Physics-Based Dynamic Modeling of Solar-Powered Off-Grid Cold Storage for Perishables Using Modelica: A Case Study – Xingalool, Somalia

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Abstract

This paper presents a dynamic, physics-based Modelica model for simulating solar-powered, off-grid cold storage systems used to preserve perishables. A preliminary component library, developed using the Modelica Standard Library, supports modular modeling of photovoltaic (PV)-powered chillers, thermal loads, and latent thermal energy storage (LTES), which maintains cooling during non-solar hours. The library is applied to a 200 m³ cold room in Xingalool, Somalia, designed to stay at 5 °C. A case study simulating 500 kg of crop loading at 8:00 and unloading at 17:00 demonstrates the system's dynamic behavior under realistic solar and ambient conditions.

Keywords: Off-Grid, Cold Storage, Digital Twin, Agriculture

1 Introduction

Post-harvest losses of perishable crops remain a pressing challenge, particularly in low- and middle-income countries. In regions such as sub-Saharan Africa and South Asia, up to 50% of harvested fruits and vegetables are lost due to the absence of proper cold storage near farms (Amjad et al. 2023). These losses not only reduce farmer income and worsen food insecurity but also contribute significantly to greenhouse gas emissions (de Souza Garcia et al. 2024).

To mitigate these issues, solar-powered off-grid cold storage systems are increasingly seen as promising solutions for remote agricultural communities (Natarajan et al. 2023). However, their design is inherently complex due to the fluctuating nature of solar energy, variable cooling demands, and the need for reliable energy storage (electrical or thermal) for maintaining the desired temperature in the cold room continuously when the sun light is not present. Dynamic modeling provides a way to calculate system performance under varying conditions and improve design and operation (Purcell et al. 2023). Modelica, a physics-based, equation-oriented modeling language, offers a powerful framework for capturing such multi-domain, dynamic behavior and guiding performance-driven design (Modelica Association 2017).

In this research, a dynamic Modelica model of a solar-PV-powered off-grid cold storage system for perishables is developed for the first time. The system integrates a vapor compression chiller and a latent thermal energy storage (LTES) unit using water/ice to extend cooling during periods without sunlight. The model captures dynamic processes on both demand (e.g., product loading/unloading, wall and infiltration loads) and supply sides (e.g., PV variation, LTES charging/discharging). This work lays the foundation for a digital twin capable of scenario testing, optimization, and real-time analysis.

2 Modelica Modeling Approach

A preliminary component library was developed in Modelica with open-source Modelica Standard Library (MSL) to represent the thermal behavior of solar-powered, off-grid cold storage systems for perishables. The library enables modular and object-oriented construction of system models, simplifying configuration and simulation using reusable components.

In this paper, the library is applied to simulate a representative system in Xingalool, Somalia, consisting of a 200 m³ cold room maintained at 5 °C with time-dependent cooling loads such as product entry and removal, product respiration, wall and infiltration heat gains, and lighting. A vapor compression chiller with a variable-frequency drive (VFD) compressor is powered directly by photovoltaic (PV) panels. The compressor speed adjusts with available solar power, delivering variable cooling capacity. To ensure reliable operation during low or no solar input, a latent thermal energy storage (LTES) unit is incorporated, using roll-bond heat exchangers for energy exchange.

The model focuses on thermal energy transfer through heat ports and omits fluid flow dynamics to maintain computational efficiency. Figure 1 illustrates the three-stage energy flow: during sunlight hours, PV electricity drives the chiller to cool the cold room directly and any surplus power charges the LTES unit; once solar input falls below chiller demand (e.g. at dusk or under cloud), the stored latent thermal energy becomes the sole cooling source, sustaining the cold-room temperature until PV power resumes.

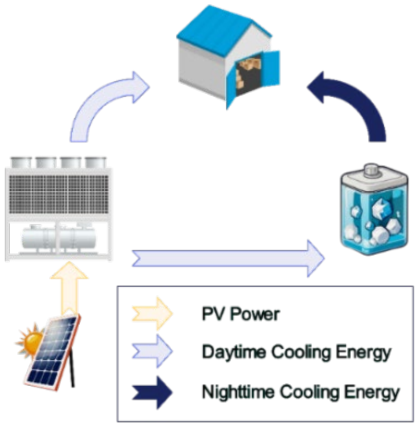

Figure 1. Thermal Model Energy Flow

3 Component Modeling

This section describes the dynamic modeling approach for key components in the cold storage system.

Cold Room and Cooling Loads: The cold room, sized at 200 m³ (4 m × 11 m × 4.6 m), is modeled as a single-node control volume, assuming uniform air temperature throughout, which justifies a lumped capacitance assumption due to well mixing of air in the room. The space is maintained at 5 °C and insulated from direct solar exposure, and is assumed to be filled to 50 % capacity with perishable crops. Cooling demand is dynamically driven by both internal and external loads, including crop loading/unloading, wall heat transfer, infiltration, lighting, and occupant presence.

- Product Sensible Heat Load: To capture the dynamic thermal impact of crop handling, a simplified discretization approach is used. The product mass is divided into two tanks to approximate the first-in-first-out (FIFO) behavior during cooling and storage. Fresh crops enter the first tank at 8:00, exchange heat with the cold room air, and are transferred to the second tank once their temperature converges with that of the second tank. Crops are assumed to be removed at 17:00. This method captures the transient sensible load from crop cooling and removal throughout the day. The logic of the proposed approach is presented in Figure 2 and Equation (1), where Tm_1 and Tm_2 denote the temperatures of the product masses m_1 and m_2 in the first and second tanks, respectively; ε is an infinitesimal tolerance (ε→0).

$$if\ T_{m_1} = T_{m_2} \pm \varepsilon\ \ (\varepsilon \to 0)\ then$$
$$m_1 \to 0; m_2 = m_1 + m_2 \quad (1)$$

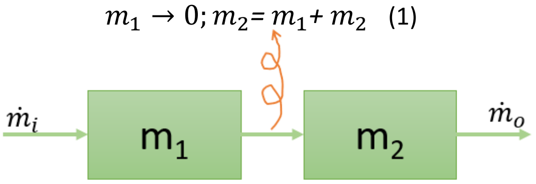

Figure 2. The logic of product sensible heat load model

- Additional Cooling Loads: Time-dependent cooling loads are included to reflect realistic system behavior. Wall heat transfer is modeled using an R-C approach with a U-value of 0.125 W/m²·K, and material properties accounting for thermal mass. Respiration heat from stored crops is computed based on cold room temperature and total product mass dynamically (Blumenthal et al. 2023). Infiltration gains arise from air leakage through a 1.4 m × 2.4 m door and vary with ambient conditions. Occupant heat is modeled using a fixed schedule with two persons entering the room for 2 hours in the morning and afternoon. Lighting is triggered by occupancy and set at 6 W/m².

PV Power Generation: On the supply side, the model accounts for variations in solar irradiance and ambient temperature, which affect PV output. A temperature-dependent efficiency model is used to convert solar input into electrical power, capturing realistic system behavior under varying environmental conditions. (Olukan and Emziane 2014).

Latent Thermal Energy Storage (LTES): To maintain cooling during non-solar hours, a latent thermal energy storage system using roll-bond heat exchangers (RHXs) is integrated. The LTES tank is filled with phase change material (PCM) and connected to a heat transfer fluid (HTF) circuit that charges or discharges the PCM based on energy availability and cooling demand. In the simplified thermal energy-based Modelica model the heat transfer to or from LTES is carried out via a heat port rather than directly involving fluid medium.

Figure 3 shows the LTES tank as a rectangular prism filled with water/ice, into which identical roll-bond heat-exchanger plates are inserted in parallel at 31 mm center-to-center spacing.

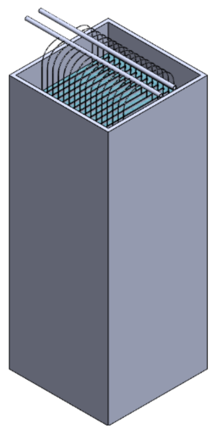

Figure 3. 3D schematic of LTES

Because empirical correlations for natural convection during PCM melting and solidification over a vertical roll-bond heat exchanger are lacking, heat transfer within the PCM has been assumed to occur solely by one-dimensional conduction. A single roll-bond plate plus the half-spacing of PCM is thus defined as the “base unit.” A lumped-capacitance assumption for the entire PCM domain in the base unit would introduce large errors due

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to steep temperature gradients during phase change; consequently, the PCM thickness of each base unit is discretized into multiple control volumes (Figure 4).

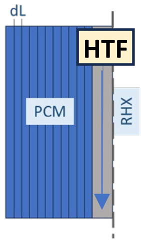

Figure 4: Base element of the LTES model

Within each volume, transient heat storage and transfer are represented by a thermal capacitance and a conduction resistance, whose governing equations are presented in Equations (2)–(7).

PCM Heat Capacity:

$$m.C.\frac{dT}{dt} = Q_{flow} \tag{2}$$

$$C = \begin{cases} C_{ice} & T < T_s \\ \dfrac{h_{sl}}{T_l - T_s} & T_s \leq T \leq T_l \\ C_w & T > T_l \end{cases} \tag{3}$$

$$f_{liq} = \begin{cases} 0 & T < T_s \\ \dfrac{T - T_s}{T_l - T_s} & T_s \leq T \leq T_l \\ 1 & T > T_l \end{cases} \tag{4}$$

PCM Heat Transfer:

$$Q_{flow} = G.(T_{hot} - T_{cold}) \tag{5}$$

$$G = \frac{K_{eff}.A}{d} \tag{6}$$

$$K_{eff} = K_{ice}.(1 - f_{liq}) + K_w.f_{liq} \tag{7}$$

In these equations, m is the mass of PCM in each control volume, C the specific heat capacity of the PCM, T the local PCM temperature, Q_{flow} the heat flow into or out of the PCM, f_{liq} the liquid fraction of the PCM, G the thermal conductance between hot and cold faces, A the heat-exchange area, d the conduction path length, K_{eff} the effective thermal conductivity, The solidus and liquidus temperatures, T_s and T_l, are specified as 272.85 K and 273.15 K, respectively. A CFD conduction-only charging simulation was conducted with the roll-bond boundary held at 259.15 K, and the Modelica model was run under the same condition; the validation comparison is presented in Figure 5.

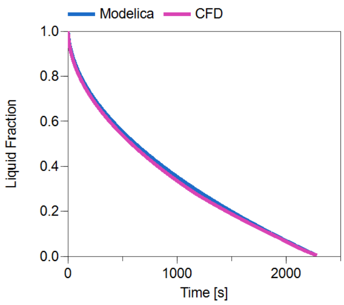

Figure 5: CFD validation results for liquid fraction

4 System Integration and Case Study Results

With all key components developed, the system is now ready for integration under a coordinated control logic. The initial control strategy, shown in Figure 6, distinguishes between normal and cloudy days. On normal days, energy from the PV is first used to cool the cold room. Once the cold room reaches the desired temperature, excess energy is redirected to charge the LTES. On cloudy days, if solar radiation is insufficient to run the chiller, the LTES is discharged to maintain the cold room temperature.

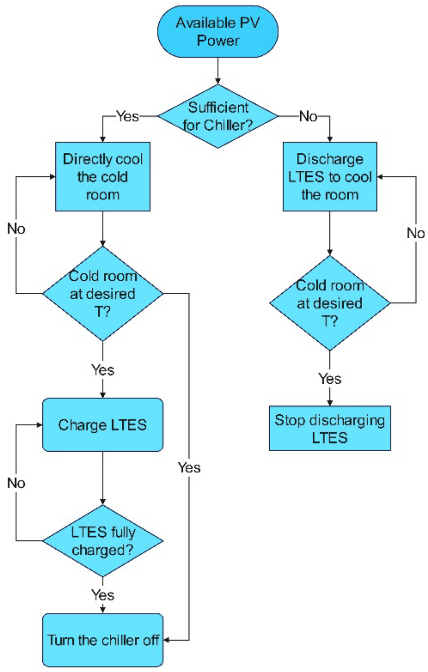

Figure 6: Control Strategy for Normal and Insufficient PV Power Conditions

Representative simulation results are provided for Xingalool, Somalia. Figure 7a shows the cold room temperature during a typical sunny day. The blue line indicates how crop loading in the morning introduces a heat disturbance, prompting the chiller to cool the products. Later, door opening in the afternoon causes another rise in temperature due to infiltration of warm air. The temperature zig-zagging in the cold room is due to the hysteresis mechanism considered for the chiller to avoid chattering and unlimited on/off cycles. To demonstrate the role of LTES in mitigating temperature fluctuations, two consecutive cloudy days were simulated (Fig. 7b), showing how the LTES supports temperature regulation when solar power is unavailable. It can be seen that LTES with 20 roll-bond heat exchangers is not capable of maintaining the cold room temperature under normal loading conditions in two consecutive cloudy days. Hence, in case this occasion is going to be repeated, either the LTES capacity should increase or loading behavior should change when sun light is absent.

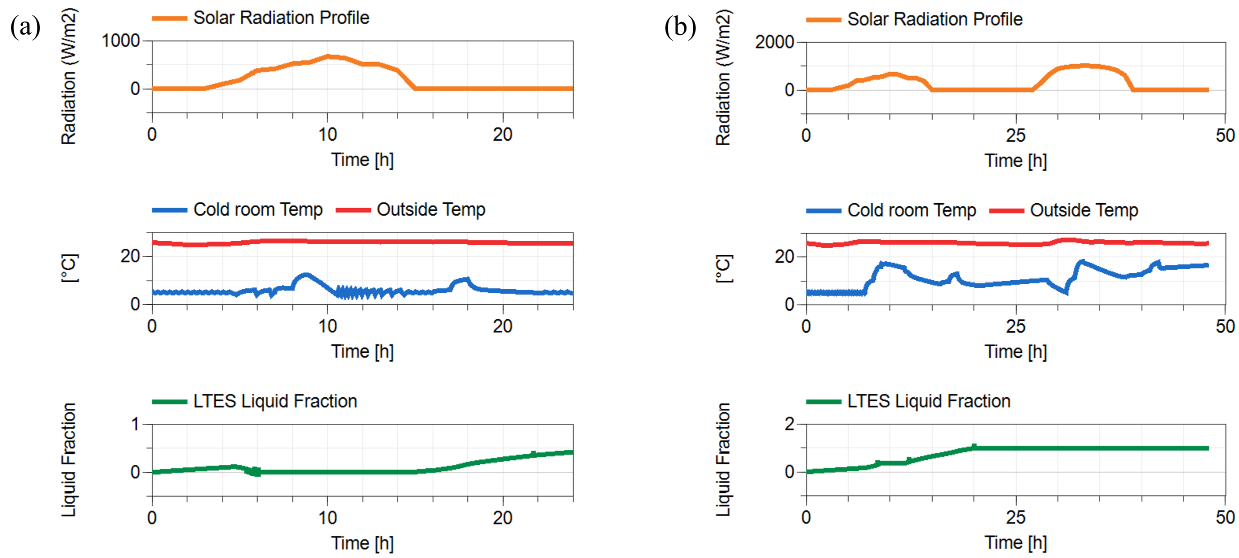

Figure 6: Represantative results for (a) normal sunny day, (b) two consecutive cloudy days

5 Conclusion

This work presents a dynamic, physics-based Modelica model for simulating solar-powered, off-grid cold storage systems for perishables. By leveraging Modelica's object-oriented, equation-based framework, a modular component library was developed that can be readily extended or reconfigured for alternative system variants, such as different PCM geometries, chiller types, or control strategies, without rewriting core equations. The library was applied to a 200 m³ case study in Xingalool, Somalia, demonstrating accurate capture of time-dependent thermal behavior under realistic solar and load profiles. These results underscore Modelica's strengths in rapid prototyping, and parameterized system variation, for sustainable cold-storage design and optimization..

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