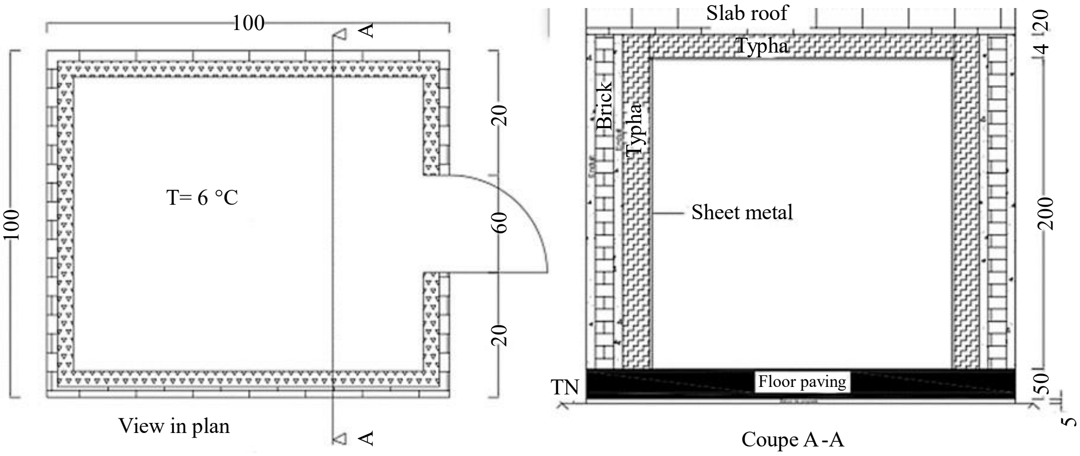

Figure 6. Construction of the walls of the cold room.

In order to know the cooling capacity of the machine, we will make the thermal balance of the loads to be evacuated to meet the cooling needs (Figure 6). The equations used to determine the cold balance are presented in the following paragraph [7].

CALCULATION OF REFRIGERATION LOADS

The purpose of calculating the thermal loads of a cold room is to determine the cooling capacity of the equipment to be used for the refrigeration of this room in accordance with the specifications established above.

Products Cooling Heat (Qr)

$$Q_r = m \times c \times \Delta T$$

AN:

$$Q_r = \frac{500\ kg}{6} \times 3{,}85\ kJ/kg\ \times (25 - 6)$$

$$Q_r = 6095{,}83\ kJ$$

m: mass of the products to be cooled in 24 hours
C: Specific heat of the product
ΔT: difference between the inlet temperature of the product and its final temperature; If C is not known, as a first approximation, we can use the following relation:

$$c = \frac{4{,}186a + 1{,}674b}{100}$$

With
a: water content of the product
b: dry matter content of the product
or take
c= 3 kJ/kg. °C for meat
and
c= 3.85 kJ/kg. °C for fruit and vegetables.

Heat from Packaging

As the products are sometimes packaged, it is necessary to take into account the amount of heat to be removed from these packaging, we will have:

$$Q_{emb} = m_e \times c_e \times \Delta T$$

$$Q_{emb} = \frac{50\ kg}{6} \times 2{,}72\ \mathrm{kJ/kg.°C} \times 19\ °C$$

$$Q_{emb} = 430{,}66\ kJ$$

With
me: mass of packaging
Ce: Specific heat of packaging

As packaging is generally made of dry matter, we will take:

Ce= 2.72 kJ/kg. °C.

As for me, it is estimated that:
me= 5%.m: polyethylene films, pallet storage;
me= 10%.m: in bulk storage crate;
me= 15%.m: pallets + wooden crate.

Breathing Heat of Fruits and Vegetables

In addition, we know that fruit and vegetables continue to live at temperatures above 0°C, resulting in the release of heat, water vapor and CO_2; This amount of heat can also be estimated by extrapolation, from the following two limits:

At T= 25°C, Qd25 = 4000 kcal/24h/ton

At T= 0°C, Qd0 = 200 kcal/24h/ton

For these same fruits and vegetables, there are sometimes ripening accidents due to the release of CO_2 and ethylene, hence the need to renew the air in the room; the air taken from outside is cooled and dried (or humidified) in order to have the same characteristics as the air in the room; This operation requires an amount of heat expressed by:

$$Q_{ar} = \dot{m}_{ar} \times \Delta h$$

$$\dot{m}_{ar} = \frac{\dot{m}_v}{v}$$

$$\dot{m}_{ar} = \frac{2\ m^3}{0{,}907\ m^3/kgas}$$

$$\dot{m}_{ar} = 2{,}208\ kgas$$

$$Q_{ar} = 2{,}208\ kgas \times (107{,}2 - 19{,}1) kJ.kg^{-1}as^{-1}$$

$$\mathrm{Q_{ar}} = 194{,}52\ \mathrm{kJ}$$

With
$\dot{m}_{ar}$: Mass flow rate of the renewal air,
Δh: enthalpy difference between outdoor and indoor air,
$\dot{m}_V$: Volume Flow = 1 times the volume of the cold room per 24 h,
v : mass volume of air (obtained from the humid air diagrams).

Calorific Input Through the Walls

For the calculation of the heat balance of refrigerated rooms, a distinction is made between two types:

- Installations at more than 0°C: an economic loss of 8 W/m² is imposed,
- Installations below 0°C: recommended economic loss of 6 W/m² (because the lower the temperature, the more expensive it is to produce refrigeration) [8].

For these installations, good floor insulation is often necessary. In order to obtain the previous losses, the following convection coefficients are adopted:

- *7 kcal/h/m² °C:* crawl space (void between the floor and the floor),
- *15 kcal/h/m² °C:* inside cold room,
- *20 kcal/h/m² °C:* outdoor air (depends on weather parameters),
- *25 kcal/h/m² °C:* tunnel interior. This balance therefore makes it possible to obtain the heat losses through the walls (Qp), we have:

$$Q_p = \sum p \times K_P \times S_p \times \Delta T \times 86{,}4 \ \ (kJ)$$

$$K_p = \frac{1}{\frac{1}{h_e} + \sum \frac{e_p}{\lambda_p} + \frac{1}{h_i}}$$

In this work we have a wall that is made up of five layers of different materials.

- Cement with a thickness ec = 20 mm on both sides;
- Fired clay with a thickness ea = 100 mm;
- Typha with a thickness eisola = 108 mm;
- Plastic with a thickness epl = 0.06 cm and
- Zinc sheet with a thickness etol = 0.06 cm.

In total, a wall with a thickness of em = 248 mm.

$$Q_p = \sum p \times K_P \times S_p \times \Delta T \times 86{,}4 \ \ (kJ)$$

$$K_p = \frac{1}{\frac{1}{h_e} + \sum \frac{e_p}{\lambda_p} + \frac{1}{h_i}}$$

Wall transmission surface
This transmission concerns:
The ceiling, the four walls, and the floor (hypothetically there is no input).

The transmission surface is the geometric mean of the inner and outer surfaces. The geometric shape of the chamber is a square, so all the walls have the same measurements [9].

$$S_p = \sqrt{S_{int} \times S_{ext}}$$

$$S_{int} = 5 \times 1\ m^2 \times 1\ m^2$$

$$S_{int} = 5\ m^2$$

$$S_{ext} = 5 \times 1{,}248\ m^2 \times 1{,}248\ m^2$$

$$S_{int} = 7{,}78\ m^2$$

$$S_p = \sqrt{7{,}78\ \times 5}$$

$$S_p = 6{,}23\ m^2$$

$$Q_p = 0{,}35\ \times 6{,}23 \times (33 - 6) \times 86{,}4\ \ (kJ)$$

$$Q_p = 5960{,}30\ kJ$$

With
he: Coefficient of heat transfer by external convection (W m-2 °C-1),
hi: Heat transfer coefficient by internal convection (W m-2 °C-1),
ep: wall thickness of the material in m,
λp: thermal conductivity of the material (W/m. K)
Kp: overall exchange coefficient W/m² °C,
Sp: wall area (m²),
ΔT: temperature difference between the inside and outside of the cold room.

Heat Input Due to Air Renewal

The amount of heat due to air renewal is given by the relationship:

$$Q_{Ra} = N_{Ra} \times \frac{V}{\nu_e} \times \Delta h$$

$N_{Ra} = \frac{70}{V^{0,5}}$, for positive chambers;

$N_{Ra} = \frac{80}{V^{0,5}}$, for negative rooms.

$$Q_{Ra} = 77 \times \frac{2}{0{,}907} \times 88{,}1$$

$$Q_{Ra} = 14958{,}54\ kJ$$

With:
NRa: Air exchange rate taken from the table in the appendix,
V: Interior volume of the cold room,
ve: Mass volume of the air that will be sent into the room,
Δh: Enthalpy difference between the air sent into the room and the air in the room.

Calorific Inputs Due to the Work of Fan Motors

During their operation, electric motors give off a certain amount of heat, which can be estimated from the following relationship:

$$Q_v = \sum i \times P_i \times t$$

Pi: unit power of the engines in kW
t: operating time in seconds
In this study, the heat input due to the work of the fan motors is zero.

Calorific Inputs Due to Handling Machines

The amount of heat released by handling machines is equal to:

$$Q_m = 0{,}6 \times P \times t$$

P: power of the machines in kW,
0.6×P: power of the machines released in thermal form in kW,
t: residence time of the machines in seconds.
We don't have handling machines in our refrigerator which implies Qm = 0

Heat Input from Lighting

Generally speaking, it can be estimated that all lighting fixtures convert their energy into heat. For incandescent lamps, the amount of heat released by the lighting will be estimated by the relationship:

$$Q_e = P \times t$$

P: total power of the lamps,
t: lighting time in seconds.
Inside the room we do not have incandescent lamps so the heat input due to the lighting is negligible.

Heat Intake Due to Occupants

The metabolism of the human body causes a release of heat, the intensity of which depends on the degree of activity of the body. The amount of heat released will be given by the relationship:

$$Q_p = N \times q_m \times t$$

With:
N: number of people,
qm: heat of metabolism,
t: residence time
The heat input due to the occupants is considered zero.

Evaluation of the Overall Balance Sheet

The general balance sheet is drawn up taking into account the unquantifiable inputs as follows:

$$Q_t = \sum_i Q_i + \frac{(10\ \text{à}\ 20) \times \sum_i Q_i}{100}$$

$$Q_i = Q_r + Q_{emb} + Q_{ar} + Q_p + Q_{Ra} + Q_e + Q_m + Q_{pers}$$

Cooling Capacity

The refrigeration balance is carried out under the most unfavorable conditions for the worst month, and the time (t) for the operation of the installation is then chosen, taking into account the quantity of heat to be absorbed and the operating conditions of the warehouse. The total power of the refrigeration unit or refrigerants installed in a cold room is equal to its maximum heat balance divided by the daily operating time of the machine:

$$\Phi_0 = \frac{Q_t}{t}$$

$$\Phi_0 = \frac{8{,}45\ kWh}{16\, h}$$

$$\Phi_0 = 0{,}528\, kW$$

t is set a priori at: 14 h $\leq t \leq$ 16 h for commercial machines and 18 h $\leq t \leq$ 20 h for industrial machines. The compressor will run 16 hours a day.

After calculating the heat balance, we have drawn up Table 1. After plotting the refrigeration cycle on the R134a diagram, we listed the thermodynamic characteristics of the fluid at the different points in the Table 2. From the thermodynamic characteristics of the fluid, we have calculated the characteristics of the refrigeration machine, and we have drawn up the following Table 3.

The efficiency of the installation calculated in this way may be different from the actual operating efficiency because it includes irreversibility and the resulting heat losses. After the thermal balance and the size of the refrigeration system, we had to determine the electrical power required to operate this refrigeration installation. We will first size the generator to be installed to provide electrical energy in sufficient quantity and quality.

Table 1. Refrigeration balance of the cold room.

S.N.	Description	Units
1	Cooling heat of products	7315 kJ
2	Heat from packaging	317 kJ
3	Respiration heat of fruits and vegetables	134 kJ
4	Heat input through the walls	3677 kJ
5	Heat gain due to air renewall	868 kJ
6	Contributions due to the work of fan motors	0
7	Heat input due to handling machines	0
8	Heat input due to lighting	9 kJ
9	Heat input due to occupants	0
10	Safety factor (10%)	1232 kJ
11	Daily load	3.76 kWh
12	Cooling capacity	0.269 kW

Table 2. Fluid characteristics at different points in the cycle.

Points	Temperatures (°C)	Pressures (Bar)	Enthalpies (kJ/kg)	Mass volumes (m^3/kg)
1	6,000	3,00	402,3	0,06782
2	56,36	12,51	432,32	0,01696
3	48,00	12,51	421,71	0,01591
4	48,00	12,51	268,65	-
5	43,00	12,51	262,17	-
6	1,000	3,00	262,17	-
7	1,000	3,00	392,00	-

Table 3. Characteristics of the refrigeration machine.

Designations	Results	Units
Mass flow of refrigerant	0.00186	kg/s
Aspirated volume flow	0.000124	m^3/s
Compression ratio	3.66	No unit
Volumetric efficiency	0.82	No unit
Swept volume flow	0.000151	m^3/s
Theoretical compressor power	0.049	kW
Power to be supplied to the compressor shaft	0.066	kW
Useful power of the electric motor	0.069	kW
Power absorbed by the engine	0.077	kW
Condenser power	0.347	kW
Refrigeration performance coefficient	3.45	No unit
Carnot coefficient of performance	6.73	No unit
Installation performance	51	No unit

Recognizing the importance of renewable energy for sustainable development, we chose to power the cold room with the solar photovoltaic system [10]. In Senegal, we have a lot of sunshine throughout the territory with maximums in the northern part. The sunshine is fairly regular except in August. The average monthly values observed vary from 5 to 6 kWh/m^2 per day, and the average duration of sunshine is 8 hours per day. This state of affairs leads to a significant potential for the development of solar energy in Senegal at competitive costs. And finally, the size of the photovoltaic system allowed us to draw up the following Table 4.

Table 4. Characteristics of the photovoltaic installation.

Designations	**Quantities**
Total number of solar panels (250 Wc, 24 V)	2
Number of panels in series	1
Number of panels in parallel	2
Panel installation surface	4
Storage batteries (110 Ah, 12 V)	2
Series storage batteries	1
Parallel storage batteries	2
Charger regulator SOLELEC 30 A/24 V	1
Regulator charger to PV fields (distance 10 m) copper cable of 6 mm^2	-
Charger regulator to batteries (distance 10 m) copper cable of 6 mm^2	-
Fuse for general protection type PV of caliber	1

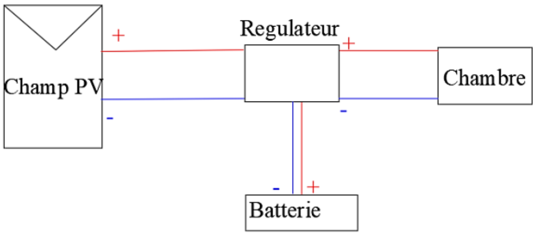

Figure 6. Synoptic of the photovoltaic installation.

Figure 7. Prototype of the cold room.

Table 5. Price of the photovoltaic installation.

Designation	**Quantity**	**Unit price (F CFA)**	**Total price (F CFA)**
Solar panel 250 W; 24 V	2	100,000	200,000
Solar battery GEL 110 Ah/12 V	2	70,000	140,000
Regulator SOLELEC 30 A/24 V	1	50,000	50,000
Others (cables, supports, fixing, labor)	-	10% total material	39,000
Total			429,500

The overview of the installation is shown in Figure 6. In this study, we opted for a 24 V DC voltage power supply for our cold room with a battery storage system with a suitable charge controller to maximize the life of our batteries. So, the proposed cold room is as follows (Figure 7).

This prototype of a cold room designed at a lower cost will guarantee the storage of our farmers' crops and in turn boost agricultural production (Table 5). Thus, we have drawn up the price table for the photovoltaic solar installation to give you an idea of the cost of the installation [11].

The cost of installation can be further reduced because the implementation of such a system does not require skilled labor. However, the cost of the photovoltaic installation varies from country to country and may be less expensive in some countries than others.

CONCLUSION

This work allowed us to design and manufacture an ecological and sustainable solar cold room to contribute to the reduction of post-harvest losses and waste in the sub-Saharan region. The use of local materials for the construction of cold rooms greatly contributes to improving the living conditions of farmers. Pairing with off-grid renewable energy sources is an alternative to boost the agricultural sector. However, in a future article we will do a comparative financial study between containerized solar cold rooms and solar cold rooms built using local materials. The ecological off-grid cold room offers a sustainable solution by harnessing renewable energy sources, primarily solar power, to provide consistent and reliable cooling for perishable goods. This approach not only extends the shelf life of agricultural products but also reduces losses, thereby improving food availability and affordability for local communities. Additionally, by reducing dependency on fossil fuels and conventional grid electricity, the system contributes to environmental conservation and resilience against energy price volatility.

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