Solar Cooling System: An Innovative Solution for Drug Conservation in Mozambique

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2 authors:

Jorge Nhambiu
Eduardo Mondlane University

Fernando Chichango
Universidade Zambeze

Solar Cooling System: An Innovative Solution for Drug Conservation in Mozambique

Jorge Nhambiu
Engineering Faculty, Eduardo Mondlane University,
Mozambique Av., Km 1.5, Maputo, Mozambique
E-mail: nhambiu@gmail.com

Fernando Chichango
Engineering Faculty, Environmental and Natural Resources, Zambeze University,
Chimoio RS-523, Manica, Mozambique
E-mail of the corresponding author: fernando.chichango@uzambeze.ac.mz

Abstract
Considering the lack of electricity in rural areas of Mozambique, which compromises the proper preservation of medicines, this study investigates viable technological solutions for implementing a sustainable refrigeration system. The objective is to identify and evaluate refrigeration technologies that can be used in areas without access to electricity, focusing on technical and economic feasibility. To this end, an absorption refrigeration system is analysed, utilizing a generator heated by a solar collector, a condenser, an absorber, and energy storage with thermal oil. Thus, it is observed that the designed system, with a capacity to store 1000 vaccines, is efficient and economically viable, with initial costs of 222,410.00 MZN and annual cash flows of 50,000.00 MZN. This allows concluding that absorption refrigeration is a practical and sustainable solution for the preservation of medicines in rural areas of Mozambique, recommending future studies on insulation materials, solar collectors, and alternative storage systems to improve the technology.
Keywords: Foreign fund, Challenge Absorption refrigeration, Solar energy, Thermal insulation, Vaccines, Sustainability.
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1. Introduction

Mozambique, located in southeastern Africa, faces significant challenges in its vast rural areas, particularly the lack of basic infrastructure such as electricity. According to the World Bank (2024), 61% of the population resides in rural areas, yet only 5% of these areas have access to electricity, compared to 75% in urban regions (World Bank, 2022). This severe shortage of electricity hampers the preservation of essential medicines, especially those requiring refrigeration, which is critical for maintaining public health. Access to healthcare and medicines is a fundamental human right, underscoring the urgency of addressing this issue.

Forecasts by Nhambiu & Chichango (2024b) indicate that Mozambique's population will continue to grow in the coming years. Without significant improvements in energy infrastructure to match this growth, the impact of diseases could become even more severe. The lack of electricity in rural areas not only affects daily life but also poses a serious threat to public health, highlighting the need for immediate and effective solutions.

The absence of electricity in rural Mozambique also undermines the achievement of the Sustainable Development Goals (SDGs) for 2030, particularly SDG 3, which focuses on health and well-being, and SDG 7, which aims for affordable and sustainable energy. Solar energy, being both clean and inexhaustible, presents a promising solution to this problem. According to Chichango & Cristóvão (2021), harnessing solar power could significantly improve the situation by providing a reliable source of energy for refrigeration and other essential services.

This study explores viable technological solutions to implement a sustainable refrigeration system for preserving medicines in Mozambique's rural areas without electricity. It evaluates the technical and economic feasibility of these proposed solutions, aiming to ensure that essential medicines remain accessible and effective, thereby improving health outcomes and supporting the broader goals of sustainable development.

1. 1. Theoretical Framework

The research focuses on sustainability, refrigeration technology, and public health in rural areas, aiming to promote development that meets current needs without compromising the ability of future generations to meet their own needs (Brundtland Commission, 1987). Central to this study are the 2030 Sustainable Development Goals (SDGs), particularly SDG 7, which emphasizes affordable and sustainable energy for all.

Solar and absorption cooling systems emerge as viable solutions for regions lacking access to electricity (Hassanien et al., 2016; Srikhirin et al., 2001). These systems are particularly suitable for remote areas, where traditional electricity infrastructure is often unavailable or unreliable.

Absorption cooling systems, which utilize pairs such as water-ammonia and lithium-water bromide, offer sustainable and efficient cooling solutions (Carmello & Gallego, 2011; Brown & Green, 2019). These systems can provide the necessary refrigeration for preserving medicines and other essential supplies, thereby supporting public health in rural communities.

By implementing these technologies, the research aims to address critical public health needs while also contributing to broader sustainability goals. This approach not only improves health outcomes but also supports the development of resilient and self-sufficient rural communities.

The cold chain is essential for preserving the quality of medicines and vaccines, and any interruption can significantly compromise their effectiveness (WHO, 2021). In Mozambique, where rural areas often lack electricity, maintaining this cold chain is particularly challenging. It is crucial to consider the economic feasibility of solutions, weighing financial costs against social and public health benefits (Boardman et al., 2018). Adapting technologies to local conditions is vital to ensure their effectiveness (Hassanien, Li, & Tang, 2016).

Further studies are needed to assess the technical and economic feasibility of these solutions (Srikhirin, Aphornratana, & Chungpaibulpatana, 2001). Additionally, local technical training is essential to implement and maintain these technologies effectively, following methodologies proposed by Chichango et al. (2023). However, providing such training remains a significant challenge (Brown et al., 2014).

2. Methodology

The document represents a preliminary step in the construction of a refrigeration system for the conservation of medicines in remote areas of Mozambique. The data collected reflect the needs of isolated communities in Mozambique, where lack of electricity and the need for conservation of medicines are common issues (Patton, 2015).

The methodological stages and procedures of the research are Identification of Refrigeration Needs; Assessment of local Environmental Conditions; Refrigeration Cycle Selection; Dimensioning of Components; Thermodynamic Analysis; Simulation and Modelling and Economic Evaluation.

2.1 Identification of Needs

The input data for the design of the solar absorption cooling system for the conservation of inactivated poliomyelitis (IPV) vaccines, in rural communities in Mozambique and without access to the electricity grid. It was also considered that the vaccines are placed in the chamber at 31º C, a value above the local average ambient temperature. The amount of 10 boxes containing 10 vials can immunize approximately 1,000 people, considering that IPV is usually administered in doses of 0.5 ml per person (WHO, 2023).

2.2 Assessment of Environmental Conditions

In remote areas of Mozambique, access to electricity is limited, with grid coverage of only 54% by 2023 (Nhambiu & Chichango 2024). The situation is more serious in rural areas, where only 5% of the population has access to electricity, compared to 75% in urban areas. The exploration of renewable energies is an imperative in Mozambique, considering the energy transition phase and the warning about the environmental impacts mentioned in the study by Nhambiu & Chichango (2024a).

However, Mozambique has great potential for solar energy, with average annual temperatures between 20°C and 30°C and a significant solar irradiance of 5 to 6 kWh/m²/day (Chichango & Cristóvão, 2021).

2.3 Refrigeration Cycle Selection

For remote regions without electricity, cooling options include Solar Coolers: Sustainable, but with high initial cost and maintenance of the panels; Gas Coolers: Use propane or butane, reliable where gas is more accessible, but require regular filling; Refrigerators with Absorption System: They use solar energy and gas, efficient in low insolation, but complex and with specialized maintenance. Refrigerators with Cold Accumulation Modules: Store cold for later use, depend on initial energy. Water heater coolers: They use phase-change materials, maintain a stable temperature, but have a high initial cost and need periodic recharging.

For Mozambique, solar cooling is suitable for this: Compression Solar Cooling, which uses electricity from solar sources, or Absorption Solar Cooling, which uses heat from solar sources (Genier, 2013; IT, 2015).

The promotion of solar energy promotes the reduction of environmental impacts, which occur in Mozambique in the form of cyclones that cause significant damage (Meque et, al., 2023).

2.3.1 Compression Solar Cooling

Solar energy is converted into electricity to run a compressor in vapor compression refrigeration systems (Creswell & Plano Clark, 2017). The challenges of this type of system include high initial cost, energy efficiency, storage, maintenance, durability, and environmental impact (Genier, 2013; IT, 2015).

Solar Absorption Cooling: Invented by Ferdinand Carré in 1860, it uses thermal energy and does not require electrical components (Junior et al., 2004; Brites, 2013; Micheletti, 2023). The refrigerant is absorbed, pumped, heated, evaporated, condensed, and returned to the evaporator (Micheletti, 2023; Da Silva et al., 2008). However, for good performance, the system requires a low-power electric pump to move the solution (Brown & Green, 2019).

2.4 Working Fluids

In addition to the selection of the refrigeration cycle, the operating capacity of the working fluid must also be considered. The advantages and disadvantages of the most common refrigerant pairs. Water-Ammonia: Ideal for intense refrigeration, it operates at high pressure, but ammonia is toxic. Lithium-Water Bromide: Less toxic, it operates at low pressure but limited to temperatures above 3°C. Water-Ammonia-Hydrogen: Good for small, quiet systems, but complex and with high maintenance costs.

However, in addition to observing operational advantages and disadvantages, it is also necessary to consider specific factors in the choice of the working fluid pair. Some key properties to consider: Thermodynamic Properties: High condensation and evaporation temperature; Chemical Compatibility: Chemically stable and non-corrosive; Safety and Environmental Impact: Non-toxic, non-flammable, safe for ozone; Physical Properties: High specific volume, energy efficient.

2.5 Components Sizing

2.5.1 Cold Room

IPVs are stored in the cold room, which is refrigeration equipment specifically designed to keep IPVs and other biologics at controlled temperatures. Storage in the chamber is essential to ensure the efficacy and safety of vaccines.

Cold rooms for IPVs are regulated to maintain temperature, without major variations, usually between 2°C and 8°C (WHO, 2021). The infrastructures are equipped with temperature monitoring systems to avoid variations that could compromise the quality of the vaccines (Centre for Disease Control and Prevention, 2020). In addition, they are essential for proper conservation during transport and storage in health centre (Pan American Health Organization, 2019).

To maintain the thermal conditions in the cold room, a specific insulation system must be considered. There are two synthetic insulators most used in small and medium-sized cold rooms: Polystyrene or polyurethane. The thermal conductivity of polyurethane on average is 1.7 times lower than that of polystyrene, when compared to the values of thermal conductivity for the same thicknesses (Çengel & Ghajar, 2009).

2.5.1.1. Calculation of the thermal load in the cold room

The calculation of the thermal load of a cold chamber can be estimated based on the plots recommended by Venturi and Pirane (2005). The total thermal load is the sum of the different load portions that can affect the performance of the camera. Through the calculations of each of these plots, it is possible to estimate the total thermal load of the cold room using Equation (1). In addition, a 10% safety factor is added, as recommended by ASHRAE (2006).

$$Q_{tota;} = 1.1 \cdot (Q_P + Q_T + Q_{inf} + Q_i) \quad (1)$$

Where: Q_P - Product Heat Load (W)

Q_T - Transmission Heat Load (W)

Q_{inf} - Infiltration Heat Load (W)
Q_i - Lighting Heat Load (W)

In equation (1) each load plot is estimated in a particle form, and the calculation factors are presented in the report manual of Venturi and Pirane (2005).
To maintain a temperature gradient between the outside and the inside, cold rooms must have an insulating material that resists the flow of heat, reducing the thermal load of transmission (Çengel, 2009). To select the minimum thickness (t) that the panel should have, Equation (2) is used and then an iteration is made assuming the quality of the insulation to be excellent (Ferreira, 2021).

$$t = \frac{k \cdot \Delta T}{(\frac{Q}{A})} \quad (2)$$

Where: k- Thermal conductivity of the material (W/m.K); ΔT- Temperature difference between the external and internal environment (°C); Q/A- Heat flux (W/m^2).

2.5.2 Generator capacity calculation

The condenser is crucial in refrigeration systems, acting as a heat exchanger (Smith, 2020). The generator's refrigerant condenses and is sprayed into the evaporator, completing the absorption cycle (Brown & Green, 2018; Johnson, 2019). It facilitates the transition between gaseous and liquid states (Brown & Green, 2018; Smith, 2020). The Coefficient of Performance (COP) on the generator can be calculated by Equation (3)

$$COP = \frac{Q_e}{Q_g} COP = \frac{Q_e}{Q_g} \quad (3)$$

Where:
Q_e – System refrigeration capacity (W); and
Q_g – Heat supplied to the Generator (W).
To size the condenser, consider the Cooling Capacity (Qe), which quantifies the heat removed (Smith, 2020). The dissipated thermal energy is equal to the cooling capacity (Qc = Qe) (Brown & Green, 2018). The Mass Flow Rate of Refrigerant (ṁ) using the enthalpy of condensation h_fg (Johnson, 2019). Generator sizing can include calculating the Refrigerant Mass Flow Rate (ṁ) shown in Equation (4) (Smith, 2020).

$$\dot{m} = \frac{Q_g}{h_{fg}} \quad (4)$$

The generator must accommodate the mass flow rate of the refrigerant, and the thermal energy required, considering thermal efficiency and heat losses (Brown & Green, 2018). In sizing, it is essential to consider the properties of the refrigerant and absorbent, such as operating pressure and temperature, which influence performance and efficiency (Johnson, 2019; Smith, 2020).
2.5.3 Condenser Sizing

The condenser is essential in refrigeration systems, acting as a heat exchanger (Smith, 2020). The generator's refrigerant undergoes condensation (Brown & Green, 2018) and is sprayed into the evaporator, completing the absorption cycle (Johnson, 2019). The condenser facilitates the transition of the refrigerant between gaseous and liquid states (Brown & Green, 2018; Johnson, 2019; Smith, 2020).

To size the condenser, consider the Cooling Capacity (Qe), which quantifies the heat to be removed (Smith, 2020). The thermal energy to be dissipated is equal to the cooling capacity (Qc = Qe) (Brown & Green, 2018). You can use Equation (5) for the Refrigerant Mass Flow Rate (ṁ) and enthalpy of condensation h_fg (Johnson, 2019).

$$\dot{m} = \frac{Q_C}{h_{fg}} \quad (5)$$

The required heat exchange area can be calculated using Equation (6)

$$Q_c = U \cdot A \cdot \Delta T_m \quad (6)$$

Where (U) is the overall heat transfer coefficient, (A) is the area of heat exchange, and (ΔT_m) is the logarithmic mean temperature difference. And this can be obtained by Equation (7).

$$\Delta T_{ml} = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}} \quad (7)$$

Where: – Logarithmic mean temperature (ºC); - Temperature difference at the evaporator inlet (ºC); e – Temperature difference at the evaporator outlet (ºC). Based on the calculated heat exchange area, one can select a condenser that meets these requirements and consider factors such as thermal efficiency and heat losses (Smith, 2020).

The surface of the condenser is connected to fins to increase the heat transfer area. The fin area is calculated using Equation (8). This area depends on the fin radius (r_2), the external radius of the condenser tube (r_1) and the thickness of the fin (t) according to Çengel (2009).

$$A_{fins} = 2\pi \cdot (r_2 - r_1) + 2\pi \cdot r_2 \cdot t \quad (8)$$

According to Çengel (2009). The heat released by a fin is calculated using Equation (9).

$$Q_{fins} = A_{fins} \cdot h \cdot (T_s - T_\infty) \quad (9)$$

The input values for the query on the abacus are calculated by Equations (10.1) and (10.2).

$$\delta = \frac{r_2 + \frac{t}{2}}{r_1} \quad (10.1) \qquad \varepsilon = (L + \frac{t}{2}) \cdot \sqrt{\frac{h}{kt}} \quad (10.2)$$

Where: t Fin Thickness (m); r_2 — Outer radius of the fin (m); r_1 — External radius of condenser tube (m); h - Convective coefficient (W/m2K); and k-Thermal conductivity of the fin material (W/mK). The actual heat of the fin is calculated using Equation (11).

$$Q_{r,a} = \eta_{fin} \cdot Q_{fin} \quad (11)$$

Where: $Q_{r,a}$ – Real fin heat (W); η_{fin} — Fin Efficiency (%); e Q_{alheta} – Fin heat (W). And the heat exchanged in the condenser is calculated using Equation (12).

$$Q_{total} = Q_{s,a} + N \cdot Q_{r,a} \quad (12)$$

Onde: $Q_{s,a}$ – Heat exchanged without fin (W); N – Number of Fins; e $Q_{r,a}$ – Heat exchanged for a Fin (W).

The specific properties of the refrigerant, such as operating pressure and temperature, should also be considered when sizing (Johnson, 2019). According to Brown & Green, (2018) the temperature and operating pressure of the condenser directly influence its performance and efficiency.

2.5.4 Evaporator Sizing

The evaporator is a key component in refrigeration systems. It is in this that the refrigerant evaporates, allowing the absorption of heat from the environment or the product that is to be cooled (Smith, 2020). This device transforms refrigerant from a liquid state to a gaseous state (Brown & Green, 2018). During this transformation, heat is absorbed, resulting in cooling of the environment (Johnson, 2019). According to Brown & Green (2018), Johnso (2019) and Smith (2020) the evaporator sizing procedure is like the condenser described above.

2.5.5 Absorber Sizing

The absorber is essential in absorption refrigeration systems, where the refrigerant vapor is absorbed by the concentrated solution, allowing the refrigerant to return to a liquid state and continue the cycle (Smith, 2020). It is crucial for 3.5.5 Absorber to system efficiency (Brown & Green, 2018; Johnson, 2019). Sizing depends on desired cooling capacity, solution type, and operating temperatures.

Another parameter to calculate is the amount of heat to be absorbed that can be obtained using the energy balance equation. Equation (13) determines the amount of heat that the absorber needs to remove from the coolant.

$$Q = m \cdot c_p \cdot \Delta T \quad (13)$$

Where (Q) is the amount of heat, (m) is the mass of the soda, (c_p) is the specific heat capacity and (ΔT) é Temperature difference. The area required for heat transfer can be determined using Equation (14).

$$A = \frac{Q}{U \cdot \Delta T_m} \quad (14)$$

Where (A) is the heat transfer area, (U) is the overall heat transfer coefficient, and (ΔT_m) is the logarithmic mean temperature difference. Consideration is also given to choosing materials with good thermal conductivity and corrosion resistance. Including the decision of the type of heat exchanger (e.g. plate, shell and tube heat exchanger).

2.5.6. Gas Heat Exchanger (ghx)

The gas heat exchanger (GHX) is used to exchange heat between the refrigerant that leaves the evaporator to the absorber and the hydrogen that leaves the absorber to the evaporator. The overall heat exchange coefficient is a measure of efficiency with which heat is transferred across a surface composed of different materials or layers. It can be determined using Equation (15).

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_e} + \frac{\Delta x}{k}} \quad (15)$$

Being: h_i - Heat transfer coefficient on the inner side (W/m^{2}K); h_e - Heat transfer coefficient from the outside (W/m2K); Δx- Material layer thickness (m); and k- Thermal conductivity of the material (W/mK). The heat exchange area in the exchanger is calculated using Equation (16).

$$A = \frac{Q}{U.\Delta T_{lm}} \quad (16)$$

Where: Q- Heat Transfer Rate (W); U- Overall heat transfer coefficient (W/m2K); and ΔT_{lm}- Logarithmic mean temperature difference (ºC). The length of the pipe can be calculated using Equation (17).

$$L = \frac{A}{\pi d_e} \quad (17)$$

Where: d_e - Tube diameter (m); A- Exchange area (m2).

2.5.7 Suction Pump Sizing

The pump in an absorption cooling system plays a role of raising the pressure of the ammonia-water solution from the absorber to the generator. In the absorber, the refrigerant is absorbed by the absorbent, forming an ammonia-rich solution. The pump then lifts this solution to the generator, where heat is applied to separate the solution allowing the cycle to continue (Unicamp, 2023; UFPR, 2023).

To select a suitable pump for the circulation of the solution in an absorption cooling system, it is important to consider several factors, including pumping capacity, resistance to the fluids involved, and energy efficiency.

The pumping capacity includes the calculation of the flow rate, flow rate required for the circulation of the solution. This also depends on the amount of solution that needs to be moved per unit of time. The flow rate is based on the cooling capacity and the characteristics of the absorption cycle, it can be calculated by Equation (18).

$$Q = \frac{P}{\Delta T \cdot C_p} \quad (18)$$

where (Q) is the flow rate, (P) is the cooling capacity, (ΔT) is the temperature difference and (C_p) is the specific heat of the solution (Smith, 2020).

The calculation of Total Manometric Headroom (TMH) includes static height and head losses in the system by Equation (19) according to Jones (2019).

$$TMH = H_{estática} + H_{perdas} \quad (19)$$

To choose a suitable pump for absorption cooling systems, the following points can be considered:

1. Pump Type: Centrifugal pumps are preferred for their ability to handle large volumes and efficiency (Smith, 2020).
2. Mechanical Seals: They must be reinforced or tightly sealed to prevent leaks and resist ammonia corrosion (Jones & Brown, 2019).
3. Fluid Resistance: The pump must be made of corrosion-resistant materials, such as stainless steel, to withstand the ammonia and water-ammonia solution (Doe, 2018).
4. Sealing: It must be robust to prevent leaks and ensure the safety of the system (White, 2021);
5. Energy Efficiency: Choose pumps with high efficiency to minimize energy consumption (Green, 2022);
6. Variable Speed Control: Pumps with this feature are advantageous because they allow you to adjust the flow rate as needed, saving energy (Black & Blue, 2023).

2.6 Thermodynamic Analysis

Thermodynamic analysis includes mass and energy balance calculations for each component of the system and the calculation of the system's COP to assess efficiency. For the calculation of the mass balance, all the input and output currents in the system must be identified. The mass balance equation is applied to each component by means of Equation 20. For a steady-state system, the accumulation is zero (Smith, 2020a).

$$\sum \text{Entradas} = \sum \text{Saídas} + \text{Acúmulo} \tag{20}$$

2.6.1 For the energy balance, all forms of energy entering and leaving the system (heat, work, internal energy, etc.) are considered. Then the energy balance equation (21) is applied:

$$\sum Enenrgia\ de\ \text{entradas} - \sum Enenrgia\ de\ saída = \Delta Enenrgia\ interna \tag{21}$$

For a steady-state system, the internal energy change is zero (Jones, 2019).

2.6.2 The coefficient of performance (COP) is a measure of the efficiency of a cooling system and is defined as the ratio of the amount of heat removed from the cooled environment to the work done by the system can be calculated by Equation (22).

$$\text{COP} = \frac{Q_{\text{removed}}}{W} \tag{22}$$

Where: Q_{removed} is the heat removed from the refrigerated environment. W is the work done by the system (Brown, 2018). For an absorption cooling system, the COP can be calculated by considering the energy supplied to the generator and the energy removed by the evaporator (White, 2021).

2.7 Heat Source Sizing

To size a heat source in absorption refrigeration systems, consider: **1. Dermal Energy:** It must be sufficient for the absorption cycle. **2. Choice of Fluids:** The refrigerant should evaporate at low temperatures and the absorbent should be less volatile. **3. System Efficiency:** It depends on the temperature difference between the hot and cold source. **4. Cooling Capacity:** Calculate the heat to be removed from the environment. **5. Pressure Maintenance:** Maintain the pressure difference between the absorber and the heater (Paz, 2009). 6. Choice of Heat Source: Evaluate the availability of natural gas, biomass or solar energy, considering costs and local conditions (Paz, 2009).

2.8 Thermal Storage System

According to Chichango, et al., (2024) there are different forms of thermal storage that are selected according to availability and economic viability factors. In this specific case, thermal oil is the most appropriate. The amount of the oil mass can be calculated using Equation (23).

$$m_{\text{oil}} = \frac{Q_{storage}}{c_{p,\text{oil}} \cdot \Delta T} \tag{23}$$

Where: $Q_{storage}$ – Storage energy (J); m_{oil} – Oil mass (kg); $C_{p,\text{oil}}$ – Specific heat of the thermal oil (kJ/kg. K); e ΔT- Temperature difference (ºC). With the mass (m_{oil}) and volumetric density of the oil (ρ_{oil}), the volume of the accumulator tank is calculated using Equation (24).

$$V_{tank} = m_{\text{oil}} \cdot \rho_{\text{oil}} \tag{24}$$

Where: V_{tank} – Tank volume (m3); m_{oil} – Oil mass (kg); ρ_{oil} – Volumetric density of oil (m3).

2.9 Simulation and Modelling

The simulation of absorption cooling systems can be done with: 1. EES (Engineering Equation Solver): Thermodynamic modelling, especially for ammonia-water (Klein, 2023); 2. TRNSYS: Simulation of thermal systems, analysing cooling rate and COP (Solar Energy Laboratory, 2023); 3. Fortran: Specific programs for detailed component analysis (Smith, 2023); 4. SOLIDWORKS Flow Simulation: Simulates the flow of liquids and gases, analysing heat transfer (CADNEA, 2024). These applications help optimize the design and understand the performance of the system.

2.10 Economic Evaluation

The economic viability of absorption refrigeration systems depends on the costs of installation, operation and maintenance, in addition to the expected benefits. The initial cost can be high due to the complexity of the components and modifications to the infrastructure (Castanheira, 2023). These systems use heat from renewable sources or industrial waste, reducing operating costs compared to electrical systems (Vazzoler, 2021). Maintenance may be less frequent, but it requires specialized technicians, increasing costs in the long run (Castanheira, 2023).

Using waste or renewable heat sources can result in significant savings and longer lifespan of the systems, offsetting the initial costs. In addition, they are more ecological, not using refrigerants that contribute to the greenhouse effect. In regions with scarce or expensive electricity, these systems can improve the conservation of medicines and vaccines (Castanheira, 2023). Annual cash flows can be estimated using the Net Present Value (NPV) Equation (25), as per Blank & Tarquin (2012).

$$VAL = \sum_{n=1}^{10} \frac{FC_t}{(1+r)^t} - \text{Io} \quad (25)$$

Where: FC_t – Annual cash flow (MZN); r- Discount rate; t- 1 to 10 years; and Io – Initial Investment (MZN). The economic evaluation of the project is essential to determine its feasibility and justify the necessary investments.

3. Results and Discussion

The results of the research are presented in Table 1 according to the proposed methodological sequence.

Table 1. Summary of the results obtained

#	Activity	Result	Observation
1	Identification of needs	1000 Vaccines (IPV). Cold room dimensions: 1.10 x1.00 x 1.25 m^3	The estimated amount can maintain the protection of 1000 children against polio. Dimensions correspond to Length x Width x Height in meters
2	Thermal load of vaccines	Specific heat: 4.18 kJ/(kg.k); Density: 997.00 kg/m3; Volume in solution : 2.50ml;	Thermal load of vaccine solution =29.17 kJ Heat load of glass vials of vaccines=25.2 kJ Total thermal load of the product=54.37 kJ Total thermal load of the product = 54.37 kJ
3	Assessment of Environmenta l Conditions	Mozambique has great potential for solar energy.	The estimated potential of more than 20,000 GW, of which about 2.7 GW are suitable for immediate implementation (EY, 2023).
4	Refrigeration Cycle Selection	Cooling System for Ammonia and Water Absorption.	This system is suitable for Mozambique, although Ammonia is toxic, it has more advantages than the pair Lithium Bromide and water.

Source: Authors

The table outlines the requirements and considerations for storing 1000 IPV vaccines in Mozambique. It details the dimensions of the cold chamber needed, the thermal load of the vaccines, and the environmental conditions favourable for solar energy utilization. Additionally, it recommends an Ammonia-Water Absorption Refrigeration System, highlighting its suitability despite the toxicity of ammonia, due to its advantages over other systems. This comprehensive assessment ensures the effective storage and preservation of vaccines in Mozambique's context.

The insulating material chosen was polyurethane. To calculate the thickness of the isothermal panel, Equation (26) was used.

$$t = \frac{k \cdot \Delta T}{\left(\frac{Q}{A}\right)} \quad (26)$$

Where the value of the thermal conductivity (k) of polyurethane was taken as 0.023 W/m2K according to the calculations, the thickness of the suitable insulation was 100mm.

3.1 Discussion of the Results Presented

Identification of Vaccine Needs: Crucial for public health; Vaccination is an effective intervention (WHO, 2021); Proper storage maintains the effectiveness of vaccines (WHO, 2021).

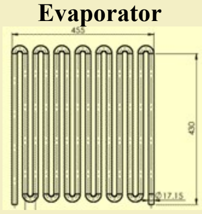
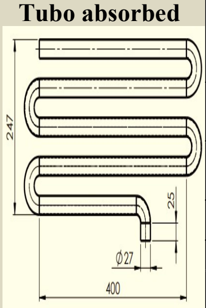
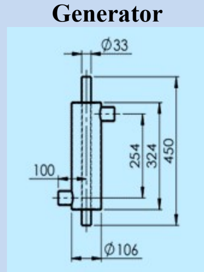
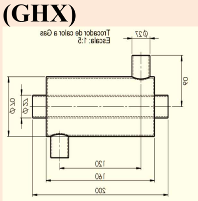
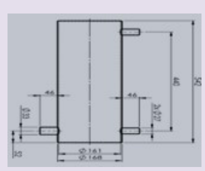
Thermal Load of Vaccines: Important for sizing refrigeration systems; - Maintaining the cold chain is critical (Vilain, 2018).

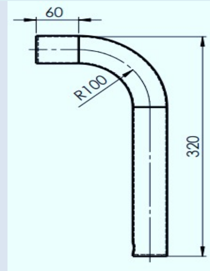
Insulating Material: Polyurethane chosen as insulator; - Maintains stable temperature, reduces energy requirement (Friocell Refrigeración, n.d.; Mecalux, n.d.); - Resistant, durable, mouldable and prevents ice and condensation.

Solar Energy: - Absorption cooling using solar thermal source is a sustainable and efficient solution for Mozambique; - Vast solar potential for vaccine refrigeration (Cristóvão et al., 2021; EY, 2023; Nhambiu & Chichango, 2024).

Working Fluid: The Ammonia-water pair was chosen. Absorption systems that operate with ammonia and water, even though ammonia is toxic, are efficient for regions with high solar energy and can reach, relatively, low temperatures (Silva, 2020), the specific case of Mozambique with intense solar radiation, as referenced by Chichango, et al., (2024). The component sizing results are in table 2.

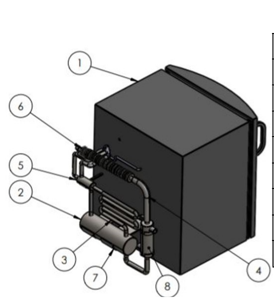
Table 2. Result of sizing components of the absorption cooling system

<table>
<tr><th>Component</th><th>Parameter</th><th>Value</th><th>Component</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="5">Evaporator
</td><td colspan="2">Material:
The Inox 304</td><td rowspan="6">Condenser
</td><td colspan="2">Material:
ASTM 304 Stainless Steel</td></tr>
<tr><td>Outer diameter of the tube</td><td>17.15 mm</td><td>Outer diameter of the tube</td><td>33.40 mm</td></tr>
<tr><td>Thickness</td><td>1.65 mm</td><td>Thickness</td><td>1.65 mm</td></tr>
<tr><td>Heat Truck Area</td><td>0.20 m^2</td><td>Heat Truck Area</td><td>0.55 m^2</td></tr>
<tr><td>Tube length</td><td>3780.00 mm</td><td>Tube length</td><td>730.00 mm</td></tr>
<tr><td rowspan="6">Tubo absorbed
</td><td colspan="2">Material:
The Inox 304</td><td>Number of fins</td><td>73.00</td></tr>
<tr><td>Outer diameter of the tube</td><td>26.67 mm</td><td rowspan="5">Generator
</td><td colspan="2">Material:
The Inox 304</td></tr>
<tr><td>Thickness</td><td>1.65 mm</td><td>Outer diameter of inner tube</td><td>33.40 mm</td></tr>
<tr><td>Heat Truck Area</td><td>0.39 m^2</td><td>Thickness</td><td>1.65 mm</td></tr>
<tr><td rowspan="2">Tube length</td><td rowspan="2">4690.00 mm</td><td>Heat Truck Area</td><td>0.03 m^2</td></tr>
<tr><td>Tube length</td><td>290.00 mm</td></tr>
<tr><td rowspan="5">Gas Heat Exchanger Tube (GHX)
</td><td colspan="2">Material:
The Inox 304</td><td rowspan="5">Absorption Reservoir
</td><td colspan="2">Material:
The Inox 304</td></tr>
<tr><td>Outer diameter of the tube</td><td>26.67 mm</td><td rowspan="3">Condensate Vol.
Evaporate Vol.
Generated Vol.
Thank Vol.</td><td rowspan="3">0.9 dm^3
0.77 dm^3
7.85 dm^3
10 dm^3</td></tr>
<tr><td>Thickness</td><td>1.65 mm</td></tr>
<tr><td>Heat Truck Area</td><td>0.01 m^2</td></tr>
<tr><td>Tube length</td><td>110.00mm</td><td>External diam.
Internal diam.</td><td>168.28mm
164.98mm</td></tr>
<tr><td rowspan="5">Rectifier Tube</td><td>Rectifier volume</td><td>0.83 dm3</td><td colspan="2">Quantity of the pair Ammonia and Water</td><td>Value</td></tr>
<tr><td>Outside diameter of rectifier</td><td>60.00 mm</td><td colspan="2">Absorber Volume (L)</td><td>10.00</td></tr>
<tr><td>Inner diameter of rectifier</td><td>57.60 mm</td><td colspan="2">Concentration of ammonia in solution (X)</td><td>0.32</td></tr>
<tr><td colspan="2">Material: AISI 304 stainless steel</td><td colspan="2">Water mass (m_{H2O})[kg]</td><td>5.00</td></tr>
<tr><td>Length of rectifier</td><td>0.32m</td><td colspan="2">Ammonia mass (m_{NH3})[kg]</td><td>2.40</td></tr>
</table>

	Mass of hydrogen	System Pressure (kPa) Hydrogen partial pressure (kPa) Hydrogen mass (m_{H2}) (in g)	2,196.00 2,022.00 20.65

Source: Authors

The table provides detailed specifications for various components of a refrigeration system, including the evaporator, condenser, absorber tube, generator, gas heat exchanger (GHX) tube, absorption reservoir, and rectifier tube. Each component's material, dimensions, and thermal properties are listed, highlighting the use of stainless steel (Inox 304 and ASTM 304) for durability and efficiency. The table also includes parameters for the ammonia-water pair used in the system, such as absorber volume, ammonia concentration, and hydrogen mass, emphasizing the system's design for optimal performance and safety in refrigeration applications.



Item	Item Name	Quantity
1	Camera	1
2	Absorption reservoir	1
3	Absorber tube	1
4	Rectifier	1
5	Gas heat exchanger	1
6	Condenser	1
7	Reservoir support	1
8	Generator	1

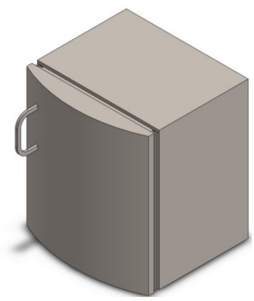


Figure 1. The Outline of the Absorption Cooling System (Rear View and Front View)
Source: Authors

3.1.1 Discussion of component sizing

Materials: AISI 304 stainless steel is corrosion-resistant and durable (Silva, 2020); Improves the efficiency and lifespan of equipment.

Heat Exchange Area: this parameter is critical for the efficiency of the systems, it must be carefully optimized (Vilain, 2018).

Volume and Weight: Influence storage capacity and efficiency; Weight reduction improves energy efficiency and reduces operating costs (EY, 2023).

Cost: Cost-benefit analysis is essential; High-quality materials reduce maintenance costs and increase durability (WHO, 2021).

3.1.2 Heat Source Sizing Results

The calculated oil accumulator tank volume was 190.00 L, the mass of oil to be stored is 163.19 kg, the temperature differential is 40ºC.

1. Solar Thermal Energy: Operating temperature: 90°C to 150°C; Solar collectors concentrating parabolic cylinders are recommended (Sbravati & Silva, 2011; Chichango & Cristóvão, 2021a). Area: Minimum of two solar collectors of 1 m². The Function: Heat water directly during the day.

2. Energy Storage: Heated thermal oil for night use or on cloudy days.

3. Efficiency and Sustainability: Solar energy is sustainable and efficient (Meque et al., 2023); - Heat storage in thermal oil increases efficiency (Almeida, 2015; Fernandes, 2017).

4. Description of thermophysical properties of thermal oil for heat storage: High Heat Capacity: oil stores a lot of heat (Smith, 2020a); Low Vapor Pressure: Operates at high temperatures without high pressure (Johnson, 2019); Thermal Stability: Stable at high temperatures (Brown, 2021);

4.1.3 Thermodynamic Analysis

The thermodynamic analysis of mass flow and energy was performed with the EES software, chosen for its efficiency in calculations of ammonia-water absorption cooling systems (Klein, 2023).

Heat exchanged in the condenser: 149.70 W; Refrigeration Capacity: 107.50 W; Generator Heat: 254.10 W; Heat lost in the Rectifier: 95.63 W; Absorber Heat: 110.60 W; COP: 0.42.

3.1.4 Results of the Economic Evaluation

Annual cash flows: 50,000.00 MZN; Initial investment: 222,410.00 MZN, recovered between the 4th and 5th year; Benefits: Conservation of medicines, less waste, reduced dependence on fossil fuels, greater energy self-sufficiency; - Economic impact: Creation of local jobs, reduction of costs with preventable diseases.

3.1.5 Simulation and Modelling

Performed in SOLIDWORKS, analysing fluid flow and heat transfer; - Generator: Calculations based on pressure, temperature, mass flow and ammonia concentration; - Results: Refrigerant vapor temperature at constant pressure.

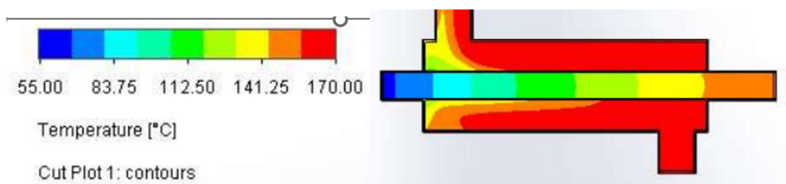


Figure 2. Suction temperature range in the generator
Source: Authors

As you can see in the figure 2, the solution enters at 55ºC and the ammonia vapor leaves at about 155ºC, while the water enters at 170º C and exits at 144º C.

Evaporator: The parameters used for the simulation of this component are pressure, temperature and mass flow, calculated in advance. Figure 3 shows the temperature variation on the surface of the evaporator tube.

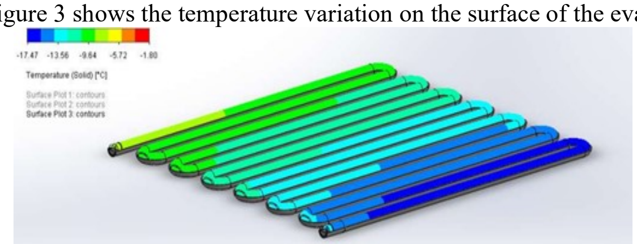


Figure 3. Temperature Variation in Wall Tube Evaporator
Source: Authors

The temperature at which the ammonia vapours exit from the evaporator is -9.5°C, which means that it will be possible to reach the storage temperature of the medicines, which is 3°C.

Condenser: Analogous to the analyses carried out in the Evaporator and Generator, the operation of the condenser was simulated. Figure 4 shows the diagram of the refrigerant temperature variation in the condenser.

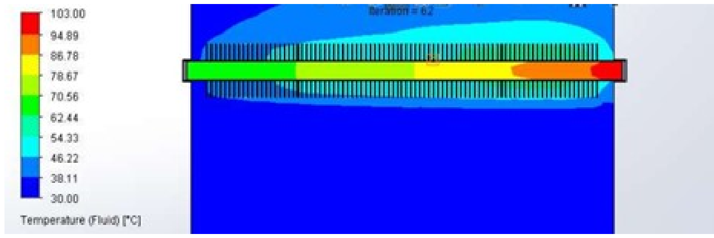


Figure 4: Operation simulation in the Evaporator

Source: Authors

It is noted from figure 4 that the condenser releases heat from the refrigerant which enters at 100ºC and exits at 63ºC.

4. Conclusion

The cold room design, with a capacity of 1.38 m³ to store 1000 vaccines, uses 100 mm polyurethane thermal insulation to reduce the thermal load. The absorption cooling system is powered by a 254.10W generator heated by a solar collector, with a condenser removing 107W of heat. The 1 m² cylindrical parabolic solar collector was chosen for its high efficiency. The energy storage system uses 163.19 kg of thermal oil to run at low radiation. With initial costs of 222,410.00 MZN and annual cash flows of 50,000.00 MZN, the system is economically viable and sustainable, making it ideal for rural areas in Mozambique. Future studies should focus on more efficient insulation materials, different types of solar collectors, and alternative storage systems. Detailed economic analyses are needed to confirm financial feasibility and identify sources of financing for similar projects that can massify the implementation of sustainable refrigeration technology in rural areas.

References

Black, J., & Blue, A. (2023). Energy-efficient pump systems. Energy Journal.

Blank, L. & Tarquin, A. (2012). Engineering Economy. 7a ed. New York, NY: McGraw-Hill.

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2018). Cost-Benefit Analysis: Concepts and Practice (5th ed.). Cambridge University Press.

Brown, D. W., Burton, A. H., Gacic-Dobo, M., & Karimov, R. I. (2014). A review of national immunization coverage assessment surveys in Africa, 2000-2010. BMC Public Health, 14, 1-14. https://doi.org/10.1186/1471-2458-14-321.

Brown, L. & Green, P. (2018). Thermodynamics and Heat Transfer in Absorption Systems. London: Academic Publishing.

Brown, L. (2018). Refrigeration and Air Conditioning. Boston: McGraw-Hill.

Castanheira, F. (2023). Design and Analysis of Technical Economic Feasibility of a Trigeneration System using Biomass. University of Coimbra.

Çengel, Y. A., Ghajar, A. J. (2009). Transfer of Heat and Mass. [S.l.]: AMGH editora, 2009.

Chichango, F. & Cristóvão, L. (2021). Mozambique Solar Thermal Energy Technologies: Current Status and Future Trends. Journal of Energy Technologies and Policy, Vol. 11(5), p13 -17. DOI: 10.7176/JETP/11-5-02.

Chichango, F., & Cristóvão, L. (2021a). Analysis of solar cooling systems. Journal of Renewable Energy, 45(3), 210-225.

Chichango, F., Cristóvão, L. (2024). Review of literature on methods and processes to produce bioethanol from banana peels for disinfection and sanitation of the environment in communities, central region of Mozambique Research, Society and Development, 13(3).e12713344921-e12713344921 2024. http://dx.doi.org/10.33448/rsd-v13i3.44921.

Chichango, F., Cristóvão, L., & Mahanuque, O. (2023). Empowering women through vocational training: Evidence from rural areas affected by armed conflict in Mozambique. Research, Society and Development, 12(14), e108121441196. https://doi.org/10.33448/rsd-v12i14.41196.

Chichango, F., Cristóvão, L., Muguirima, P., & Grande, S. (2023). Solar dryer technologies for agricultural products in Mozambique: An overview. Research, Society and Development. DOI:10.33448/rsd-v12i4.39850.

Chichango, F., Cristóvão, L., Nhambiu, J., Cumbe, F., & Mavanga, G. G. (2024). Literature review of potential materials for the construction of an alternative flat-plate solar collector. Research, Society and Development, 13(5), e0513545674. https://doi.org/10.33448/rsd-v13i5.45674

Cristóvão, L.; Chichango, F., Massinga, P., Macanguisse, J. (2021). The potential of renewable energy in Mozambique: an overview Journal of Energy Technologies and Policy 11(2), 30-37. DOI: 10.7176/JETP/11-2-04.

Doe, J. (2018). Materials for ammonia refrigeration systems. Industrial Materials Review.
EY. (2023). Mozambique and the Energy Transition. Retrieved from https://www.ey.com/pt_mz/energy-resources/mocambique-e-a-transicao-energetica.

Fernandes, M. A. S. (2017). Thermal energy storage system with adsorption module. PhD thesis, University of Coimbra.

Ferreira, A. D. (2021) Analysis of the sizing of cold rooms of a beverage distributor in relation to the demand for use. Ouro Preto-MG.

Flick, U. (2018). An Introduction to Qualitative Research (6th ed.). Sage.

Friocell Refrigeration. (n.d.). The polyurethane panel: the best insulation for cold rooms. Retrieved from https://friocell.com.mx/panel-sandwich/panel-sandwich-aislate-camaras/.

Green, P. (2022). Optimizing pump efficiency. Journal of Mechanical Engineering.

Hassanien, R. H. E., Li, M., & Tang, L. (2016). Solar energy utilization in agricultural greenhouses. Renewable and Sustainable Energy Reviews, 54, 989-1001. https://doi.org/10.1016/j.rser.2015.10.095.

INE [National Institute of Statistics]. (2023) Survey on the Impact of Access to Sustainable Energy – IAES 2022 Final Report. 82p. Retrieved from Web: www.ine.gov.mz.

Johnson, R. (2019). Refrigeration and Air Conditioning. 3rd ed. Boston: Technical Books.

Jones, M. (2019). Energy Systems Engineering. London: Springer.

Jones, M., & Brown, L. (2019). Mechanical seals in refrigeration systems. Refrigeration Technology.

Klein, S. A. (2023). Engineering Equation Solver (EES). F-Chart Software.

Mecalux. (n.d.). Thermal insulation in cold rooms. Retrieved from https://www.mecalux.com.br/artigos-logistica/isolamento-termico-nas-camaras-frigorificas.

Meque, R., Cristóvão, L., Chichango, F. (2023). Socio-environmental impacts caused by tropical cyclones Idai and Eloise in Sussundenga District, Mozambique Journal of Research, Society and Development.12(14),1-8. 01-Aug. DOI: http://dx.doi.org/10.33448/rsd-v12i14.40818.

Nhambiu, J., & Chichango, F. (2024). Prognosis of the environmental impact of vehicular emissions in Mozambique: A quantitative analysis of the use of fossil fuels and the growing import of used vehicles. Research, Society and Development, 13(7), e8013746368. https://doi.org/10.33448/rsd-v13i7.46368.

Nhambiu, J., Chichango, F. (2024a). Comprehensive Analysis of the Energy Transition in Mozambique: Opportunities and Challenges for Achieving the Established Global Goals Journal of Energy Technologies and Policy. 14(2),45 – 65. DOI: 10.7176/JETP/14-2-04.

Nhambiu, J., Chichango, F. (2024b). Forecasting energy consumption in Mozambique: A comparative analysis of advanced machine learning models from 2025 to 2045. Research, Society and Development (accepted for publication on September 2024)

Patton, M. Q. (2015). Qualitative Research & Evaluation Methods (4th ed.). Sage.
Refrigeration Portal (2024). Absorption refrigeration. Retrieved from https://refrigeracao.net/topicos/refrigeracao_absorcao. On July 20, 2024.

Sbravati, A. & Silva, A. F. S. (2011). Absorption refrigeration. Unicamp. Retrieved August 20, 2024 in https://www.fem.unicamp.br/~em672/Absorcao_Alan_Andre.html.

Sbravati, A., & Silva, J. (2011). Solar thermal energy: Applications and efficiency. Journal of Thermal Engineering, 30(2), 123-135.

Silva, J. G. (2020). Absorption refrigeration systems: Applications and efficiency. Journal of Thermal Engineering, 29(3), 45-58.

Smith, J. (2020). Fundamentals of Absorption Refrigeration Systems. New York: Engineering Press.

Smith, J. (2020a). Thermodynamics: Principles and Applications. New York: Academic Press.

Smith, J. (2023). Fortran for Absorption Refrigeration Systems. Technical Publishing.

Smith, R. (2020). Centrifugal pumps in industrial applications. Pump Engineering Journal.

Solar Energy Laboratory. (2023). TRNSYS 18: A Transient System Simulation Program. University of Wisconsin-Madison.

Srikhirin, P., Aphornratana, S., & Chungpaibulpatana, S. (2001). A review of absorption refrigeration technologies. Renewable and Sustainable Energy Reviews, 5(4), 343-372. https://doi.org/10.1016/S1364-0321(01)00003-X,

Srikhirin, P., Aphornratana, S., & Chungpaibulpatana, S. (2001). A review of absorption refrigeration technologies. Renewable and Sustainable Energy Reviews, 5(4), 343-372. https://doi.org/10.1016/S1364-0321(01)00003-X

Venturini, O. J.; Pirani, M.J. (2005). Brazilian power plants, fupai/efficientia. Energy Efficiency in Industrial and Commercial Refrigeration Systems. Rio de Janeiro: Eletrobrás.3160p. Recouped https://buscaintegrada.ufrj.br/Record/aleph-UFR01-000637749/Details.

Vilain, R. (2018). Project of small cold rooms. Federal Institute of Education, Science and Technology of Santa Catarina.

White, R. (2021). Absorption Refrigeration Systems. San Francisco: Wiley.

White, S. (2021). Sealing solutions for corrosive environments. Chemical Engineering Review.

World Commission on Environment and Development. (1987). Our Common Future. Oxford University Press.

World Health Organization. (2021). Vaccines and immunization. Retrieved from https://www.who.int/healthtopics/vaccines-and-immunization.

World Medical Association. (2013). Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects. JAMA, 310(20), 2191-2194. https://doi.org/10.1001/jama.2013.281053

World Medical Association. (2013). Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects. JAMA, 310(20), 2191-2194. https://doi.org/10.1001/jama.2013.281053.