



SOPHIA

Sustainable Off-grid solutions for
Pharmacies and Hospitals In Africa

COMPARISON BETWEEN BATTERY (CHEMICAL) ENERGY STORAGE AND THERMAL STORAGE FOR REFRIGERATION SYSTEMS UNDER AFRICAN CLIMATE CONDITIONS

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D3.3: Comparison between battery (chemical) energy storage and thermal storage for refrigeration systems under Africa climate conditions

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ABBREVIATIONS

AC	Alternating current
C	total storage capacity
CEC	California Energy Commission
CO ₂	Carbon Dioxide
DC	Direct current
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
η_s	Isentropic efficiency of the compressor
GHI	Global horizontal irradiance
h	Enthalpy
H2020	Horizon 2020
$\dot{m}$	Mass flow rate of the refrigerant
P_{load}	Net charging power available after accounting for losses
PV	Photo voltaic
$\dot{Q}$	Cooling load
R290	Propane as refrigerant
R744	Carbon Dioxide as refrigerant
ρ	density
SOC	State of charge
SophiA	Sustainable Off-grid solutions for Pharmacies and Hospitals in Africa
TMY	Typical Meteorological Year
$\dot{V}$	volume flow rate
W	Work
WP	Work Package



EXECUTIVE SUMMARY

SophiA project aims to provide sustainable off-grid energy supplies and clean drinking water for rural and remote health facilities in Africa, thereby accelerating the sustainable development, growth and economic transformation, and ensuring improved access to energy and health services for all. SophiA will develop and locally manufacture innovative, modular, flexible, affordable and efficient solar containers to provide the local population in four rural health centres located in four different climatic regions where help is most needed, offering sustainable solutions adapted to the African context and then transferable to the whole of Sub-Saharan Africa. Led by Hochschule Karlsruhe (HKA), the SophiA consortium consists of 13 project partners from three European countries (France, Germany and Switzerland) and four African countries (Burkina Faso, Cameroon, South Africa, and Uganda).

This deliverable offers a thorough assessment of the energy storage system developed for solar-powered refrigeration containers, with particular emphasis on the integration of electro-chemical batteries and ice-based thermal energy storage. Through the use of a detailed simulation framework, incorporating typical meteorological year data, operational user profiles tailored to container function, and simplified representations of energy storage mechanisms, the research evaluates the performance of both storage types under a range of conditions. The simulation shows that supplementing an electro-chemical storage with a latent ice storage significantly reduces battery capacity requirements, thereby suggesting notable advantages in terms of cost-efficiency and environmental sustainability. This approach also addresses the inherent limitations of the simulation, including the exclusion of battery aging and the omission of intricate internal processes within the storage systems. Nonetheless, the analysis confirms the practical viability of maintaining continuous refrigeration using either or both storage methods. Ultimately, the results advocate for the strategic use of ice storage as a complementary solution and provide a foundation for optimizing storage configurations according to environmental, economic, and geographical factors. Future work is expected to enhance the model's fidelity through the inclusion of more sophisticated storage representations and real data from actual user environments.



1. INTRODUCTION

With rising global temperatures, increasing population, and improving living standards, the worldwide demand for cooling and air conditioning is growing rapidly. Today, this trend is evident in Africa, where climate change and extreme heat are coupled with one of the fastest-growing populations globally, particularly in Sub-Saharan regions. This surge in cooling demand is exacerbated by the lack of reliable electrical infrastructure, which directly impacts critical sectors such as healthcare and the food supply chain. In many rural and peri-urban areas, hospitals and clinics often face frequent power outages, threatening the safe storage of vaccines, medicines, and temperature-sensitive food items.

To address these challenges, the European Union-funded SophiA project (Sustainable Off-grid solutions for Pharmacies and Hospitals in Africa) is developing a fully self-sufficient, solar-powered refrigeration system housed in ISO-containers. Each unit is divided into three independently temperature-controlled chambers designed for the safe storage of medical supplies and food. These units are being piloted in diverse climatic zones at hospitals in Burkina Faso, Uganda, Cameroon, and Malawi, allowing for performance evaluation across a wide range of ambient conditions.

The cooling system employs a two-stage cascade refrigeration cycle with integrated thermal energy storage. It uses environmentally friendly refrigerants—propane (R-290) for the higher-temperature circuit and carbon dioxide (CO₂) for ultra-low temperatures. Water is used as a phase-change material to buffer thermal storage. One of the system's innovative features is a naturally circulating evaporator, which charges the thermal storage during daylight hours when solar PV is active. This allows the refrigeration units to maintain target temperatures of +5 °C for general pharmaceuticals and food, –30 °C for blood plasma and protein-based medicines, and –70 °C for ultra-cold vaccine storage, such as mRNA vaccines.

A major design challenge in off-grid PV-powered cooling is ensuring 24-hour temperature stability despite only 6–8 hours of sunlight. Traditional solutions rely heavily on electrochemical batteries, e.g. lithium-ion batteries, but this comes with cost, sustainability, and degradation concerns. The SophiA approach reduces reliance on electrochemical batteries by maximizing the use of thermal energy storage. During the day, water is frozen to store thermal energy, and at night when PV production ceases and ambient temperatures drop this frozen mass is used to maintain cooling without engaging the compressor. It should be noted that each degree Celsius reduction in the temperature difference between interior and exterior can lower compressor energy consumption by around 2%. Thus, during nighttime it is more efficient to



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charge the system but there is no energy from the PV-system. When charging at daytime the evaporator inside the thermal energy storage should be operated at a high evaporating temperature.

However, for the lower-temperature compartments (-30°C and -70°C), lithium-ion batteries are still necessary due to the higher cooling demands and inability to use thermal mass alone. Therefore, the system is designed with a hybrid storage model: thermal storage for $+5^{\circ}\text{C}$ operation and battery-backed support for ultra-low-temperature stages. The overall system was simulated and validated to ensure that the sizing of both thermal and electrochemical storage components is sufficient to maintain uninterrupted cooling across all compartments, even during prolonged cloudy periods or PV underperformance.

2. SIMULATION METHOD

The validation of the container's energy system design is carried out through a comprehensive, year-long simulation framework. This simulation integrates multiple components, including a Typical Meteorological Year (TMY) dataset, a detailed weekly user profile developed in collaboration with project partner hospitals, and simplified but representative models of both thermal and electrochemical energy storage systems. The daily behavior of the system was simulated, considering also the thermodynamic conflict that the vapor compressor cycle is working more efficient during the night due to the lower ambient temperatures thus the condensation temperature is also lower at night time. A 24-hour runtime also decreases the size of the compressor. While smaller compressors used to have lower efficiency, a compressor with a higher capacity needs a thermal energy storage which in return decreases the efficiency of the system due to the extra heat exchanging. However, the electricity production is only during the day so there is an optimum share between a chemical battery, thermal storage and compressor size.

To simulate the system operation behavior, a user profile needs to be created. The user profile includes daily and weekly patterns for the transport and storage of vaccines, blood plasma, and perishable food items, as well as emergency usage days such as the withdrawal of blood for surgical or clinical needs. This profile is repeated weekly across the simulation year, allowing for a consistent yet flexible load pattern to be analyzed under real conditions.

Meteorological input data is sourced from the Photovoltaic Geographical Information System (PVGIS), which provides reliable solar irradiance, temperature, and humidity profiles for all four



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pilot sites in Burkina Faso, Uganda, Cameroon, and Malawi [1]. These environmental inputs are crucial as they drive the heat gain through container walls, influence ventilation and infiltration heat loads during door openings, and determine the latent loads related to humidity control. The combination of ambient air temperature and humidity enables precise calculation of energy demand for maintaining the interior spaces at +5 °C, –30 °C, and –70 °C.

Using this framework, the energy demand of each cooling zone is modeled. For ultra-low-temperature compartments, detailed thermodynamic calculations are included, factoring in evaporation and condensation temperatures, the isentropic efficiency of compressors, and refrigerant-specific properties such as those for propane, CO₂, or ethane. Superheat values, including additional system-specific margins, are also incorporated to simulate realistic performance.

The +5 °C compartment is handled using two alternate cooling strategies. In the first, the propane cycle operates continuously, powered by a lithium-ion battery system to ensure overnight operation. In the second strategy, the propane cooling system is designed to run only during daylight hours when PV output is available. Any excess solar energy is then used to produce and store ice in a dedicated thermal reservoir, which passively maintains the +5 °C temperature during nighttime hours without drawing on electrochemical batteries. To model energy input, solar generation is simulated using PVLIB [2], a Python-based photovoltaic modeling library. Radiation data, cell efficiency curves, temperature coefficients, and local wind speeds are used alongside datasheet values for the PV modules to calculate hourly AC energy output throughout the year. The simulated PV output is then compared against hourly energy demand. In the chemical storage scenario, any shortfall is compensated via lithium-ion batteries. In the thermal energy storage scenario, surplus solar energy is allocated to charging the ice storage system, with the compressor sized accordingly to operate at a higher capacity during peak solar hours.

The battery system is modeled with a simplified yet realistic behavior. A maximum charge rate is set, and as the system reaches 80 percent state of charge, the charging current is gradually tapered to reflect efficiency losses and thermal management limitations, mirroring the behavior of real-world lithium-ion systems.

This multi-layered simulation provides a robust foundation for validating the technical feasibility and sizing of both thermal and chemical storage systems. It ensures that medical-grade cooling performance can be maintained across all compartments, even during extended periods of low solar input, without reliance on unstable grid infrastructure.



2.1 Methodology

This section outlines the theoretical framework and computational methodology used to analyze the performance of the container's cooling system. The analysis covers all major aspects of the system, including container design, user behavior, cooling cycles, photovoltaic energy generation, and storage. Each part contributes to a comprehensive understanding of the energy requirements and thermodynamic performance of the container.

2.1.1 Heat Flow in the Container

The container consists of three distinct compartments, each designed for a different temperature range and equipped with its own cooling cycle. Figure 1 illustrates the full layout. In this system, starting with the ethane-based cooling cycle it has its heat sink located in the -30°C compartment. Heat flows into the container from the outside environment and also from the $+5^{\circ}\text{C}$ compartment into the -30°C compartment. The CO_2 refrigeration system must absorb the internal heat load from the -30°C space, the condensing heat of the -70°C freezer box, its stored materials respectively equipment and cooling down the air after the door has been opened. The $+5^{\circ}\text{C}$ room also rejects heat to the -30°C freezing room. However, this is considerably smaller than the heat introduced into the $+5^{\circ}\text{C}$ storage space by the engine room and external walls. The engine room is assumed to operate at a temperature 15 K above the outside ambient temperature due to the operation of internal equipment. Additional heat flows resulting from air exchange and introduced goods are treated separately and are detailed in the section on user interaction and load profiles. The air exchange rate is found to be the main source of heat input into the system.

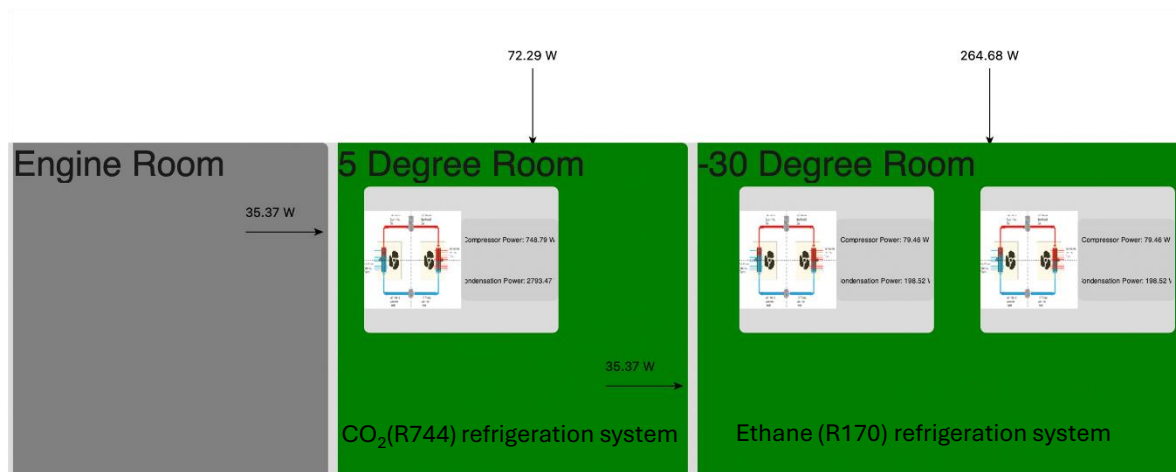


Figure 1: Heat flow model of container between cold rooms.



2.1.2 User Profile

The hourly user profile plays a crucial role in estimating the thermal loads resulting from door openings, air exchange, and the heat capacity of goods stored in the compartments. Heat capacity values are based on data from the Container Handbook [3], while the necessary air exchange rates are sourced from established literature [4]. When goods are introduced into the container, the frequency and duration of door openings result in additional air exchange. The user behavior plays a key role in the energy consumption. It was therefore necessary to reach out to the project partner “Operieren in Afrika e.V.” and ask them when their medicine is delivered, when they will take out the medicine and how long these logistic processes usually take. Because the system is new, the data provided by the hospital is based on assumptions and the 12 months experience they now have using the system. This process is modeled using humid air properties obtained from CoolProp at the site in Léo, Burkina Faso. The energy required to cool the incoming air from its external state to the internal target state is calculated using enthalpy differences and air density. Specifically, the energy is determined by equation 2.1:

$$W = (h_1 - h_2) \cdot \rho \cdot \dot{V} \quad \text{Eq. (2.1)}$$

where W is the required energy, h_1 and h_2 represent the specific enthalpies of incoming and conditioned air respectively, ρ is the air density, and $\dot{V}$ is the volume flow rate. These thermodynamic parameters are extracted using temperature, pressure, and humidity data at the hospital site in Léo from the Typical Meteorological Year (TMY) dataset from the PVGIS database and tailored to the specific room conditions. This allows for a detailed calculation of the cooling energy required for air exchange and the thermal load of the introduced goods. When combined with the heat flows through the container walls, the total heat load on the +5 °C room can be estimated. Figure 2 compares this heat load during one week in January and one in June, showing clearly that the summer and humid season results in significantly higher thermal stress on the system.



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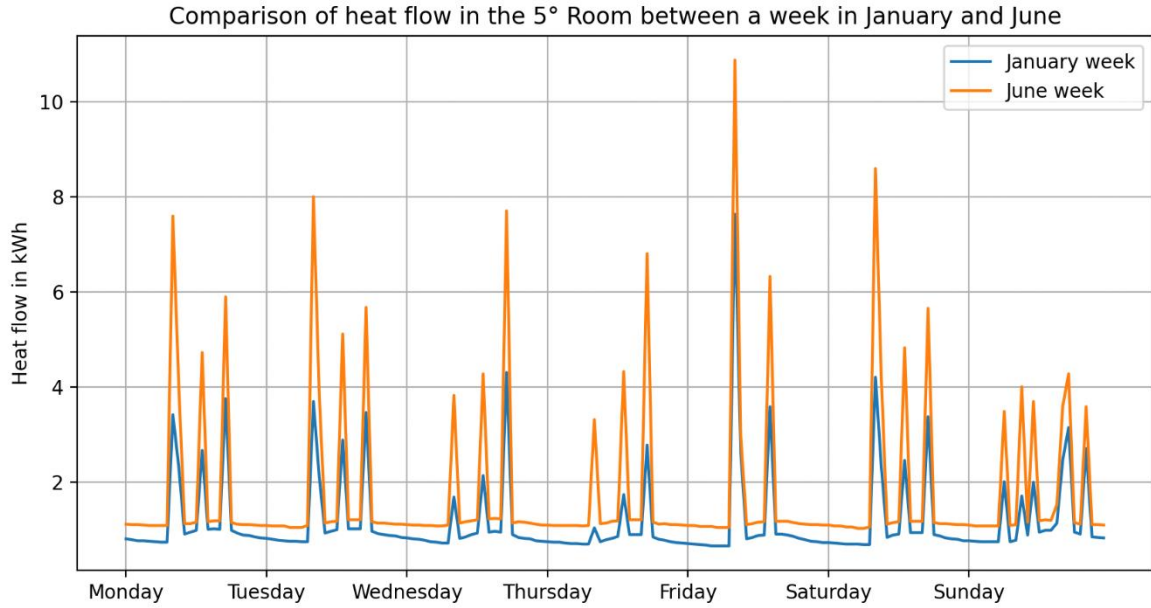


Figure 2: Hourly heat load model in a week.

It is also noteworthy that during the loading and unloading, the door is expected to remain open and the air exchange rate is increasing significantly. In reality, the door is closed automatically so the air exchange is expected to be smaller. The peak on Friday is because a weekly cleaning is scheduled resulting in a longer or more frequent door opening, thus higher air exchange rate. The higher the ambient temperature and the more humidity the air holds, the higher is the heat flow rate into the +5 °C storage room. The air exchange into the -30 °C will not differ throughout the year since it is expected that the air entering will always have the conditions of the +5 °C room which is assumed to be +5 °C and 90% rel. humidity.

2.1.3 Cooling cycle

The operation of each cooling cycle is modeled by instantiating classes with key parameters such as evaporation and condensation temperatures, evaporator characteristics including superheat, isentropic compressor efficiency, and fluid properties obtained from CoolProp [5]. From the evaporation and condensation temperatures, the corresponding pressures are calculated, which serve as the basis for determining the thermodynamic state of the working fluid. Enthalpy and entropy values before and after compression are then computed under the assumption of isentropic processes. The output enthalpy of the compressor is calculated using the relation:

$$h_{comp,out} = \frac{h_s - h_{comp,in}}{\eta_s} + h_{comp,in} \quad \text{Eq. (2.2)}$$



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where $h_{comp,in}$ and $h_{comp,out}$ are the enthalpies before and after compression, h_s is the isentropic enthalpy, and η_s is the isentropic efficiency of the compressor.

Given a required cooling load $\dot{Q}$, the corresponding mass flow rate $\dot{m}$ of the refrigerant can be determined using:

$$\dot{m} = \frac{\dot{Q}}{h_{evap,out} - h_{evap,in}} \quad \text{Eq. (2.3)}$$

The specific compressor work w_{spec} requirement is then calculated as:

$$w_{spec} = h_{comp,out} - h_{comp,in} \quad \text{Eq. (2.4)}$$

By integrating these parameters, the total electrical energy consumption of the system can be computed. The cooling loads for each stage are derived from the simulated user profiles, allowing for a comprehensive estimate of the container's total energy demand under varying environmental and operational conditions.

2.1.4 PV System

The simulation of photovoltaic energy generation is based on the specific geographical characteristics of the installation site, including latitude, longitude, altitude, and time zone. A critical component of the simulation is the accurate modeling of the solar modules, which involves detailed electrical parameters such as the maximum power point voltage and current, open-circuit voltage, and short-circuit current, typically sourced from manufacturer datasheets. In this study, the selected panels are the JA Solar JAM54S30-415/MR modules, each rated at 415 watts peak (Wp). These modules are installed on the roof of the container, with a total of 54 panels per unit. The array is configured in two orientations, as determined by the physical structure and available space.

Meteorological data is derived from the Typical Meteorological Year (TMY) dataset, providing hourly values for ambient temperature, solar irradiance, and wind speed. The irradiance is divided into three key components: global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI). The solar position throughout the year is calculated using the PVLIB library, which takes into account the geographical coordinates of the installation. Tilt and azimuth angles for the module surfaces are determined from technical drawings of the container layout.



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The electrical behavior of the PV modules is modeled using the California Energy Commission (CEC) performance model [6]. After parameterization and configuration of the PV array, the simulation calculates the DC power output using a maximum power point tracking algorithm. AC power output is then computed by incorporating the efficiency and conversion losses of the inverter. For this study, the SMA STP 20000TL-30 inverter model is used. A similar inverter is used in the first SophiA container. The resulting AC power values are generated on an hourly basis and stored for further analysis.

To verify the accuracy of the simulation, the modeled results are compared with measured data from an actual solar installation in Germany operating under similar conditions. Figure 3 presents this comparison, with blue bars representing the simulated monthly yields and orange bars showing the recorded data. The observed discrepancy is largely attributed to the use of averaged TMY data rather than real-time meteorological input. The total annual yield predicted by the simulation amounts to 9.9 MWh, whereas the measured yield from the physical system is 9.2 MWh, resulting in a deviation of approximately 8 percent.

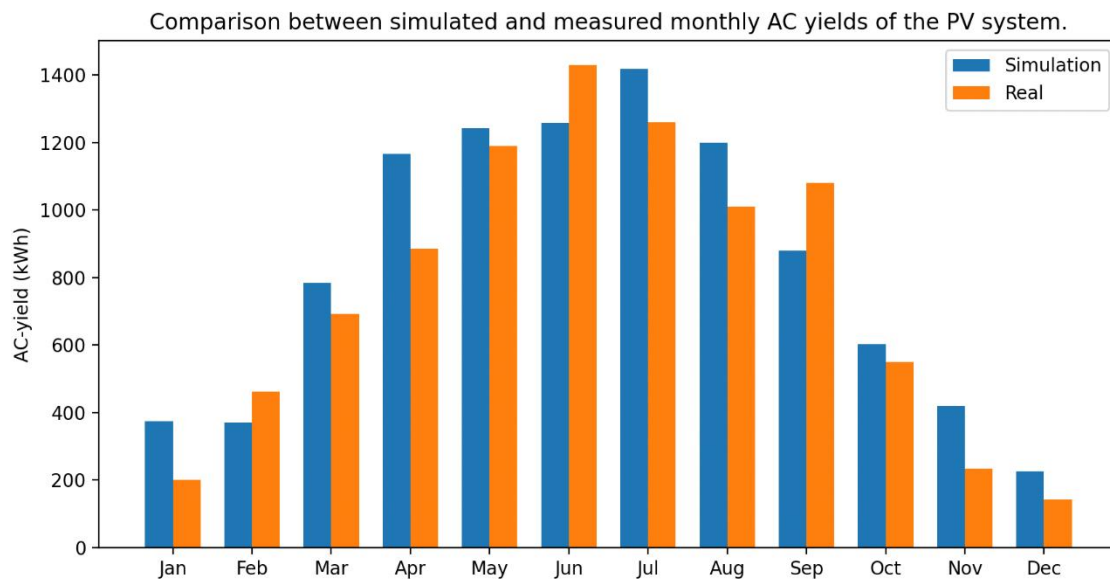


Figure 3: Comparison between simulated and measured monthly AC yields of the PV system.

2.1.5 Energy Storage

The energy storage system is modeled using a simplified structure, where both the ice-based thermal storage and the electrochemical battery storage are defined by two core parameters: their total capacity and their current state of charge (SOC). To simulate the system behavior, charge and discharge functions are used to update the SOC based on the power supplied to



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or drawn from the storage. Energy losses of 15 percent are assumed for both charging and discharging phases, reflecting typical real-world inefficiencies.

The charging process begins by evaluating whether the available power exceeds the system's charging capacity. If the input power is within acceptable limits, the state of charge is incremented accordingly. To reflect the gradual tapering of current as the battery approaches full charge, the model limits the charging rate when the SOC exceeds 80 percent. The charging function is defined as follows:

$$SOC = \begin{cases} SOC + \frac{P_{load}}{C}, & \text{if } SOC < 0,8 \\ SOC + \frac{\min(P_{load}(1 - SOC) \cdot C)}{C} & \text{else} \end{cases} \quad \text{Eq. (2.5)}$$

Where P_{load} represents the net charging power available after accounting for losses, and C is the total storage capacity. Before charging, the system ensures that the incoming power does not exceed the maximum allowed charging rate. If it does, the charging input is capped accordingly.

For discharging, a similar rule is applied. When the SOC falls below 0.2, the discharge power is restricted to prevent deep discharge, which could compromise the battery's lifespan or functionality. This approach ensures that the storage simulation aligns with the physical and safety limitations found in real-world energy storage systems.

2.1.6 Overall Simulation

The simulation operates on an hourly resolution and follows a structured sequence of computational steps. In the initial phase, energy consumption is calculated based on a predefined user profile and meteorological inputs from the Typical Meteorological Year (TMY) dataset. For each hour, relevant data (including temperature, irradiance, and energy demand) is stored in separate CSV files to facilitate organized analysis and retrieval.

Once the hourly consumption values are established, they are compared to the simulated photovoltaic energy output for the same time intervals. When the energy generated by the PV system exceeds the container's demand, the surplus energy is directed into storage. Conversely, when the photovoltaic output is insufficient to meet the container's load, the system draws from the available stored energy to compensate for the shortfall.

The simulation evaluates two distinct scenarios to explore different storage strategies. In the first scenario, energy balancing is achieved solely through chemical storage using lithium-ion



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batteries. In the second scenario, a hybrid approach is adopted, combining chemical storage with thermal storage in the form of ice. This configuration aims to reduce dependence on electrochemical storage by leveraging thermal inertia to cover part of the cooling demand, particularly during nighttime hours when solar energy is unavailable.

By comparing these two approaches, the simulation provides valuable insights into the effectiveness of ice storage as a complementary solution to traditional battery storage. It highlights the potential for improving system efficiency and reducing battery capacity requirements through intelligent integration of multiple storage technologies.



3. RESULTS

In the first scenario, the simulation begins with a baseline configuration using a 140 Ah battery at a nominal voltage of 48 V, resulting in an energy storage capacity of approximately 6.7 kWh. To assess system reliability under varying storage conditions, the number of batteries is incrementally increased, and the corresponding outcomes are illustrated in Figure 4. Each subfigure is labeled with the number of batteries deployed. The vertical axis represents the state of charge (SoC) of the energy storage system, while the horizontal axis denotes the simulation timeline over the course of the year, segmented by month. A red dashed line marks the 50 percent SoC threshold for reference.

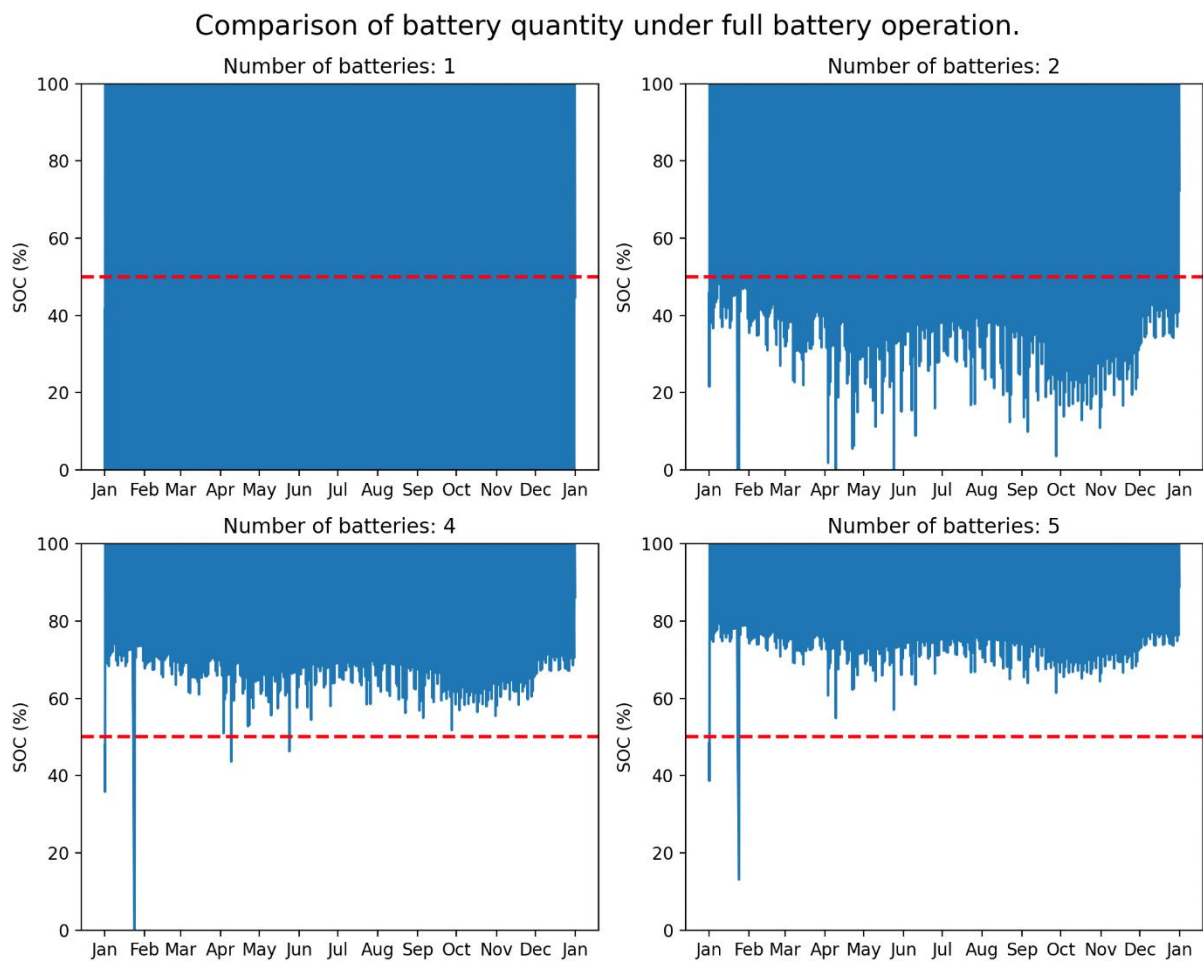


Figure 4: Comparison of battery quantity and corresponding SoC in the annual simulation.

The results show that operating the container with only one battery is insufficient. The SoC frequently drops below 50 percent and reaches full depletion on multiple occasions. When two batteries are used, performance improves slightly, but the system still exhibits frequent periods where the SoC falls below the critical threshold and occasionally empties completely. With four



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batteries, the SoC generally remains above 50 percent, with only a few brief drops and rare full discharges. Once the system is equipped with five batteries, the SoC stays consistently above 50 percent throughout the year, aside from two short exceptions. Notably, the battery bank never fully discharges in this configuration, indicating a reliable level of energy availability. The outstanding two days, the first day in January and at the end of the month, are much lower since the data in the TMY show some significant deviation from the rest of the year.

In the second scenario, ice storage is evaluated as the primary form of energy storage, with capacities ranging from 20 kWh to 70 kWh. The simulation results for this approach are presented in Figure 5. As in the previous case, the y-axis represents the system's state of charge, and the x-axis reflects the monthly timeline. A red dashed line again indicates the 50 percent SoC threshold.

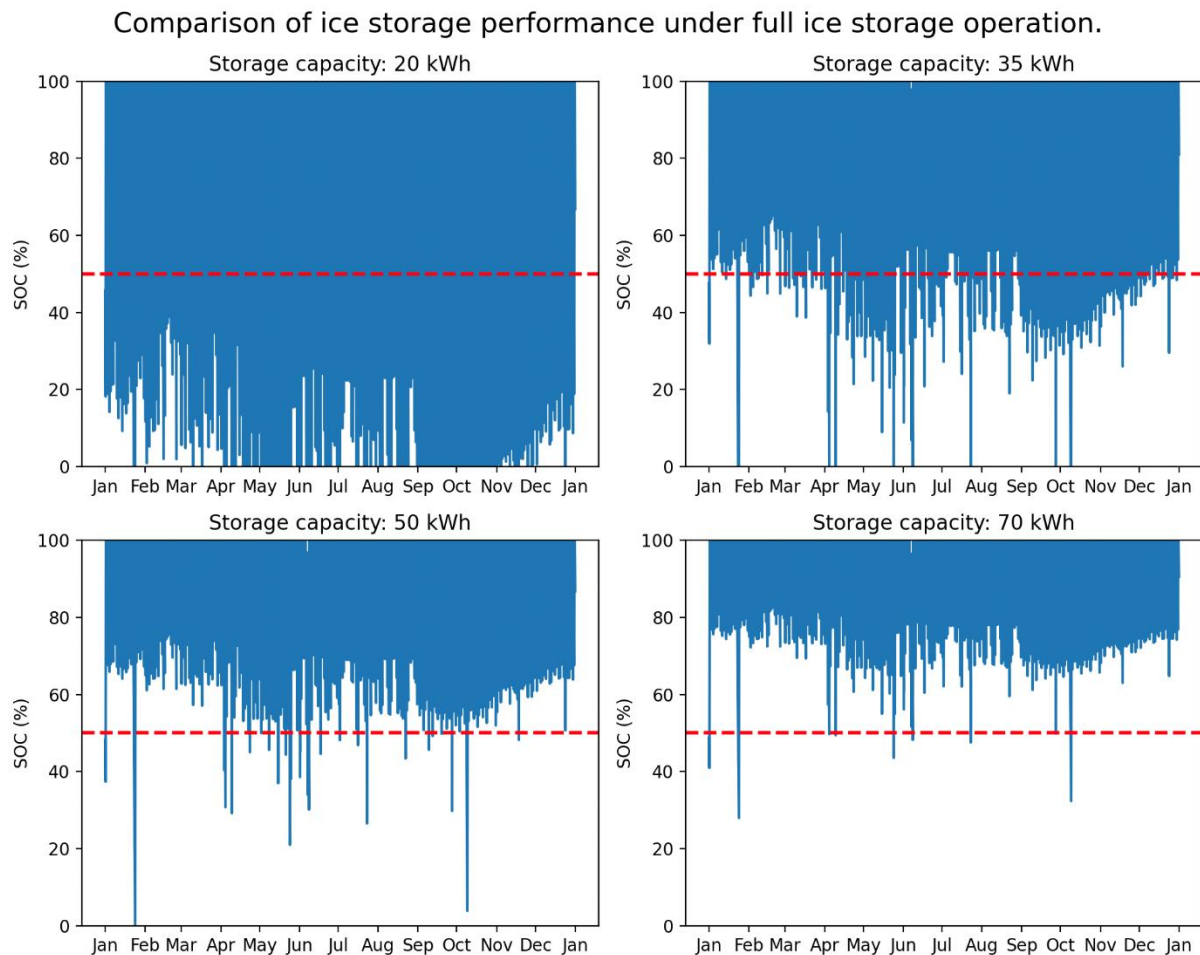


Figure 5: Comparison of ice storage size and corresponding SoC in the annual simulation.



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With an ice storage capacity of 20 kWh, the container's operation is unsustainable, as the SoC remains low and full depletion occurs frequently. Increasing the capacity to 30 kWh improves performance, but the SoC still falls below 50 percent more than half the time and is regularly exhausted. At 50 kWh, the storage system performs considerably better, maintaining SoC above 50 percent for most of the year, with only a single instance of complete depletion. A further increase to 70 kWh ensures that the SoC stays above the 50 percent threshold for nearly the entire year, with just four to five short periods where it dips below.

Although the ice storage strategy proves effective in sustaining the container's cooling needs at higher capacities, it cannot completely replace chemical energy storage. This is due to the specific energy demands of low-temperature cooling cycles, which require battery power for consistent compressor operation. To address this, a hybrid configuration is tested, combining a 50 kWh ice storage system with a single lithium-ion battery. The results of this setup are shown in Figure 6. The battery demonstrates stable charging and discharging behavior, maintaining a charge level near 50 percent for most of the year. There is only one significant discharge event observed at the beginning of the year, after which the system stabilizes. Throughout the rest of the simulation, the ice storage effectively supports the energy requirements of the container, with only minor periods of strain.



State of Charge of battery and ice storage

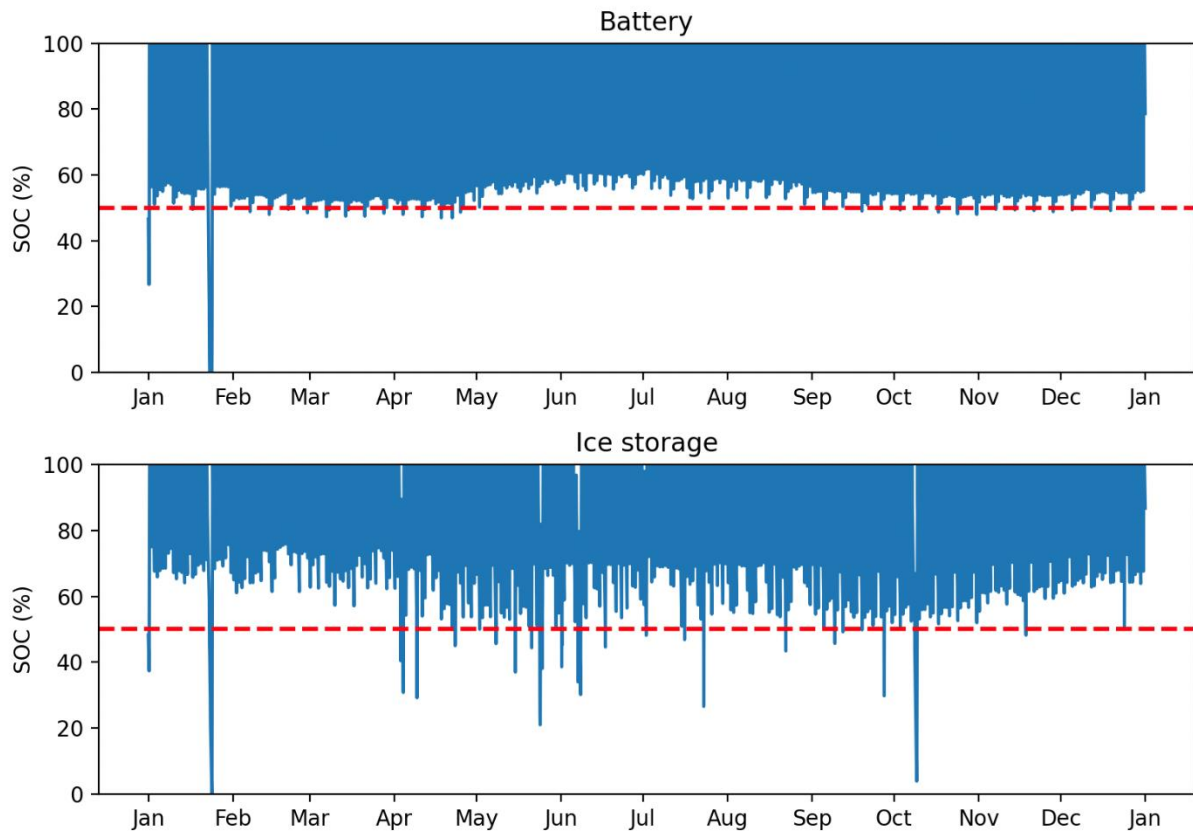


Figure 6: Integration of a battery and ice storage in the system with the resulting SoC.

This hybrid configuration illustrates the benefit of combining thermal and chemical energy storage. It allows for a reduction in battery count while still maintaining reliable operation, optimizing both system performance and cost-efficiency.



4. DISCUSSION

The solar energy simulation used in this study does not account for potential shading from surrounding structures, which could reduce the actual photovoltaic output in certain locations. Additionally, the models for battery and ice storage are simplified and do not incorporate the internal thermodynamic or electrochemical processes that occur within these systems. While these simplifications limit the granularity of the simulation, they offer the significant advantage of enabling rapid and scalable analyses across different geographic locations and extended time periods.

Nonetheless, the use of simplified models introduces certain limitations. Both chemical and thermal storage simulations are affected by the lack of detailed internal modeling, which may lead to deviations from real-world performance. Moreover, the simulation does not incorporate battery aging effects, such as the gradual decline in storage capacity over time due to repeated charge-discharge cycles. In contrast, ice storage systems do not experience a comparable degradation process, and their performance is assumed to remain stable throughout the simulation period and well beyond.

Despite these limitations, the results demonstrate that both energy storage strategies, chemical and thermal, are capable of sustaining the container's operation under the given conditions. In the case of battery-only systems, the minimum number of batteries required for reliable operation can be identified. For scenarios involving ice storage, the results provide a framework for optimizing both the size of the ice storage system and the supporting battery capacity.

This simulation methodology offers a practical and transferable tool for assessing similar containerized cooling solutions in other geographic regions. It supports scalable design and deployment by balancing accuracy with computational efficiency, and it provides a solid foundation for further refinement using more complex storage models or real-world monitoring data.



5. CONCLUSIONS

The simulation results demonstrate a substantial reduction in the required quantity of chemical energy storage when ice storage is incorporated. Specifically, the system's reliance on lithium-ion batteries decreases from five units to just one when supplemented with appropriately sized ice storage. Given the relative simplicity of constructing ice-based thermal storage systems, along with their lower cost and superior environmental performance compared to electrochemical batteries, ice storage emerges as a highly compelling alternative.

An additional advantage of ice storage lies in its durability. Unlike batteries, which degrade over time and require periodic replacement, thermal storage does not experience significant aging, making it a more stable long-term solution. The advantages are already picked up by the medical certified refrigerators which also include a water-ice storage ensuring the cooling capacity in times of black outs. To further enhance system resilience, the inclusion of an emergency generator could be considered. This would ensure continued operation during rare periods of complete storage depletion and could also allow for a further reduction in overall storage capacity.

Determining the optimal combination of battery and ice storage capacity depends on several factors, including environmental goals, financial constraints, and site-specific conditions such as local climate and solar resource availability. These findings suggest the potential to develop a decision-support algorithm capable of recommending an ideal storage configuration based on input parameters and project goals. Investigating the chemical to thermal battery ratio can improve any other applications where cooling or heating is required around the temperature of the phase change material used. The goal should be to minimize the use of Lithium-Ion batteries which reduce the carbon footprint and environmental impact.

Looking ahead, the accuracy and applicability of this modeling approach could be further improved by integrating more sophisticated energy storage models and incorporating real-world user data. Data collected from pilot projects, such as those currently underway in Burkina Faso, could provide valuable insights into actual usage patterns and environmental impacts. By refining user profiles and improving the representation of storage system dynamics, future research can advance the development of optimized, location-specific energy storage strategies for off-grid and containerized cooling systems worldwide.



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