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Numerical model of solar-driven cold storage for small-scale fisheries

Sajid Mehmood[1*], Muhammad Usman[2], Wayan Gede Santika[3], Renaldi Renaldi[1]

1 School of Water, Energy and Environment, Cranfield University, Cranfield, MK43 0AL, United Kingdom

2 Mechanical Engineering Department, University of Engineering and Technology, Taxila, Pakistan

3 Department of Mechanical Engineering, Politeknik Negeri Bali, Bali, Indonesia

ABSTRACT

The need for cold storage is growing worldwide, especially for small-scale fisheries in tropical coastal regions where access to a continuous power supply and modern preservation methods is limited or nonexistent. This deficiency in adequate storage facilities significantly diminishes their catch quality. Novel renewable, grid-independent solutions are required to address this problem. This study proposes and demonstrates a solar-driven grid-independent cold storage unit through a dynamic model developed in TRNSYS simulation software. A detailed parametric study highlights the critical parameters for optimal sizing related to cold storage insulation, sizing of air conditioning systems, and photo-voltaic battery systems. Moreover, the optimal integration was compared with conventional (grid-based) cooling solutions for cold storage. The results show that grid-independent cold storage of 20 feet to store 1,285 kg of fish daily at -20°C requires 24.5 kW of PV array, 10 kW inverter and a battery storage of 151296 Wh to meet the annual electricity demand of 32.3 MWh. The parametric analysis shows that insulation of 150mm reduces thermal energy demand for cooling by 12.3% (from 74 MWh to 64.9 MWh), and a further increase in insulation does not provide significant benefits. The analysis shows how the cooling rate influences the sizing of the HVAC system, how the collector tilt angle adjustment frequency impacts PV performance, and how the battery backup time influences the battery size. The proposed system can save 23.3 tons of carbon emissions annually compared to grid-connected conventional cold storage. The paper discusses the design and implementation of the PV-driven grid-independent vapour compression cooling system, highlighting key influence design parameters, control strategies, and energy management techniques to minimise excessive cooling in the cold storage freezer room.

Keywords: cold storage, grid-independent, TRNSYS, fisheries, solar energy, heat pump

NONMENCLATURE

Abbreviations

BEMS	Building energy management system
COP	Coefficient of performance
FSOC	Fractional state of charge
HR	Heat of respiration
PVBS	Photovoltaic battery system
PV	Photo-voltaic

Symbols

Q_{surf}	Convective heat gain from opaque surfaces
Q_{ishcci}	Absorbed solar fraction on internal shadings
Q_{int}	Internal convective gains
Q_{solar}	Convective solar gains
Q_{vent}	Ventilation gains
Q_{inf}	Infiltration gains
Q_{cplg}	Gains due to boundary conditions

1. INTRODUCTION

Fish and seafood play a vital role in meeting the nutritional needs of billions of people worldwide, serving as an essential source of protein, vitamins, and nutrients crucial for maintaining overall health. Over the past five decades, global fish and seafood production has increased fourfold [1]. Fresh fish is a highly perishable food characterised by a short shelf-life. For this reason, it must be appropriately handled and stored to slow its deterioration and ensure microbial safety and marketable shelf-life [2]. There is a growing demand for cold storage worldwide, especially in developing countries like Indonesia.

Indonesia ranks as the world's second-largest seafood producer, trailing only China. In 2022, Indonesia's total fisheries production exceeded 22 million tons, contributing to 9% of the global fishery production. Within Indonesia, small-scale fishers constitute a significant portion, accounting for approximately 90% of fishers. This translates to around 2 million individuals engaged in small-scale fishing activities.

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Despite Indonesia's abundant islands and a significant population engaged in small-scale fishing, there are substantial challenges. Most small-scale fisheries are among the country's poorest, with a lack of access to a continuous supply of electricity and cooling technologies such as cold storage and ice makers to maintain the freshness of their catch. As a result, a significant portion of their fish goes to waste, leading to significant economic setbacks for these communities. This situation contributes to substantial post-harvest losses, estimated to be as high as 30%.

One promising avenue for addressing this issue lies in harnessing solar energy for cold storage applications. However, the numerical methods to investigate solar energy for cold storage are limited and not well explored in the literature. Existing literature has predominantly focused on solar energy for space cooling applications, typically designed for positive temperature ranges [3,4]. In contrast, cold storage necessitates sub-zero temperatures, ranging from -10 to -60 °C, contingent upon the specific product being stored. Furthermore, none of these studies have considered the performance of grid-independent cold storage systems in remote, extremely hot and humid regions with high demand and a unique synergy between cold storage requirements and solar availability.

This research aims to develop a numerical model of grid-independent cold storage in Indonesia's extremely hot and humid climate for fish storage at -20°C. The optimisation of the proposed system is conducted through a comprehensive parametric analysis within the TRNSYS framework, considering various factors such as insulation thickness for cold storage, cooling time to achieve design temperature, and photovoltaic battery system sizing.

The paper follows a structured format, with Section 2 outlining the materials and methods employed. Section 3 delves into the discussion of the results, while Section 4 draws the conclusions.

2. MATERIALS AND METHODS

This section is divided into the following sub-sections. Section 2.1 defines the climate data for the investigated location. Section 2.2 define the building archetype used in the model. Sections 2.3, 2.4 and 2.5 elaborate on the methodology employed for building (cold storage) model, air source heat pump, and photovoltaic battery system in TRNSYS.

2.1 Climate

This study uses recent (2007-2021) typical meteorological weather files collected from "climate.onebuilding.org" [5] for Liran, Indonesia. The hourly variation of outdoor dry bulb temperature is shown in Fig. 1.

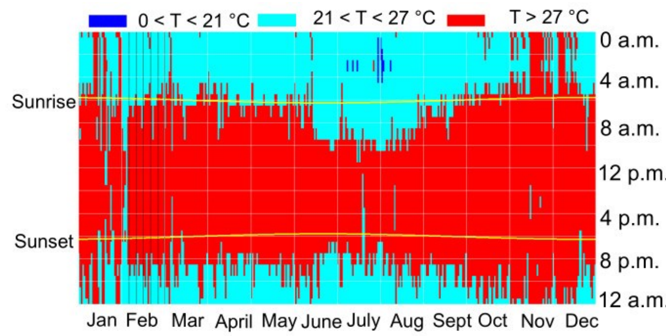

Fig. 1 Hourly variation of dry bulb temperature

This location's climate is extremely hot and humid (0A) according to ASHRAE 169-2020 climate zone classification. Hourly outdoor air temperatures range from 19.2 to 36.4°C, with more than 62% of the year exceeding 27°C. The monthly mean temperature ranges from 26-29°C. The annual global horizontal irradiance for Liran, Indonesia, is 2177 kWh/$m^{2,}$ making this location a good option for solar-driven cooling technologies.

2.2 Reference case study

This paper selected a cold room shaped like a container. It has two zones. The first zone is called anteroom and is used for processing the fish before storing it. The second room, the freezer room, stores the fish. The design temperature for the anteroom and freezer room was 5 and -20°C. The anteroom has 2 x 2.6 x 2.7 m dimensions, and the cold storage has 4 x 2.6 x 2.7 m dimensions. The main parameters of cold storage fabric are shown in Table 1.

Table 1. Characterisation of investigated building archetype

Element	Definition	U-value
Façade	Steel, polyurethane foam, aluminium	0.46 W/m^2K
Roof	Steel, polyurethane foam, aluminium	0.46 W/m^2K
Floor	Concrete slab, steel, polyurethane foam, aluminium, non-slippage coating	0.43 W/m^2K
Door	Steel, polyurethane foam, aluminium	0.46 W/m^2K

The outer walls and roof of the cold storage unit comprise three layers, from the inside to the outside: stainless steel, polyurethane foam for insulation, and aluminium sheets. The inner layer of stainless steel is 9 mm thick, which makes it easy to clean. The polyurethane foam insulation layer helps reduce transmission load through the facade, making the storage more energy-efficient. The outermost layer is lightweight 8 mm aluminium, making the whole container easier to transport. The floor is built on a concrete foundation and includes layers of steel, polyurethane foam insulation, and aluminium. A non-slip coating has been applied to the floor to prevent accidents due to slipping.

Infiltration leakage was defined by an ACH value of 0.5 per hour. Occupancy profiles were considered as follows: two occupants in an anteroom working from midnight to 6 a.m. for 6 hours daily to process the caught fish. The lighting gains were considered as 10 W/m^2 in these working hours. The equipment heat gains are due to evaporator fans and were considered 80 watts during the chiller operation hours. The product load was calculated considering the storage quantity of fish, 9,000 kg weekly with an entering temperature of 25°C and considering 12 hours to freeze one batch of fish. The fish considered for cold storage is Tuna fish; the physical properties of this fish are shown in Table 2.

Table 2. Properties of Tuna fish

Parameter	Units	Values
Density	Kg/m^3	1030
Freezing point	°C	-2
Specific heat capacity above freezing point	kJ/kg.K	3.43
Latent heat of fusion	kJ/kg	227
Specific heat capacity below freezing point	kJ/kg.K	2.19
Thermal conductivity	W/m.K	0.56

2.3 Building modelling

The study used TRNSYS v18 for numerical modelling. TRNSYS is a flexible graphical simulation software used to model transient system behaviour and is widely used in building energy modelling. The flow diagram employed in building modelling is shown in Fig. 2.

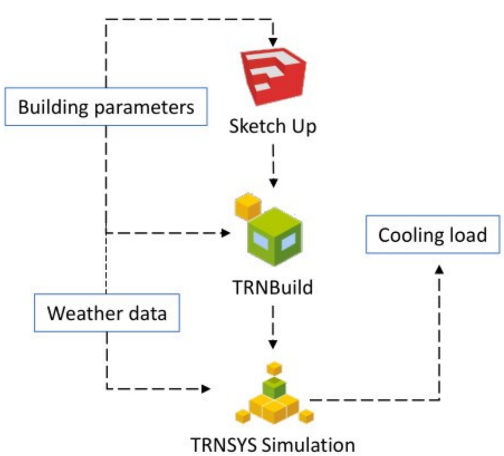

Fig. 2 Flow diagram for the numerical model

Sketchup was used to create a 3D building model of cold storage with an ante and freezer zone. This model was then imported into TRNBuild v3.0 to incorporate the information on building element layers, internal gains (lighting, people, equipment and product load) and their variability over time, ventilation and infiltration loads and schedule. After describing all the attributes, a "*.b18" file was produced using TRNBuild. This file was then utilised as input in Type 56, a multi-zone building model, within the TRNSYS simulation studio to determine the cooling requirement of the cold storage room.

The heat balance of cold storage is the sum of convective heat gains from opaque surfaces (Q_{surf}), internal convective gains (Q_{int}), convective solar gain (Q_{solar}), absorbed solar fraction on all internal shading (Q_{ishcci}), ventilation gains (Q_{vent}), infiltration gains(Q_{inf}), and gains due to coupling or boundary condition (Q_{cplg}). Mathematically, this can be written with Equation 1 [6].

$$Q_{sen} = +Q_{surf} + Q_{int} + Q_{solar} + Q_{ishcci} + Q_{vent} + Q_{inf} + Q_{cplg} \quad (1)$$

The internal gains in the cold storage rooms are due to product load, lighting, people and equipment. It's essential to recognise that around 70% to 80% of heat gains in cold storage rooms are from the product load. The following equation can be used to calculate the total sensible and latent heat that must be eliminated for product cooling.

$$Q_p = (m.C_{pa}.\Delta T_a) + (m.h_l) + (m.C_{pb}.\Delta T_b) \quad (2)$$

where

m is the mass of the product (kg)

C_{pa} is specific heat capacity of the product above freezing point (kJ/kg.K)

ΔT_a is temperature decrease above freezing (K)

h_l is *latent heat of freezing (kJ/kg)*

C_{pb} is specific heat capacity of the product below freezing point (kJ/kg.K)

ΔT_b is temperature decrease below freezing (K)

The first term on the right side in Equation 2 shows heat removal above freezing point, the second shows heat removed during phase change and the third shows heat removal below the freezing point.

Some stored products consume their sugar or starch reserves and consume oxygen in the process, and the heat generated in this process is called heat of respiration (Q_h). Mathematically, it can be written as

$$Q_h = m.HR \quad (3)$$

where HR is heat of respiration (kJ/kg)

It is important to note that heat of respiration is only for the product above freezing point and the value of heat of respiration varies from product to product.

2.4 Numerical model of air source heat pump

In this study, two different sizes of air source heat pumps (one for the anteroom and one for the cold room) were modelled for cooling with TRNSYS Type 119. This type of model air-to-air heat pump for cooling or heating using the manufacture catalogue data approach. For this particular study, manufacture data was collected from INTARCON. The properties of the selected heat pump for cooling are given in Table 3.

Table 3. Design conditions and performance data of selected heat pumps for ante and freezer room

Parameter	Units	Ante room	Freezer room
Temperature	ºC	5	-20
Manufacturer	-	INTARCON	INTARCON
Equipment model	-	MSF-QY-10 068	BSF-QF-33 215
Cooling capacity	W	5067	8405
Power input	kW	1.98	6.03
Evaporator airflow	m^3/h	2000	6200
Condenser airflow	m^3/h	3200	6500
COP	W/W	2.56	1.39
Refrigerant	-	R134a	R404A
Construction		Split Units	Split Units

2.5 Photovoltaic-battery system

The Photovoltaic battery System (PVBS) was designed for electricity supply to cold storage. This system was modelled in TRNSYS using Type 103 for the GSM500-96 PV modules manufactured by GreensunSolar, Type47 for the battery storage, and Type 09 for the data reader of the electricity load of the cold storage. The typical properties of PVBS are provided in Table 4. The PVBS was sized for June, with minimum available solar radiation throughout the year. A building energy management system (BEMS) was incorporated into the PVBS to control the electricity generated by the PV array.

Table 4. Main characteristics of Photovoltaic battery system (PVBS)

Parameters	Value
Rated Maximum Power [W]	500
Maximum Power Voltage [V]	48.6
Maximum Power Current [A]	10.3
Module Efficiency [%]	19.5
Temperature Coefficient of short circuit current	+0.06% / ºC
Temperature Coefficient of open circuit voltage	-0.33% / ºC
Temperature Coefficient of power	-0.40% / ºC
Losses in the PVBS	0.20
Upper limit of fractional state of charge ($FSOC^{UL}$)	0.95
Lower limit of fractional state of charge ($FSOC^{LL}$)	0.20

Fig. 3 shows the schematic of the rule-based control of the BEMS for the consumption of solar power supply and the charging/discharging of battery storage.

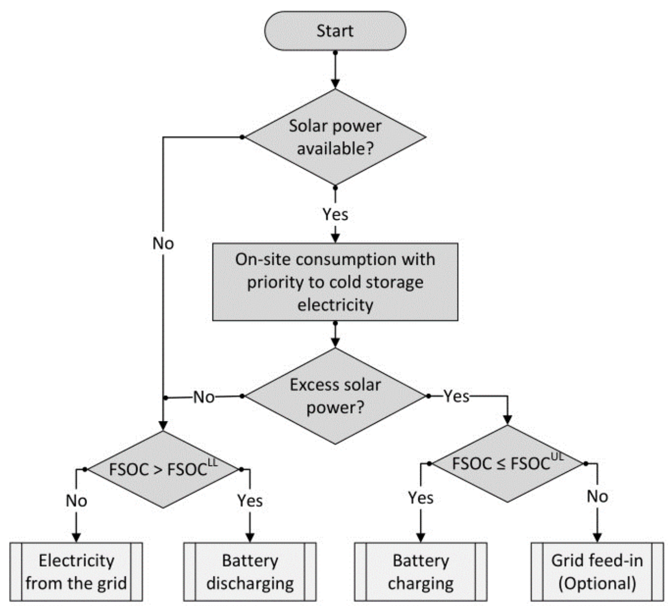

Fig. 3. Rule-based control of BEMS for solar power supply

In this study, solar power was consumed on-site with priority to the electricity load of the cold storage unit. If the generated electricity surpassed the cold storage electricity demand, excessive solar power was utilised to charge the battery storage until the upper limit of a fractional state of charge (FSOC) was achieved. The battery storage discharged to the lower limit of FSOC during the hours of no solar power supply. Priority to the heat pump load was assigned to avoid the battery storage unit's charging and discharging losses.

3. RESULTS AND DISCUSSION

This section shows the result and discussion of a grid-independent cold room for fish storage. It is divided into four sections. First, the cooling demand profile and system sizing are introduced (Section 3.1). Second, parametric analysis results are discussed for optimal configuration (Section 3.2). Third, the performance of solar-driven cooling systems is discussed (Section 3.3). Finally, the photo-voltaic battery system's performance and annual carbon emissions reduction are discussed (Section 3.4).

3.1 Cooling demand profile and system sizing

This section discusses the anteroom cooling demand and system sizing. Fig. 4a shows the variation of daily thermal cooling demand throughout the year in the anteroom, varying from 27.64 to 28.63 kWh. Fig. 4b shows the load duration curve (cooling capacity, in kW) with a maximum peak hourly cooling demand of 4.93 KW.

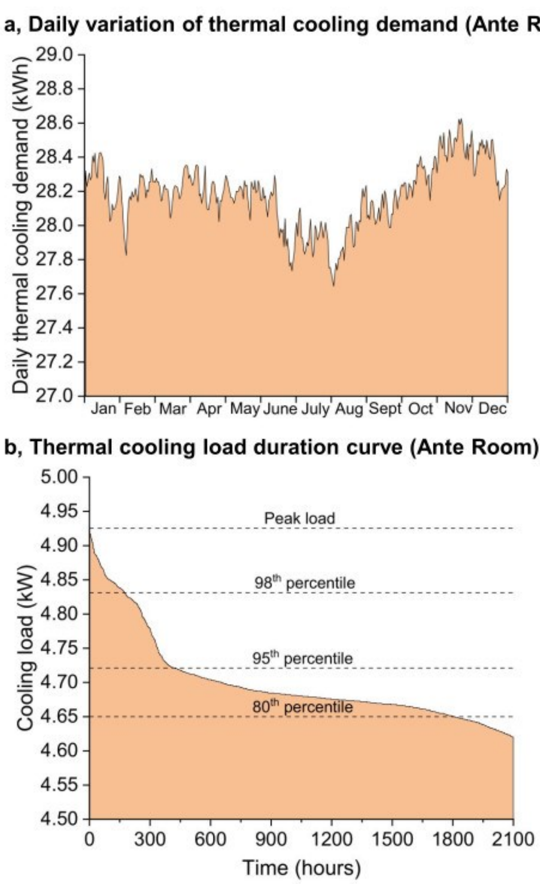

Fig. 4 Analysis of the thermal cooling demand profile of the anteroom. a, Daily variation of thermal cooling demand. b, Thermal load duration curve

Similarly, the daily average freezer room thermal cooling demand was 121.5 kWh, with a maximum peak hourly cooling demand of 8.46 kW.

3.2 Parametric analysis of solar-driven cold storage

This section shows the results of optimal sizing of grid-independent cold storage to reduce cold storage's total thermal and peak demand, capture the maximum solar radiation for PV generation, and achieve grid independence using a battery storage unit. Fig. 5 summarises the parametric study results.

Fig. 5a shows the changes in total thermal demand for cooling with varying insulation thickness. The findings show that thermal energy demand decreases with increased insulation thickness. However, increasing the thickness beyond 150 mm does not result in significant improvements. Fig. 5b shows the cooling time to achieve the design temperature. The analysis covers cooling time from 3 to 15 hours. The findings show that increasing cooling time reduces HVAC system size, but the effect diminishes after 9 hours, revealing a non-linear relationship. Fig. 5c shows the importance of the correct tilt angle to ensure maximum solar irradiance. The optimal slope angles for each month were identified to capture the maximum available solar radiation by PV panels. PV array could receive 5.4% more solar radiation compared to annual fixed adjustment if the tilt angle varied every month, as shown in Fig. 5c. The backup time of the battery storage was analysed for fixed PV power generation and storage capacity to meet the total electricity demand of cold storage without grid utility. Fig. 5d shows the energy supply from the battery and grid with different backup times. The findings show that the system will be grid-independent with a backup time of 36 hours or higher.

Based on these parametric results, the optimal configuration comprises a 150 mm insulation thickness of polyurethane foam, a 12-hour cooling time, a system size of 8.4 kW, monthly adjustments to the PV collector tilt angle, and a 36-hour battery backup time for the PVBS. This configuration is then implemented in the numerical model to assess the performance of the solar-driven cooling system for cold storage, as detailed in the subsequent section.

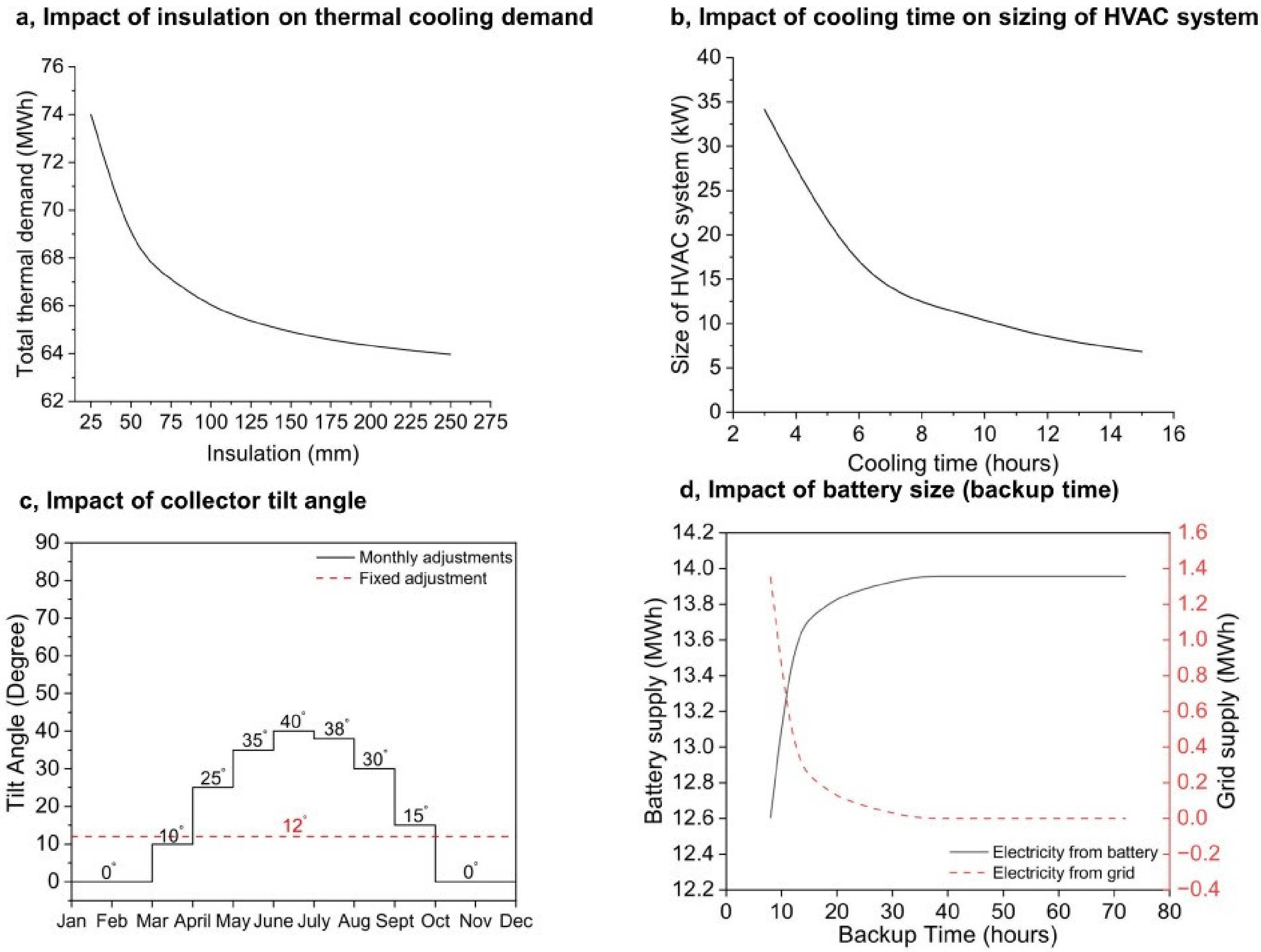

Fig. 5 Parametric analysis of solar-driven cooling system for cold storage; (a) Impact of insulation on thermal cooling demand, (b) Impact of cooling time on sizing of HVAC system, (c) Impact of collector tilt angle, (d) Impact of battery size (backup time)

3.3 Performance of solar-driven cooling system

The cooling system included a 5 kW heat pump to maintain 5 °C in the anteroom and an 8.4 kW heat pump to maintain -20 °C in the freezer room during active hours. The designed cooling system kept the indoor temperature of both zones at the desired level throughout the year. The monthly electricity loads and COPs of heat pumps in ante and freezer rooms are given in Fig. 6. The annual electricity loads of ante and freezer rooms were 3.67 MWh and 28.62 MWh, respectively. The highest total electricity load was 2.81 MWh in December, and the lowest electricity load of 2.57 MWh was observed in June. The COP of heat pumps varied around 2.8 and 1.55 in ante and freezer rooms, respectively.

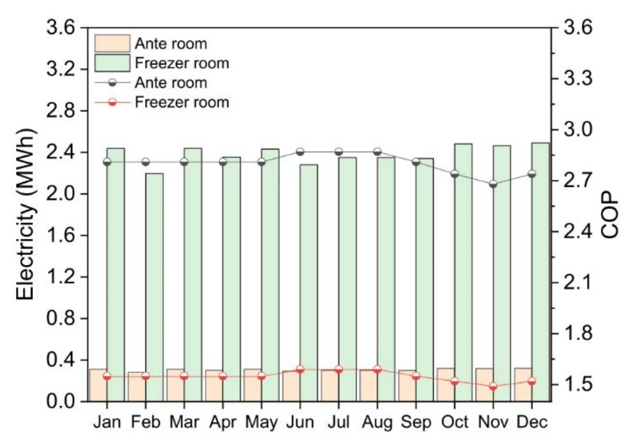

Fig. 6 Performance of PV-driven cooling system

3.4 Performance of Photovoltaic Battery System (PVBS)

The PVBS was configured to provide an uninterrupted, grid-independent electricity supply capable of delivering 32.9 MWh annually. On average, the daily electricity consumption amounted to 88.47 kWh, with the highest daily cold storage demand reaching 93.25 kWh in November. For optimal performance based on monthly tilt angles and a 36-hour backup capacity, the sizes of the various PVBS components are detailed in Table 5.

Table 5 Design capacities of PVBS components

PVBS Component	Size
System DC voltage	48 V
PV array	24.5 kW
Inverter	10 kW
Battery storage	151296 Wh (48 V, 3152 Ah)

PV array supplied 18.34 MWh of electricity to the cold storage in a year with an average value of 1.53 MWh per month. A substantial portion of excess PV-generated power, amounting to 16.42 MWh annually, was efficiently stored in batteries and subsequently supplied to the cold storage unit. As illustrated in Fig. 7, the PVBS consistently met the cold storage's electricity demands throughout the year, operating independently. The average PV efficiency stood at 16.26%, peaking at 17.78% in January and its lowest at 15.13% in June.

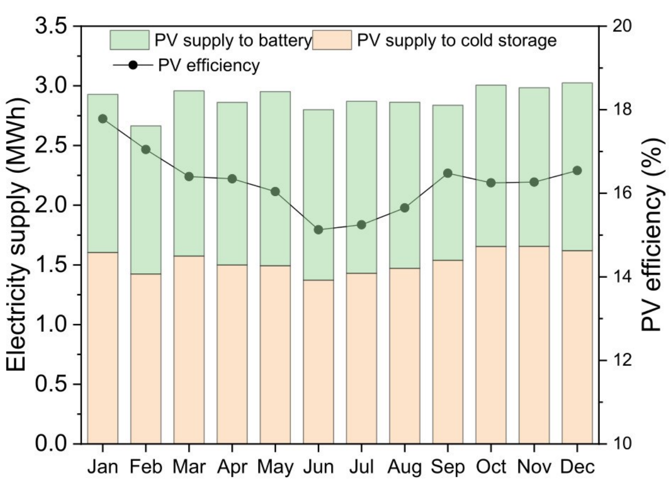

Fig. 7 Monthly results of PV

4. CONCLUSIONS

To preserve fish quality, cold storage is paramount, but it is often lacking in remote areas, posing challenges. This study proposed and demonstrated a grid-independent cold storage, the first of its kind, for small-scale fisheries in Indonesia to store 9 tons of fish weekly at -20°C. A detailed parametric study was performed to find the optimal integration through a dynamic simulation model using TRNSYS. The following conclusions were drawn:

- The results demonstrated that grid-independent cold storage of 20 feet to store 1,285 kg of fish daily at -20°C requires 24.5 kW of PV array, 10 kW inverter and a battery storage of 151296 Wh to meet the annual electricity demand of 32.3 MWh.
- The analysis shows how thermal energy demand and size of the HVAC system for the cold storage unit drastically change with optimal insulation and cooling time. The result demonstrates the benefits (5.4% higher solar irradiance) of adjusting PV panel tilt angle monthly than annual fixed adjustment. Moreover, it is shown that the proposed system will be grid-independent with a backup time of 36 hours or higher for the photo-voltaic battery system.

This paper offers valuable recommendations and strategies for designing optimal grid-independent cold storage in extremely hot and humid climates.

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