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Climate-Responsive Design for Puskesmas: Energy and Comfort Analysis in Coastal North Sulawesi

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Abstract

Primary healthcare centres (Puskesmas) in North Sulawesi's coastal and island regions operate under severe energy constraints driven by extreme thermal conditions. This investigation applies a systems-oriented assessment combining meteorological analysis, psychrometric evaluation, and energy system profiling to characterise operational performance. Analysis of Bunaken Island's healthcare facility reveals that ambient conditions met ASHRAE Standard 55 thermal comfort criteria for only 9 hours annually. The dehumidification processes alone could achieve acceptable conditions for approximately 3,409 hours (39% of operational time). The adaptive comfort model incorporating natural ventilation extends comfort hours to 4,447 hours, though 5,341 hours still require active cooling systems. Electrical system analysis confirms infrastructure vulnerabilities despite the 350 kW solar-diesel hybrid microgrid, with peak facility demand of 7.6 kW creating timing mismatches with solar generation patterns. The facility's 14.56 kWp photovoltaic array and 57.6 kWh lithium iron phosphate battery storage provide limited energy autonomy, highlighting the critical importance of electricity storage systems. Results demonstrate that hybrid environmental control strategies combining passive cooling with mechanical systems offer the most practical approach for reducing energy consumption whilst maintaining essential clinical functionality. The findings establish a technical foundation for climate-responsive healthcare facility design in tropical maritime contexts, contributing to the understanding of energy performance in off-grid environments and supporting Indonesia's net-zero emissions commitment by 2060.

Keywords
HVAC loads, Thermal performance, PV systems, Passive design, Energy resilience.

1. Introduction
Healthcare facilities in remote and climatically exposed regions face persistent energy constraints that directly affect clinical performance, service continuity, and long-term operational resilience (Naik, 2025). Buildings accounted for 34% of global energy use and 37% of energy- and process-related greenhouse gas emissions in 2022 (UNEP, 2024), underscoring the need to improve energy performance across all sectors, including healthcare. In Indonesia's coastal and outer-island districts, primary healthcare centres — known as Puskesmas — form the foundational tier of the national health system, frequently serving populations with no practicable access to secondary or tertiary care (Jung et al., 2019). In many small-island settings, a single Puskesmas functions as the sole medical facility for its community, making energy reliability a critical determinant of population health outcomes.

These facilities face an interconnected problem rooted in both climate and infrastructure. Indonesia's tropical maritime climate — characterised by persistently high temperatures and humidity — imposes substantial cooling loads on clinical spaces, cold-chain equipment, and diagnostic devices (Karyono, 2000; Lapisa et al., 2022). Cooling systems account for approximately 60% of building energy use in Indonesia's hot-humid climate (Svendsen & Schultz, 2022), and elevated sensible and latent heat loads can exceed the capacity of conventional HVAC systems, particularly in small public buildings. Design factors, including limited shading, insufficient natural ventilation, and low-resistance envelope materials, further intensify these conditions (Prianto & Depecker, 2002). Electricity supply in remote areas compounds the problem, remaining inconsistent and often dependent on small diesel generators or ageing distribution networks not engineered for continuous medical-grade demand (WHO, 2014). Supply interruptions routinely compromise vaccine storage, disrupt sterilisation processes, and force clinicians to ration services according to power availability rather than clinical need.

The logistical and economic burdens of diesel dependency are acute in an archipelagic context. Fuel transport is irregular and costly, with delivered prices frequently exceeding mainland rates by a considerable margin, whilst technical maintenance often requires mobilising external engineers to islands with no local capacity. These vulnerabilities have grown more pronounced as extreme weather events increasingly disrupt maritime transport and damage fragile energy infrastructure. Indonesia's commitment to net-zero emissions by 2060 introduces additional pressure on subnational health systems to reduce fossil-fuel dependence, even as they struggle to maintain baseline reliability. The COVID-19 pandemic further demonstrated the importance of facilities capable of autonomous operation during crises, independent of stable grid availability.

Existing health infrastructure policy in Indonesia does not adequately incorporate climate-resilient design principles suited to the conditions of rural and island facilities (Nalli et al., 2024). Many design frameworks applied in hot-humid regions are derived from temperate contexts and cannot reflect local thermal realities, including the comfort conditions specific to healthcare settings (Aderinsola et al., 2025). As Ferng et al. (2020, p. 251) observe, biases toward temperate ideals have been embedded in architectural design since the late eighteenth century and continue to shape how climatic models are applied in tropical settings. This constrains the adoption of passive cooling strategies, climate-responsive design, and renewable energy integration — all of which could meaningfully improve resilience and reduce long-term energy burdens.

Despite growing recognition of energy-resilient healthcare infrastructure as a prerequisite for sustainable development in island and coastal regions, the evidence base remains disproportionately oriented toward temperate, grid-connected contexts. Health-system planners and facility engineers operating in tropical, off-grid, or grid-limited environments lack context-appropriate design standards, operational models, and investment frameworks — precisely in the settings where such guidance is most needed.

This study investigates the energy performance of Puskesmas Bunaken, a primary healthcare centre on Bunaken Island, North Sulawesi, Indonesia — a facility that exemplifies the coupled climatic, infrastructural, and operational challenges characteristic of remote tropical island healthcare. A three-part methodological framework combining meteorological analysis, psychrometric assessment, and building energy system evaluation is employed to characterise prevailing thermal comfort conditions, quantify cooling demand, and assess the performance of the existing solar-diesel hybrid electrical infrastructure. Hybrid environmental control strategies combining passive cooling with mechanical systems are evaluated alongside demand management optimisation and renewable energy integration as pathways toward reduced energy consumption and improved operational resilience.

The findings address a recognised gap in the evidence base for tropical, off-grid healthcare facilities, where conventional international standards — developed predominantly for temperate, grid-connected environments — do not adequately reflect the thermal and energy challenges of equatorial maritime contexts. The results are intended to inform facility-level decision-making, support the development of tropical-specific design standards, and contribute to policy frameworks for energy-resilient primary healthcare infrastructure across Indonesia's remote island regions, in the context of the country's net-zero emissions commitment by 2060.

2. Methods

A mixed-methods analytical framework was employed to characterise the environmental and energy conditions at Puskesmas Bunaken, combining climate data processing, thermal comfort modelling, and energy system assessment. The methodology is structured across four interrelated areas. First, a meteorological analysis was conducted to establish a detailed climatic baseline for Bunaken Island using hourly weather data and Typical Meteorological Year (TMY) datasets, from which key parameters governing thermal and solar conditions were extracted. Second, psychrometric analysis was applied to quantify annual thermal comfort hours and identify passive and active design strategies appropriate to the hot, humid coastal climate. Third, the existing electricity supply infrastructure and on-site demand profile were assessed to understand current energy consumption patterns and the operational constraints associated with island-based power supply. Finally, onsite solar energy availability was evaluated and the PV system performance modelled to determine the generation potential of the existing installation. Together, these components provide the evidence base required to identify targeted retrofit interventions and inform integrated design recommendations suited to the specific conditions of a remote island healthcare facility.

2.1. Climate and Meteorological Analysis

Hourly weather data files were generated using Meteonorm 8.2 (Remund et al., 2020), and Climate Consultant 6.0 Build 17 (Milne, 2021) was used to plot and analyse TMY data for Bunaken Island, North Sulawesi. Key parameters extracted included monthly diurnal ambient air temperature ranges, cumulative precipitation totals, precipitation frequency distributions, sunshine duration, and horizontal solar radiation. This analysis identified retrofit opportunities to reduce energy demand by examining envelope heat and moisture transfer, cooling load distribution, and electricity consumption under actual operating conditions. Targeted improvements — including enhanced insulation, improved glazing, natural ventilation strategies, and more efficient HVAC equipment — suited to the hot, humid coastal climate were subsequently recommended.

2.2. Psychrometric Analysis

Psychrometric analysis was conducted using TMY data within the ASHRAE Standard 55 thermal comfort framework. Comfort zone boundaries were defined using the Predicted Mean Vote (PMV) model, with mean radiant temperature assumed to approximate dry-bulb temperature because of minimal radiative exchange with building surfaces. Natural ventilation comfort was additionally assessed using the ASHRAE 55-2010 Adaptive Comfort model, assuming occupants adapt clothing to conditions and maintain sedentary activity levels of 1.0–1.3 met.

2.3. Electricity Supply and Demand Analysis

A baseline was established by measuring and analysing the energy consumption patterns of Puskesmas Bunaken and its thermal response to local climate conditions. This is relevant, given that most existing research focuses on large urban hospitals in temperate climates with reliable grid connections — contexts that differ considerably from small island healthcare facilities reliant on diesel generators and intermittent supply. The electricity infrastructure was characterised through a review of the Bunaken Island hybrid solar-diesel microgrid, operated by PLN and onsite solar PV and battery storage, and a diesel generator. A typical measured daily load curve was analysed to identify demand patterns and peak load conditions.

2.4. Solar Energy Availability and PV System Analysis

Monthly average sunshine duration and horizontal solar radiation were estimated from hourly TMY data processed through Meteonorm. PV system output was modelled using the PVWatts Calculator (Dobos, 2014), developed by the National Renewable Energy Laboratory (NREL), using a reference station in Sulawesi Utara (1.57°N, 124.82°E) approximately 793 m from Puskesmas Bunaken. Solar radiation inputs were validated against reference values prior to modelling.

3. Data Collection

Site visits to Bunaken Puskesmas (Figure 1) were conducted in October 2025. The facility comprises three structures: a main building (right), a secondary structure used for office functions and storage (left), and a small building near the entrance that serves as a pantry and temporary staff accommodation during storms. The site location (Latitude 1.598389°N, Longitude 124.777861°E) was verified using Google Earth (Figure 2), and the floor plan of the main building is presented in Figure 3.

Figure 1. Puskesmas Bunaken (Photo by Nur Azhar Aulia).

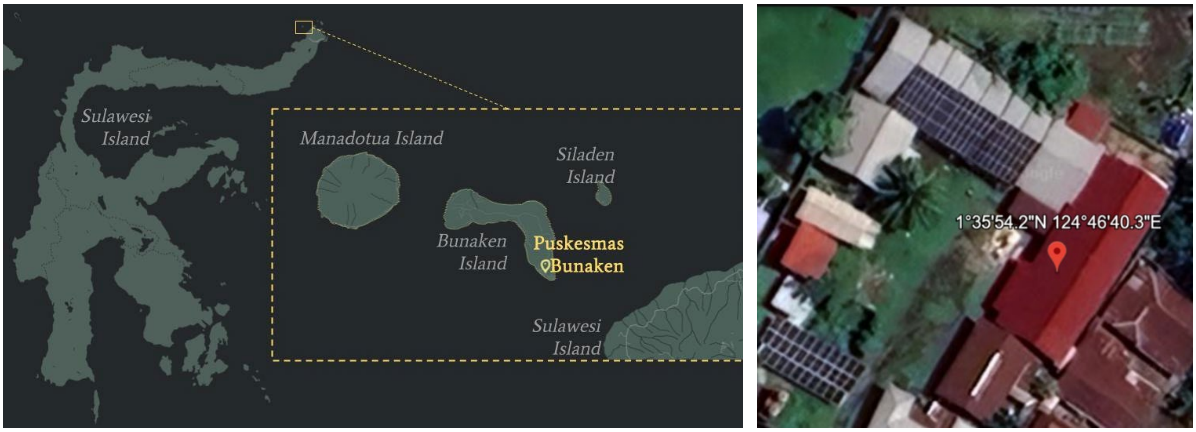

Figure 2. Location map and satellite image of Puskesmas Bunaken (Map (left) by Nadira Adiswari; Satellite image (right) from Google Earth, data attribution – March 12, 2025).

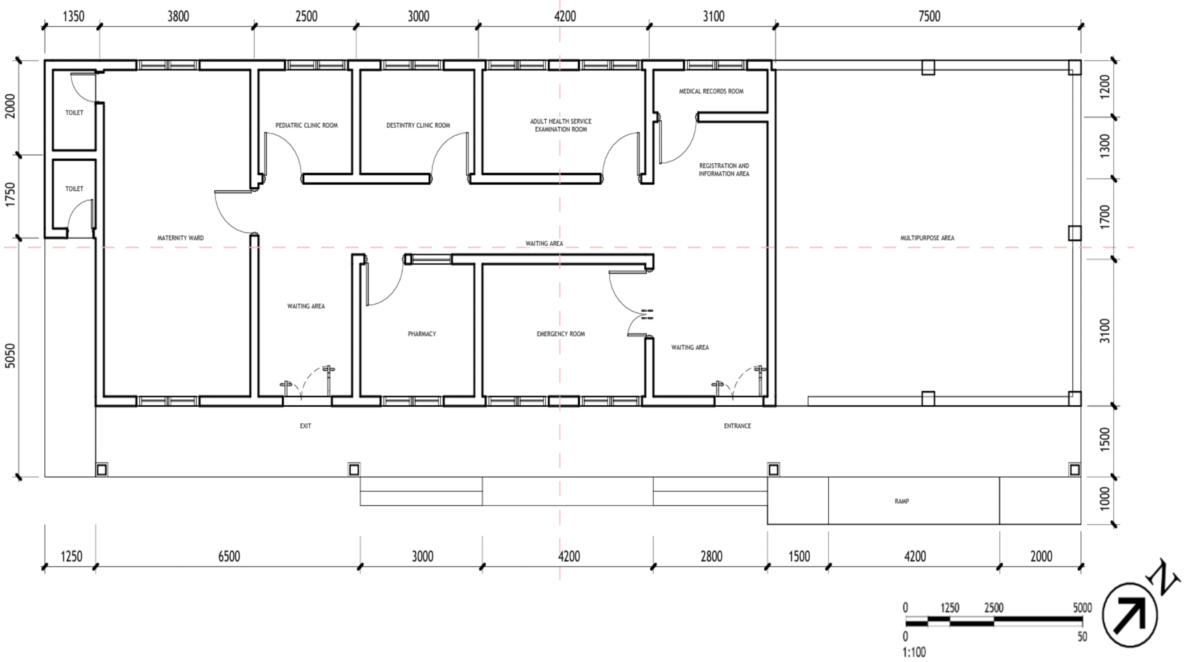

Figure 3. Floor plan of the main building

4. Results and Discussion

A comprehensive analysis of the climatic, psychrometric, energy supply, and solar resource conditions at Puskesmas Bunaken is presented in this section, providing the evidence base from which design recommendations are developed. The findings are organised across four interrelated areas: meteorological characterisation of the local climate using Typical Meteorological Year data; psychrometric analysis to identify passive and active thermal comfort strategies appropriate to the tropical humid conditions of Bunaken Island; assessment of the existing electricity supply infrastructure and on-site demand profile; and evaluation of onsite solar energy availability and photovoltaic system performance. Together, these analyses establish a detailed understanding of the environmental and energy context within which the facility operates, informing the integrated design strategies proposed in subsequent sections.

4.1. Meteorological Analysis

The meteorological analysis outputs generated through Meteonorm version 8.2 and Climate Consultant 6.0 software applications utilising TMY datasets are presented in this section. Monthly diurnal ambient air temperature ranges, monthly cumulative precipitation totals, and monthly precipitation frequency distributions are illustrated in Figure 4 and Figure 5, respectively.

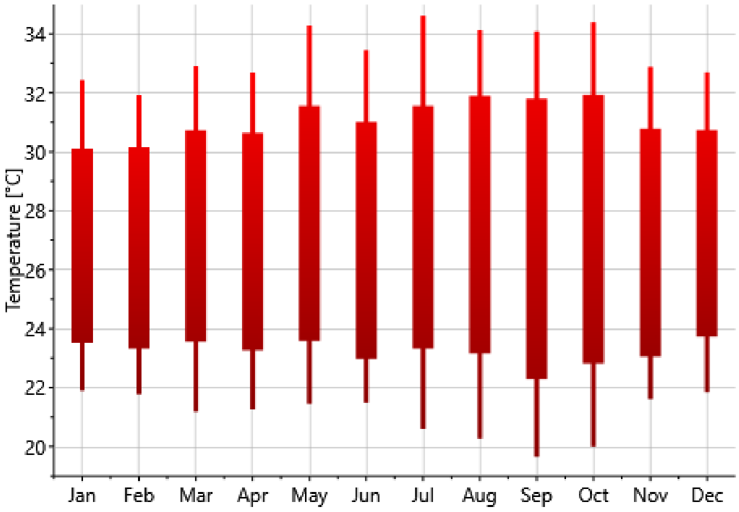

Figure 4. Monthly temperature ranges (Bunaken, North Sulawesi).

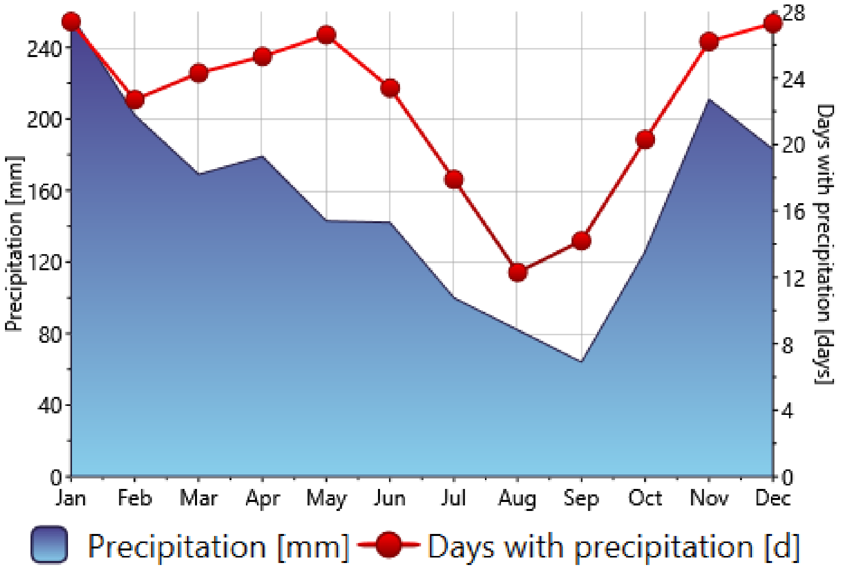

Figure 5. Monthly precipitation (Bunaken, North Sulawesi)

4.2 Psychrometric analysis

Psychrometric analysis was employed to develop design strategies. The analysis incorporates the ASHRAE Standard 55 thermal comfort criteria. For indoor environmental conditions, the mean radiant temperature is assumed to approximate the dry-bulb temperature because of minimal radiative heat exchange with building surfaces. The thermal comfort zone boundaries are determined using the Predicted Mean Vote (PMV) model. Suitable design strategies are shown in Figure 6.

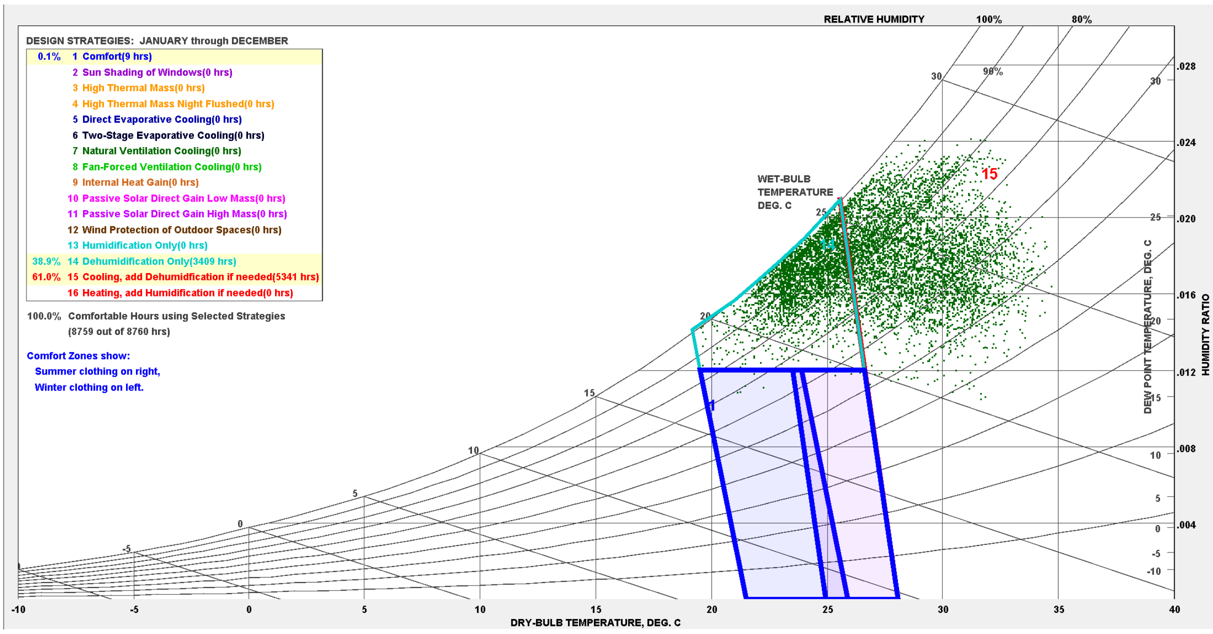

Figure 6. Psychrometric analysis and design strategies

The analysis reveals that only 9 hours (see Figure 6) throughout the year fall within the comfort zone defined by ASHRAE Standard 55. Dehumidification alone could make approximately 39% of the time (3,409 hours) thermally comfortable. Active cooling is required to make the indoor space thermally comfortable for the remaining hours (61%, 5,341 hours).

Naturally ventilated spaces allow occupants to open and close windows. In these environments, the thermal response depends partly on the outdoor climate. Occupants may also have a wider comfort range than in buildings with centralised HVAC systems. The Adaptive Comfort model is based on Standard ASHRAE 55-2010. This model assumes occupants adapt their clothing to thermal conditions. It also assumes sedentary activity levels (1.0 to 1.3 met). Natural ventilation design strategies could achieve thermal comfort approximately 50% of the time (4,447 hours) in Bunaken (Figure 7).

Occupants of naturally ventilated buildings accept warmer indoor temperatures that would feel uncomfortable in air-conditioned spaces (de Dear, 2009). In humid climates, people can tolerate a wider range of temperatures through physical, behavioural, and psychological adjustments (de Dear & Brager, 1998; Yan et al., 2020). This natural adaptation differs from fixed air-conditioning systems. Instead, it uses increased air movement—through ceiling fans or cross-ventilation—to improve sweat evaporation.

Healthcare facilities require specific air quality and infection control measures to maintain safe patient environments. Two key factors must be addressed: airborne pathogen dilution through high air change rates, which reduces transmission risk, and humidity control, which prevents mould and bacterial growth. Cross-ventilation systems with infection control features offer a practical retrofit option for existing healthcare centres, improving air quality without requiring major structural modifications.

Healthcare facilities benefit from several specific ventilation strategies that address the needs of medical environments. These include directional airflow that moves air from clean areas to contaminated areas, preventing cross-contamination between different zones. High-level intake and low-level exhaust systems prevent contaminated air from recirculating throughout the facility, whilst operable clerestory windows provide upper-level openings for continuous ventilation. Automated control systems that respond to weather ensure consistent air quality management regardless of external environmental factors.

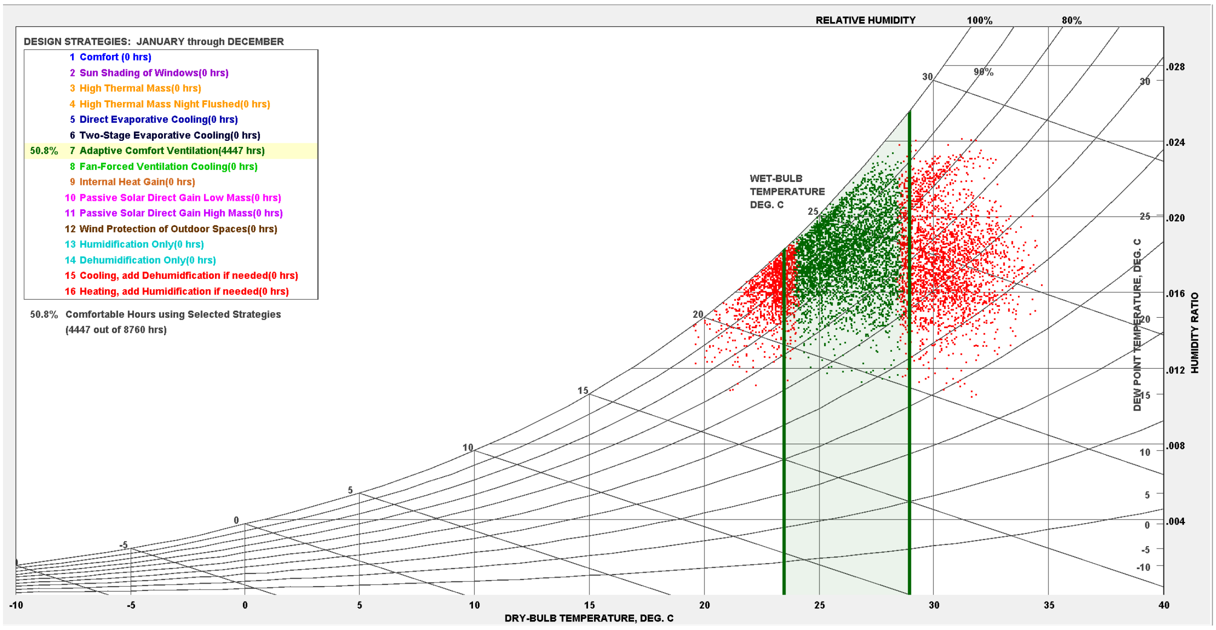

Figure 7. Adaptive comfort natural ventilation

4.3. Electricity Supply and Demand Analysis

Puskesmas Bunaken is connected to the island microgrid (Figure 8) owned and operated by PLN. Electricity supply on Bunaken Island operates via a hybrid system combining solar photovoltaic (PV) panels (350 kW), battery storage (900 kWh), and diesel generators (510 kW) to overcome limitations of remote, off-grid infrastructure (Zuhri et al., 2025). It was one of the first solar-diesel hybrid power plants in Indonesia to power an entire island for 24 hours.

In addition to the connection to the microgrid, Puskesmas Bunaken has its own PV power system: a 14.56 kWp monocrystalline array with 57.6 kWh lithium iron phosphate ($LiFePO_4$) batteries. Details of the PV system are presented in Table 1. A typical daily load curve is shown in Figure 9. The peak load of approximately 7.6 kW occurs at 10am local time.

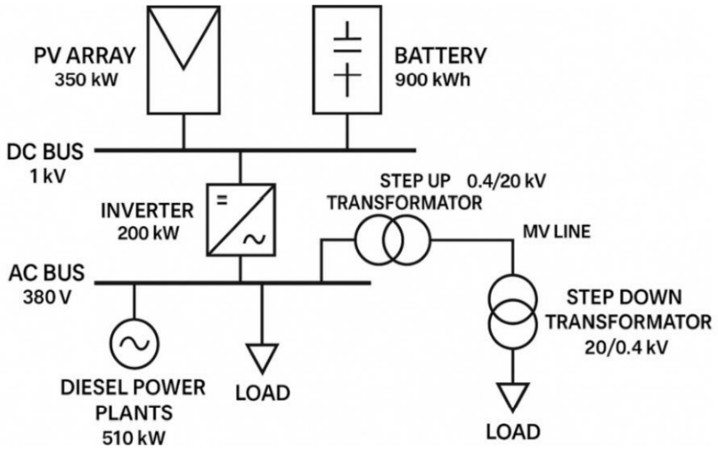

Figure 8. Bunaken island microgrid system (Source: (Zuhri et al., 2025))

Table 1. Onsite solar PV power system

Item	Specification
Brand	Enersa
Type	ENSA 14
Solar modules	Monocrystalline Silicon
Number of modules	32
Module capacity	455 Wp
Total system capacity	14.56 kWp
Module orientation	189° S (slightly west of south)
Module slope	33°
PV module warranty period	> 20 years
Inverter output voltage	220–230 V AC
Inverter output power	12 kW
Inverter warranty period	2–5 years
Battery type	Lithium iron phosphate ($LiFePO_4$)
Battery voltage	48 V DC
Battery capacity (per unit)	50 Ah
Number of batteries	24
Battery power	12 kW (limited by inverter capacity)
Total battery energy	57.6 kWh

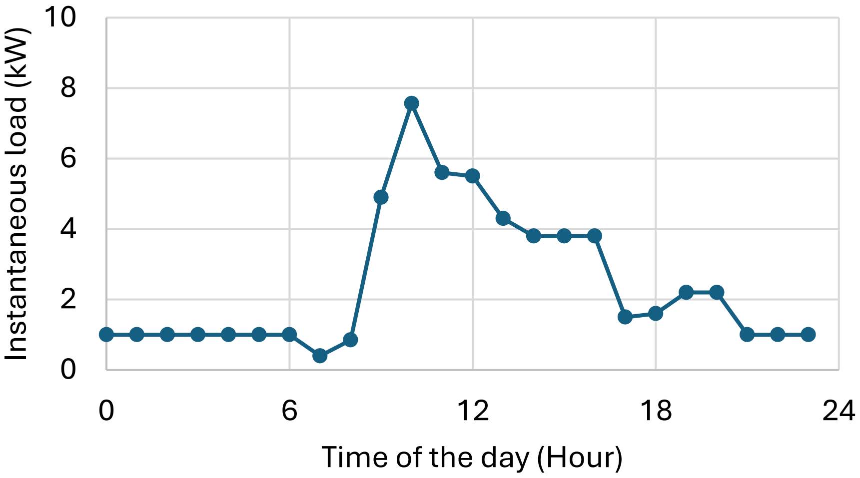

Figure 9. A typical daily load curve

4.4. Onsite Solar Energy Availability and PV System Analysis

Monthly average daily sunshine duration hours and monthly solar radiation received on the horizontal plane were estimated using hourly TMY data from Meteonorm (Remund et al., 2020). To estimate the system's power output, PVWatts Calculator (Dobos, 2014) was employed—a free web-based application developed by the National Renewable Energy Laboratory (NREL). PVWatts uses nearby reference station in Sulawesi Utara, Latitude/Longitude: 1.57, 124.82 which is 793 m away from the Pukesmas Bunaken. The solar radiation input data were compared against reference values to validate the applied input data, as the accuracy of the output depends critically on the quality of the input data. The output data are presented in Table 2.

Table 2. Outputs from PVWatts

Month	Daily average POA Solar ($kWh\ m^{-2}\ d^{-1}$)	DC Array Output (kWh)	AC System Output (kWh)
Jan	5.09	1821	1735
Feb	5.44	1749	1668
Mar	5.30	1888	1799
Apr	4.57	1553	1478
May	3.92	1364	1293
Jun	3.19	1072	1013
Jul	3.88	1377	1307
Aug	4.30	1534	1458
Sep	5.14	1770	1687
Oct	5.38	1884	1796
Nov	5.64	1916	1828
Dec	4.93	1763	1679
POA = Plane of array			

5. Conclusions

Ambient conditions at Puskesmas Bunaken exceed ASHRAE Standard 55 comfort parameters for 99.9% of operating hours, with only 9 hours annually satisfying thermal comfort criteria. Dehumidification alone may achieve acceptable indoor conditions for approximately 3,409 hours per year (39% of operational time), rising to 4,447 hours when the adaptive comfort model incorporating natural ventilation is applied. The remaining 5,341 hours require active mechanical cooling — a substantial load that reflects the fundamental mismatch between tropical maritime climates and conventional comfort standards. Hybrid environmental control strategies, combining passive cooling with existing mechanical systems, represent the most viable pathway for reducing energy consumption without compromising clinical functionality.

The electrical system analysis reveals significant infrastructure vulnerabilities. Peak facility demand of 7.6 kW during morning clinical operations creates a pronounced timing mismatch with solar generation patterns, despite the 350 kW solar-diesel hybrid microgrid serving Bunaken Island. The onsite 14.56 kWp photovoltaic array and 57.6 kWh lithium iron phosphate battery storage provide a degree of energy autonomy, though load profile analysis points to unrealised potential in demand management. Bridging this gap will require coordinated scheduling of equipment operation alongside targeted investment in storage capacity.

Taken together, these findings establish a technical foundation for climate-responsive healthcare facility design in tropical maritime contexts. Conventional international guidelines, developed predominantly for temperate and grid-connected environments, do not adequately address the thermal performance and energy supply challenges encountered here. The integration of renewable energy systems with climate-responsive building design emerges not merely as an efficiency measure, but as a prerequisite for operational resilience — particularly given Indonesia's net-zero emissions commitment by 2060.

This study has a number of limitations that bear on interpreting results. Most significantly, the analysis draws on a single facility, and the findings should be interpreted with caution until validated across a broader range of island healthcare settings. Thermal comfort assessments relied on ASHRAE Standard 55 criteria applied to TMY climate data; the PMV model carries inherent uncertainty in tropical clinical environments, a concern noted elsewhere in the literature (Aderinsola et al., 2025; Ferng et al., 2020). Occupancy data were not collected, meaning cooling load and comfort estimates reflect assumed rather than observed conditions. PV system performance was modelled rather than measured, and no economic analysis of proposed interventions was undertaken — gaps that are consequential given the financial and logistical constraints facing archipelagic healthcare facilities.

Several intervention priorities follow from these findings. Passive cooling measures — enhanced insulation, improved shading, cross-ventilation, and high-performance glazing — should be addressed first, reducing the cooling demand that mechanical systems are subsequently required to meet. These passive measures should be integrated within a hybrid strategy that retains existing mechanical systems whilst incorporating healthcare-specific ventilation requirements for airborne pathogen dilution, directional airflow, and humidity control. The coastal setting introduces elevated ambient humidity; whilst condensation on interior surfaces is not expected — given the dehumidification capability of the installed units and the thermal mass of occupied spaces — the interaction between natural ventilation and air conditioning operation merits closer attention. Post-implementation monitoring is recommended to assess hygrothermal performance and inform any necessary operational adjustments.

On the energy side, staggered equipment start-up and load scheduling aligned with peak solar generation periods are recommended to reduce the morning demand peak and improve utilisation of the onsite PV array and battery storage. A systematic occupancy evaluation would strengthen both energy modelling and comfort assessments. In the longer term, expansion of renewable energy capacity and sustained performance monitoring are essential if facilities such as Puskesmas Bunaken are to contribute meaningfully to Indonesia's decarbonisation agenda whilst maintaining the standards of care that their communities depend upon.

CRediT authorship contribution statement

Yulia Nurliani Lukito: Conceptualisation, Data curation, Visualisation, Writing – original draft, Writing – review & editing. **Muhammad Bachtiar Nappu:** Data curation, Writing – review & editing. **Muhammad Arsyad Thaha:** Funding acquisition, Supervision, Writing – review & editing. **Elisa Lumantarna:** Resources, Writing – review & editing. **Lu Aye:** Conceptualisation, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualisation, Writing – original draft, Writing – review & editing.

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Data availability

The data that support the findings of this work are available from the corresponding author (LA) upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

AI Usage Statement

A large language model was used to support language refinement and structural editing during manuscript preparation. The authors retain full responsibility for the manuscript's content, and all analyses, interpretations, and conclusions were developed and independently verified by the authors. AI assistance was limited strictly to improve clarity and readability.

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Biographies

Yulia Nurliani Lukito is an Associate Professor and researcher in the Department of Architecture, Faculty of Engineering at University of Indonesia. Her research examines the complex negotiations between cultural identity and architectural practice in post-colonial Indonesia. She pays particular attention to how contemporary design mediates between local traditions and global modernisation pressures. Dr Lukito's research has focused on colonial-era cultural events such as Pasar Gambir, analysing how architectural forms were deployed as instruments of political control and cultural appropriation. This work has informed her understanding of how supposedly "traditional" Indonesian architectural elements were often constructed through colonial intervention rather than representing authentic vernacular practices. Her current practice-based research addresses heritage preservation in rapidly urbanising contexts. Recent projects include museum revitalisation initiatives and community-engaged public space design, where she employs participatory methodologies to spotlight local voices in architectural decision-making processes. Dr Lukito has increasingly incorporated digital documentation techniques, particularly 3D scanning technologies, to record heritage structures threatened by urban development. Her work contributes to broader debates about architectural decolonisation and the politics of heritage in Southeast Asian cities. Through both historical analysis and contemporary practice, she seeks to develop architectural approaches that acknowledge colonial legacies whilst supporting culturally grounded urban futures.

Muhammad Bachtiar Nappu is a Professor of Electrical Engineering at Hasanuddin University (UNHAS). He has spent his career exploring how modern power systems can become more reliable, efficient, and sustainable. His work spans renewable energy integration, power system operation, and competitive electricity markets, with a particular interest in how emerging technologies can strengthen grid resilience. Professor Nappu has contributed widely cited research on congestion management, distributed generation, and under-voltage load shedding. In 2024, he was inaugurated as a full professor at UNHAS—an acknowledgment of his long-standing dedication to advancing Indonesia's energy transition and shaping practical solutions for the country's evolving electricity landscape.

Muhammad Arsyad Thaha is a professor in the Department of Civil Engineering at Hasanuddin University (UNHAS). He is a leading Indonesian scholar whose career in coastal and harbour engineering spans more than three decades of research, teaching, and public service. His work reflects a deep commitment to strengthening Indonesia's resilience in the face of growing coastal and maritime challenges. Professor Thaha currently serves as the first Deputy Chair of the UNHAS Board of Trustees, where he contributes to institutional strategy, development, and partnerships. His leadership record includes serving as Dean of the Faculty of Engineering and Head of the Civil Engineering Department, roles through which he helped shape academic programmes, research culture, and engineering education in Indonesia. Professor Thaha is an Executive Committee member and assessor for the Independent Engineering Accreditation Institute (IABEE), playing a key role in elevating national engineering education to international standards. He also serves as an expert advisor to Bappenas and the Ministry of Marine Affairs and Fisheries, where his insights inform national policy on coastal infrastructure and marine resource management. Professor Thaha is widely respected in Indonesia because he brings together strong scientific knowledge, practical engineering experience, and active involvement in policy to support sustainable infrastructure.

Elisa Lumantarna is a Senior Lecturer in the Department of Infrastructure Engineering, Faculty of Engineering and Information Technology at the University of Melbourne, and a specialist in structural engineering and natural hazard resilience. Her research examines the seismic performance and vulnerability assessment of existing buildings, particularly within regions of low-to-moderate seismicity. She serves as the Associate Director for Early Career and Graduate Researchers at the Centre for Disaster Management and Public Safety, where she also co-leads the Dynamic Hazards Mitigation research unit. Beyond earthquake engineering, Dr Lumantarna also develops sustainable construction methods, investigating carbon-neutral materials such as hemp and creating infrastructure applications from upcycled solar PV waste. Dr Lumantarna contributes to the advancement of safer, more resilient urban environments through both her teaching and interdisciplinary research.

Lu Aye is the leader of the Renewable Energy and Energy Efficiency Group in the Department of Infrastructure Engineering at the University of Melbourne, Australia. With more than 45 years of engineering experience, he has built an international reputation as an expert in low-carbon technologies for built environment applications, spanning university teaching, research, development, demonstration, and commercialisation of renewable energy and energy efficiency technologies. Professor Aye's research focuses on heating, ventilation, air-conditioning and refrigeration (HVAC&R) systems, waste-to-resources applications, and complex systems modelling. He applies phenomenological modelling and simulation approaches to optimise energy systems, while also using computational and participatory methods for modelling socio-ecological systems under deep uncertainty. His system models serve practical purposes, identifying the effects of policy interventions. They also support robust decision-making processes. Professor Aye has been recognised as a leading expert in modelling, simulation, optimisation, and forecasting of complex systems behaviours. Through his work, Professor Aye bridges rigorous engineering research with real-world implementation, supporting industry, government, and community partners in accelerating the transition to sustainable operations. His contributions continue to inform policy development and guide the adoption of energy-efficient technologies across Australia and beyond.