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Research Paper

Study and Sizing of the Electrical Energy Components of a Photovoltaic Solar Cold Room Dedicated to the Preservation of Agri-Food Products

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ABSTRACT

The aim of this work is to carry out a study on the design and theoretical analysis of a cold room intended for the preservation of agricultural products, designed with a technical room for the installation of electrical equipment and the refrigeration unit, and using the refrigerant R404A. The refrigeration space studied, powered by photovoltaic solar panels installed above the roof, and features two ceiling-type evaporator units for air flow diffusion. The cold store, including the equipment room, has external dimensions of 5.00 × 3.00 × 2.60 m^3 (L × W × H). Thermodynamic modelling was carried out, not only to determine the optimum thickness of the thermal insulation of the wall, but also to establish the heat balance, the purpose of which is to determine the cooling capacity of the chiller required to ensure the correct operation of the installation. Dynamic modeling of the refrigeration circuit is also carried out to determine the electrical energy required to operate the compressor. The energy requirements were sized to determine the appropriate configuration for the solar photovoltaic array. The results of this study showed that heat loss increases with wall thickness, so the choice of insulation thickness would depend on the specific requirements of the products to be preserved. On the basis of onion preservation, the optimum power for the motor-compressor unit was calculated at 1104.4 Watts, or 1.5 horsepower, to ensure reliable operation of the refrigeration machine in the installation area.

Keywords: cold room, refrigeration unit, photovoltaic solar system, refrigerant, cooling capacity

INTRODUCTION

The post-harvest preservation of agricultural produce is a major challenge in developing countries, particularly in sub-Saharan Africa. Every year, large quantities of perishable foodstuffs are lost due to the absence of suitable preservation technologies or the lack of accessible refrigeration infrastructures. According to the Food and Agriculture Organization of the United Nations [1], between 30 % and 50 % of perishable foodstuffs are lost between harvest and consumption, a phenomenon that is even more pronounced in tropical climates. In such a context, the development of high-performance, energy-efficient and environmentally-friendly preservation solutions adapted to the local context is essential.

In the context of cold production by mechanical vapour compression, solar-powered cold rooms, presented by the authors KABORE et al [2], play an essential role in the preservation of vaccines, pharmaceutical products, meat and above all fruit and vegetables, by maintaining low temperatures to extend their shelf life. These cold rooms operate with R12, R22, R134a refrigerants, etc. However, their operation requires a reliable power source, which can be a problem in regions where access to electricity is limited or unstable. The integration of photovoltaic systems to power these installations offers a sustainable and autonomous solution, particularly suited to sunny areas.

In a hot, dry climate zone like Burkina Faso, where solar irradiation ranges from 3 $kWh.m^{-2}.jr^{-1}$ to 7.5 $kWh.m^{-2}.jr^{-1}$ [3], and more specifically 5.1 $kWh.m^{-2}.jr^{-1}$ in Ouagadougou [4], using this radiant energy to power the photovoltaic field of our cold store will not only be beneficial for the environment (no CO_2 emissions), but will also make the cold store energy self-sufficient.

In this article, we focus on the thermodynamic and dynamic modeling and dimensioning of a photovoltaic solar cold store. The guiding framework for the sizing is the conceptual study of a cold store of around 40 m^3 designed to preserve onions at a temperature of between 0 ºC and 4 ºC, and whose refrigeration unit runs on R404A.

The overall heat exchange coefficient through the walls of the solar photovoltaic cold store is evaluated at 0.3 W/ (m^2.K) for a thickness of 100 cm. In terms of refrigeration machine performance (COP), it is evaluated at 3.06 for optimal onion storage operation. COP is a key indicator of the efficiency of a refrigeration system. A high COP means that the system produces more cold for a given amount of energy. It is equal to 194.76 MJ in our case.

MATERIALS & METHODS

MATERIALS

The solar photovoltaic cold room model presented by KABORE et al [5] and shown in Figure 1, has a volume of around 40 m^3, with sandwich panel insulation, made up from outside to inside as follows: galvanized steel - polystyrene - galvanized steel (λ_steel = 50 W/ (m.K), λ_polystyrene = 0.03 W/(m.K)). This solar cold room is designed to preserve leguminous products such as onions during the production period. The target storage temperature is 0 °C to 4 °C, with a relative humidity of over 70 %.

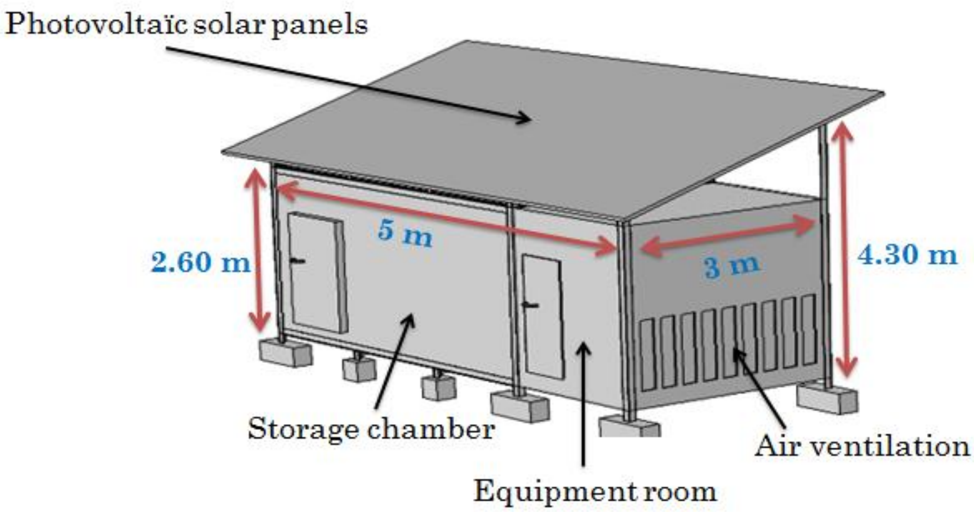

Figure 1: Bioclimatic model of the solar cold store

METHODS

Working assumptions

The operating assumptions for the refrigeration cycle using the zeotropic blend fluid R404A (52 % R143a, 44 % R125, 4 % R134a) are as follows:

- Evaporating temperature to = -15 °C;
- Condensing temperature Tk = 45 °C;
- Compression is assumed to be isentropic;
- Isentropic efficiency: 75%;
- Subcooling: 5 °C;
- Superheating: 5 °C;
- Pressure losses are negligible throughout the refrigerant circuit.

Modeling

Thermodynamic modelling of this cold store is carried out by establishing a heat balance, the aim of which is to determine the cooling capacity (P_f) of the refrigeration unit required to ensure correct operation of the installation. The heat balance consists of taking stock of the quantities of heat to be extracted from inside the cold room to maintain the temperature of the foodstuffs at a constant level. These heat quantities are calculated over 24 h and are given by the following relationships [6], [7], [8], [9], [10], [11], [12], [13], [14]. The cooling capacity is determined by the following expression:

$$P_f = \frac{Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7 + Q_8 + Q_9}{t} \quad (1)$$

With,
Q1: Heat input through walls
Q2: Heat input through air exchange
Q3: Heat input through food introduction
Q4: Heat input through product respiration
Q5: Heat input through product packaging
Q6: Heat input through people
Q7: Heat input through lighting
Q8: Heat input through evaporator unit fan motors
Q9: Heat input through defrosting

Dynamic modeling of the refrigeration circuit determines the electrical energy required to operate the compressor at maximum thermal load. It is established for a specific reference thermodynamic cycle [7]. Based on the choice of circulating refrigerant and the cooling capacity, we can plot the theoretical refrigeration cycle. The Mollier diagram, obtained from CoolPack, a collection of simulation programs, in Figure 2 for the R404A fluid enables us to determine the thermodynamic characteristics of the various points in the refrigeration cycle, and consequently to assess the theoretical performance of the refrigeration system to be installed.

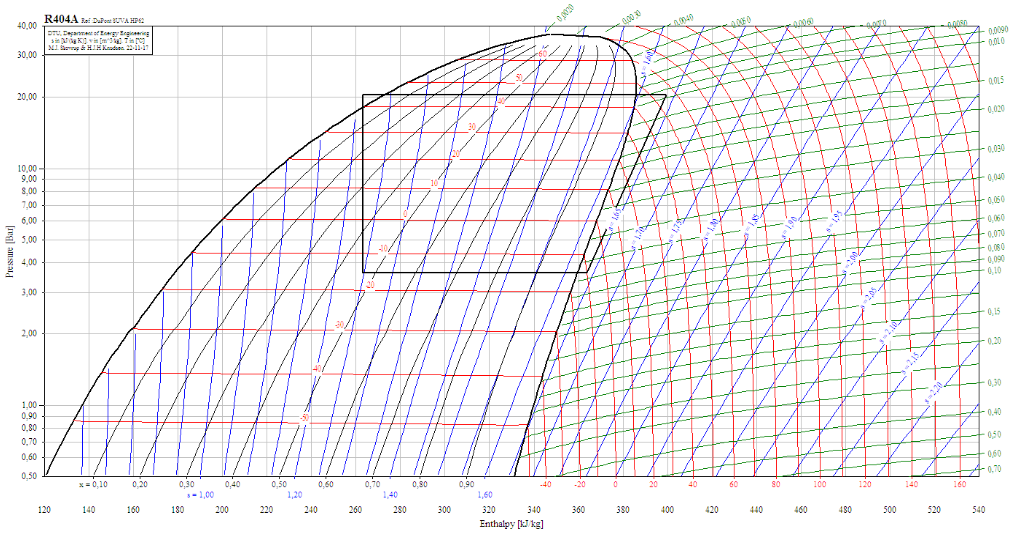

Figure 2: Mollier diagram for R404A

Several authors have proposed models for calculating refrigerant circuit parameters. Here, we propose the equation model provided by TECHNIQUE DU FROID [15], based on the use of the enthalpy diagram. Figure 3 shows the main enthalpy and absolute pressure diagrams of a heat exchanger in an orthonormal frame of reference.

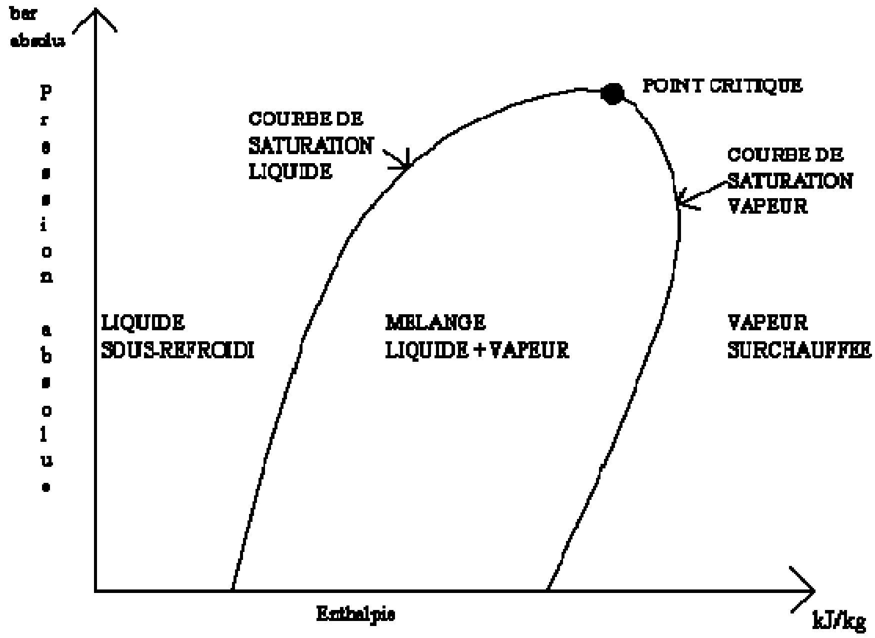

Figure 3: Enthalpy diagram

The various equations can be calculated either manually or using a computational tool. This can be done as follows:

Mass flow rate of circulating refrigerant (qm)

$$qm = \frac{P_f}{\Delta ho} \quad (2)$$

Where
qm ($kg.\ s^{-1}$)
P_f is cooling capacity (kW)
Δho is enthalpy variation between evaporator inlet and outlet ($kJ.kg^{-1}$)

Power absorbed by electric motor (Pa)

$$Pa = \frac{Pu}{hel} \quad (3)$$

Where
Pa (kW)
hel is electrical efficiency

Cooling coefficient of performance (Cf)

$$Cf = \frac{Pf}{Pa} \quad (4)$$

Once energy requirements such as thermal loads, which include internal and external heat inputs, are known, the solar photovoltaic system can be sized. Sizing the solar photovoltaic cold store involved determining the three main quantities: the size of the field of photovoltaic modules producing electrical energy, the electronic components such as the inverters converting the energy coming from the PV modules into alternating current energy, and the energy storage capacity. To this end, a sizing algorithm written on Matlab R2015a has been developed to calculate the energy requirements of the cooling system and determine the components of the solar PV system, and is shown in Figure 4 below.

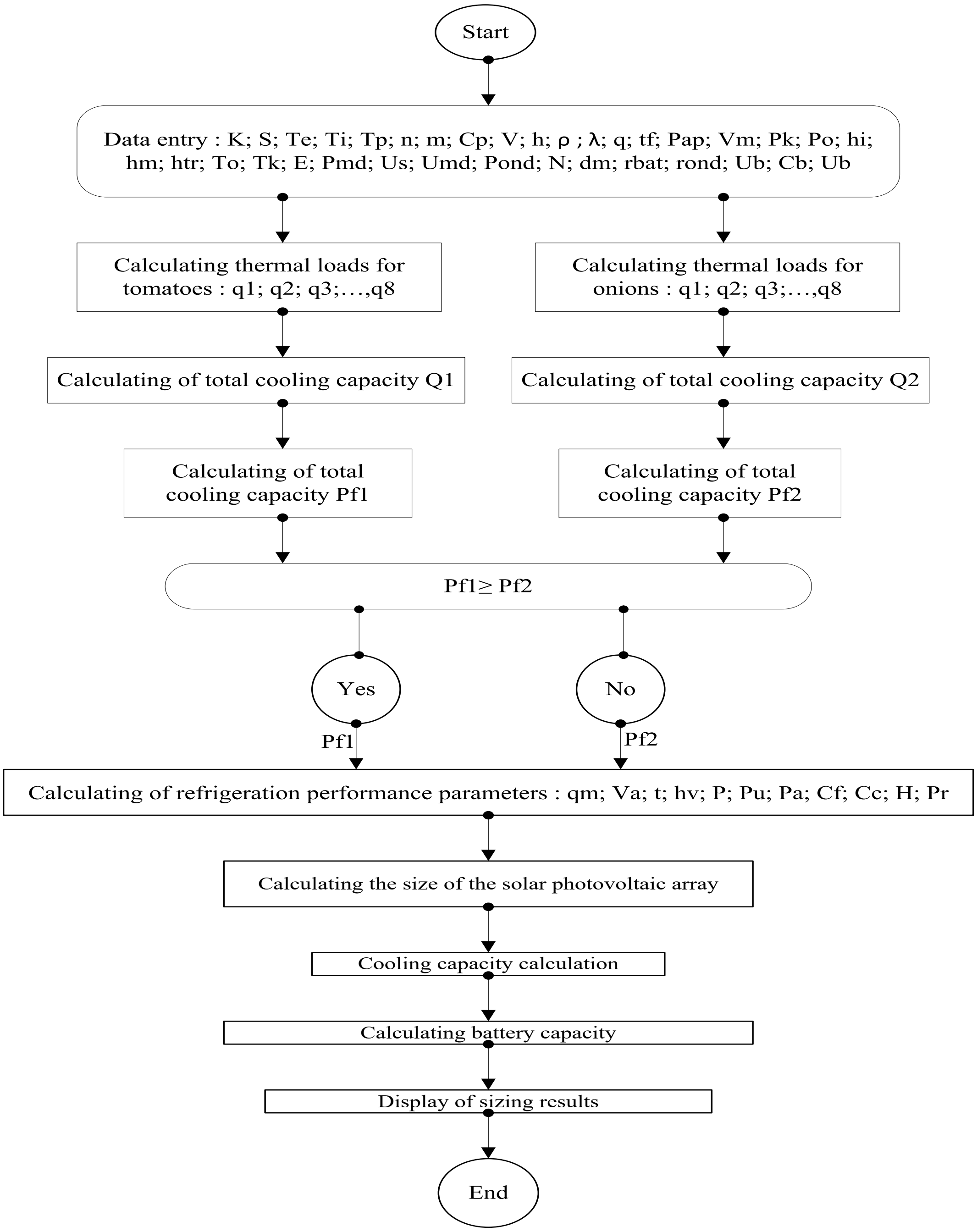

Figure 4: Cold store sizing flow chart

RESULT & DISCUSSION

Figure 5 shows the variations in heat gain as a function of the surface area of the enclosure to be cooled, for different insulation thicknesses. Generally speaking, for a given thickness of polystyrene, heat loss increases linearly with the surface area of the cold device. This means that the greater the surface area, the greater the heat loss (1200 MJ for 40 m^2 and 20 mm thickness), and this proportionally. Polystyrene thickness has a significant impact on heat loss. The greater the thickness, the lower the heat loss. There's a big gap between the 20 mm curve and the others, then a progressive narrowing of the curves with increasing thickness. Furthermore, the choice of insulation thickness will depend on the specific needs of the application. For applications requiring maximum insulation (e.g. industrial freezers), a greater thickness (over 100 mm) is preferable. For less demanding applications, a lesser thickness may suffice.

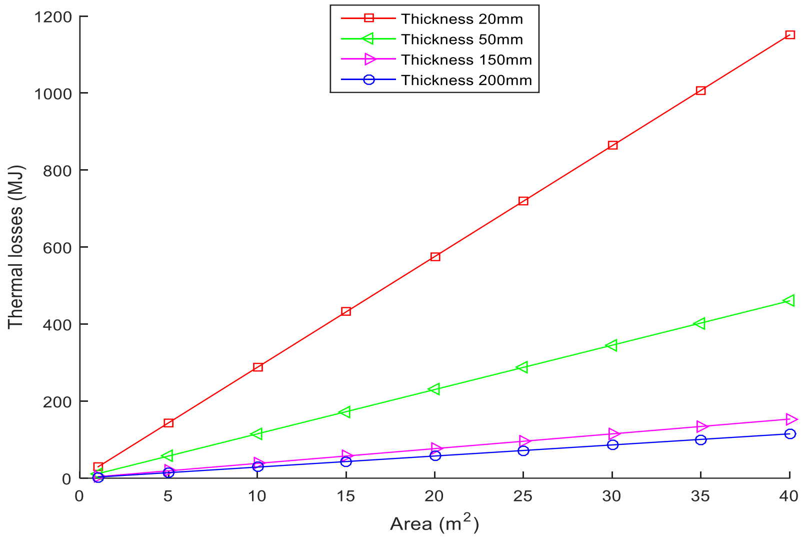

Figure 5: Variations in heat gain as a function of the surface area of the enclosure to be cooled for different insulation thicknesses

Figure 6 shows an inverse relationship between heat transfer coefficient (K) and insulation thickness. As insulation thickness increases, the heat transfer coefficient decreases. This decrease is rapid for low insulation thicknesses (less than 100 mm), then gradually stabilizes for greater thicknesses (beyond 100 mm thickness, K becomes less than 0.5 W/m^2. K). This curve illustrates Fourier's law, which states that heat flow through a material is proportional to the temperature difference and inversely proportional to the material's thermal resistance. The thickness of polystyrene increases thermal resistance, thus reducing heat flow.

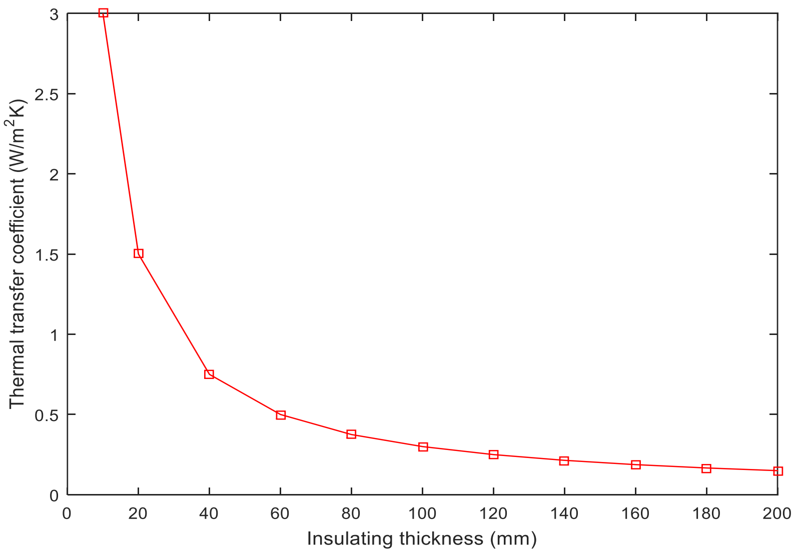

Figure 6: Variation in overall heat transfer coefficient (K) as a function of insulation thickness

Figure 7 shows the evolution of the refrigeration coefficient of performance (COP) as a function of the power absorbed by the electric motor, for different values of enthalpy variation. For each enthalpy value (10 kJ/kg, 50 kJ/kg and 100 kJ/kg), the COP decreases as the compressor power input increases (2 kW as maximum power). This means that the more energy the motor consumes, the less efficient the system is in terms of cold production. The system is more efficient when the enthalpy difference (which represents the amount of heat extracted) is higher.

COP is a key indicator of a refrigeration system's efficiency. A high COP means that the system produces more cold for a given amount of energy.

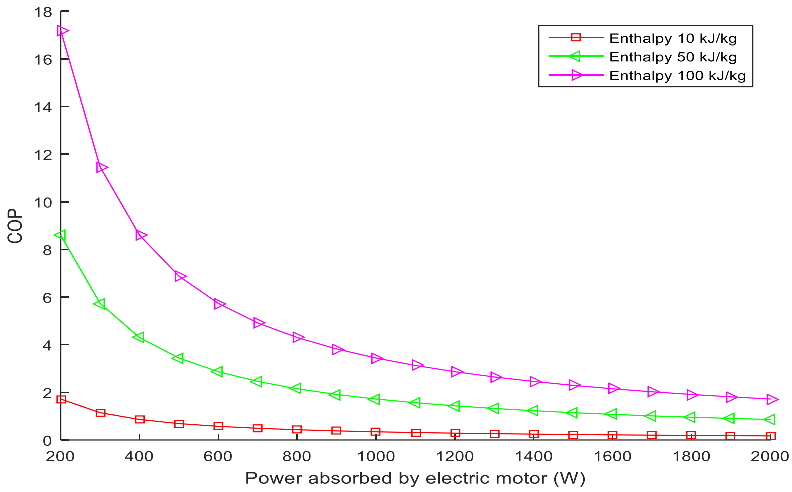

Figure 7: Coefficient of cooling performance as a function of the power absorbed by the electric motor, for different enthalpy variation values

Figure 8 shows the evolution of peak power required by PV modules and COP as a function of daily solar irradiation for an enthalpy variation of 100 kJ/kg in the evaporator. Generally speaking, the curves show an inverse relationship with solar irradiation. As solar irradiation increases, peak power and COP decrease. Solar irradiation has a significant impact on a system's peak power and COP. The decrease in COP as solar irradiation increases can be due to a variety of factors, such as increased heat loss and reduced compressor efficiency at high temperatures. In any case, in areas with low solar irradiation, for optimum operation of the refrigeration system (1.7 kWh/m^2.jr; 15.75 kWp; 4.25 COP), it may be necessary to oversize the PV system to achieve the desired peak power.

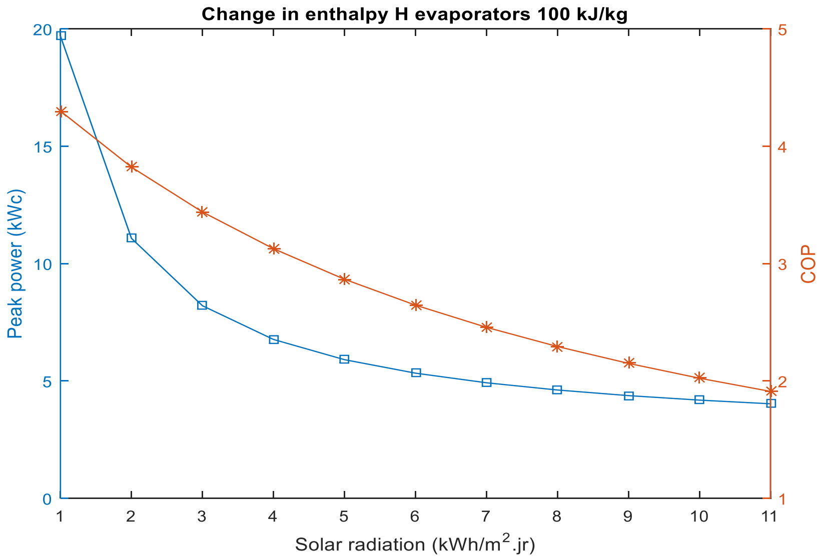

Figure 8: Evolution of peak power and COP as a function of daily solar irradiation for an enthalpy variation of 100 kJ/kg in the evaporator.

Table 1 below shows an example of the application of solar photovoltaic cold storage sizing for onion preservation. The results of the table show that the cooling power required by the machine to overcome the heat input for tomato products is lower than for onion products. Subsequently, the cooling capacity of the onion was used for the calculation, due to the fact that being able to preserve the onion in the cold device will also be possible to preserve tomatoes in the same device in terms of capacity. However, the reverse will not be possible, as the refrigeration machine will not be able to withstand the thermal loads during onion preservation.

Table 1: Some key parameters for dimensioning a solar photovoltaic cold store

Parameters	Values	
	Tomatoes	**Onions**
Daily requirements (MJ)	143.09	194.76
Cooling capacity (kW)	2.48	3.38
Compressor power consumption (kW)	1.10	
Average COP	3.06	
Power rejected at condenser (kW)	4.18	
Peak power (kWc)	5.27	
Total number of PV modules - 250 Wc	21.11 ≈ 20	
Solar system storage capacity (Ah)	716.46	
Total number of batteries 12V/200Ah	14.32 ≈ 12	
Number of inverters 5 kVA	2 either 1/string of PV module	

Figure 8 shows the synoptic model of the solar photovoltaic cold store.

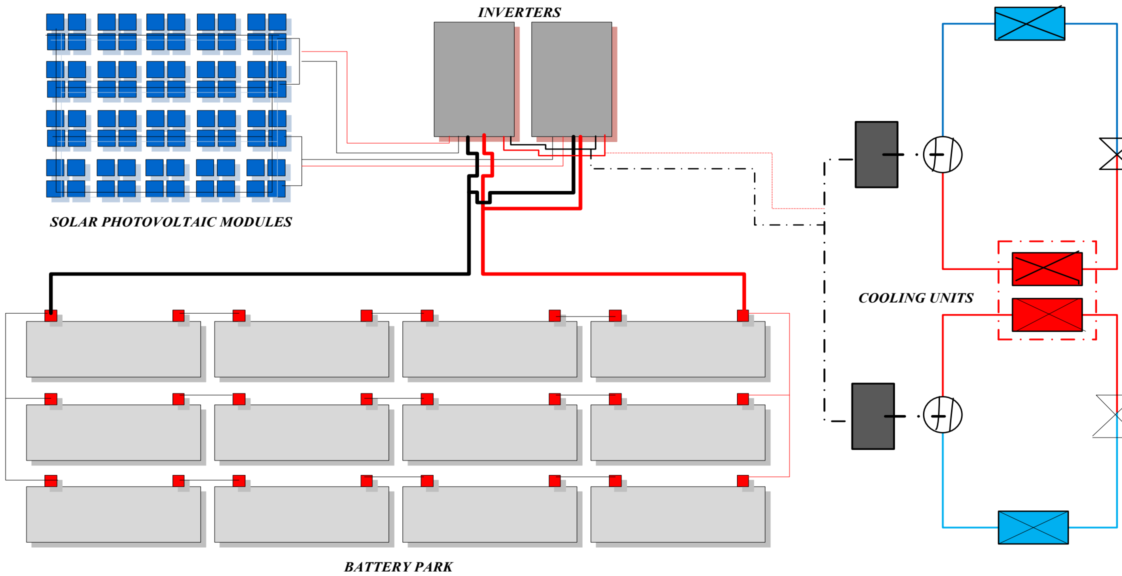

Figure 9: Synoptic diagram of the energy supply for the photovoltaic solar cold store

CONCLUSION

This work has enabled us to identify and determine all the essential factors and parameters, namely:

The optimum wall insulation thickness;
The overall heat exchange coefficient;
The refrigeration capacity;
The power absorbed by the motor compressor;
The refrigeration coefficient of performance;
The capacity of the photovoltaic solar array;
The battery storage capacity.

These results have enabled us to design and build a bioclimatic cold room specifically for preserving agricultural produce, notably onions, in remote and isolated areas, or in areas where access to electricity is expensive.

Declaration by Authors
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Conflict of Interest: No conflicts of interest declared.

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