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

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Introduction

- Remote healthcare = energy-constrained
- Tropical maritime climate
- High temperature + humidity
- Cooling-dominated demand

Global & National Context

The building sector contributes significantly to global energy use and emissions.

Healthcare facilities are particularly energy-intensive due to strict environmental requirements.

Indonesia's net-zero target by 2060 reinforces the need to improve energy efficiency, especially in underserved regions.

Problem Statement

The central issue is the mismatch between high climate-driven cooling demand and unreliable energy supply.
Diesel dependence introduces logistical and financial burdens, while power instability directly affects critical healthcare services such as refrigeration and sterilisation.

Research Gap

Most building standards are developed for temperate, grid-connected environments.

These frameworks do not adequately reflect tropical humidity, solar exposure, or unstable energy systems, leaving a gap in design guidance for remote healthcare facilities.

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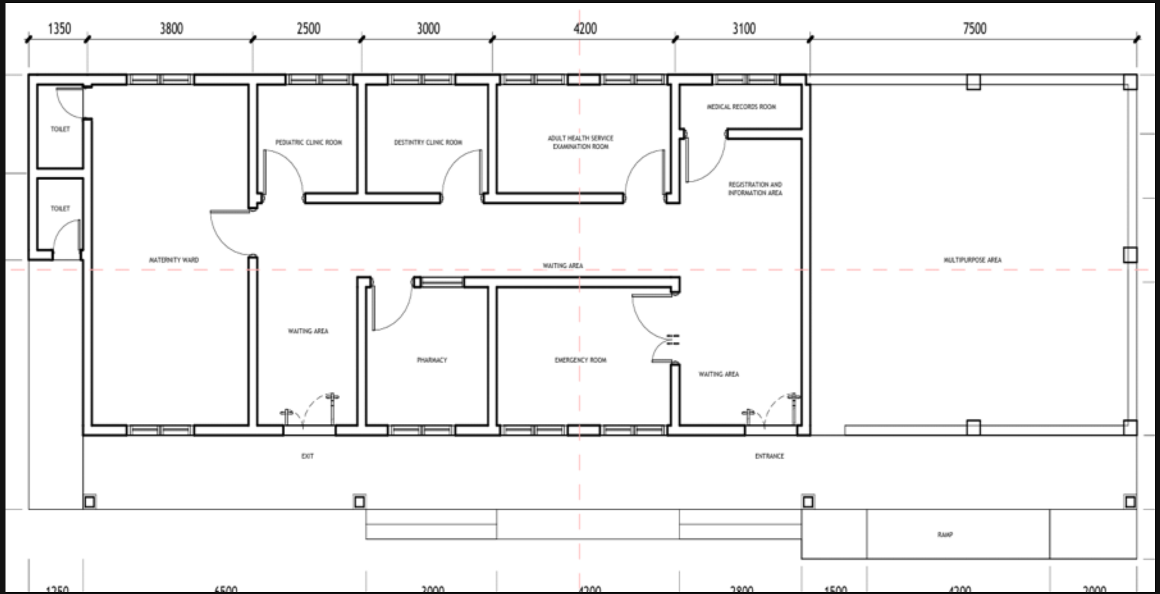
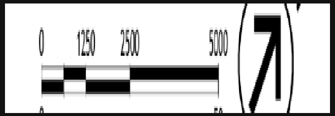
This study aims to quantify thermal comfort conditions, evaluate energy supply and demand, and identify hybrid design strategies that combine passive and active systems to improve performance in a tropical island context.

Puskemas Bunaken

Puskesmas Bunaken is an Island-based Puskesmas. Puskesmas Bunaken consists of a main clinical building, a secondary support structure, and a small auxiliary building.

It operates within a hybrid energy system and represents a typical small-island healthcare facility facing climatic and infrastructural constraints.





Data Collection

Fieldwork was conducted to document building configuration and operational conditions (Oct 2025).

The site location was documented using drone, camera, energy & thermal measurement tools, and architectural layouts were analysed to support energy and environmental assessment.

Methods

A mixed-methods framework integrates environmental data analysis with building performance evaluation.

This approach allows for a comprehensive understanding of both climatic conditions and energy system behaviour.

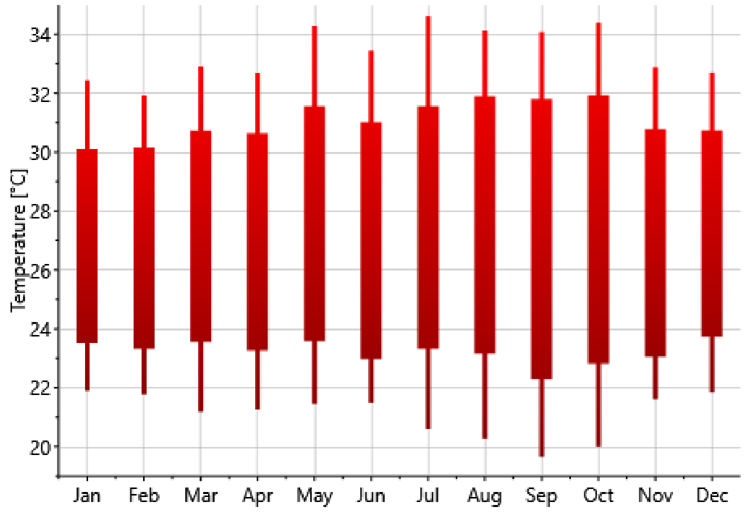
Climate analysis

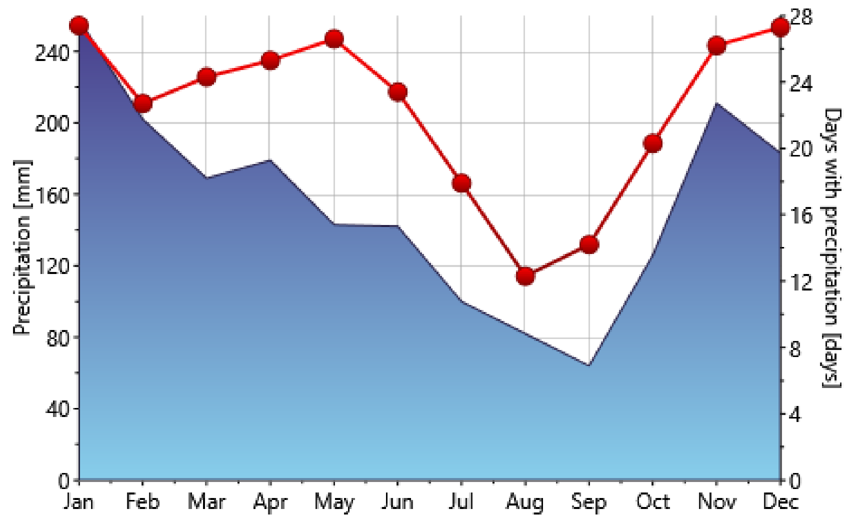
Psychrometric analysis

Energy system analysis

Solar PV modelling

Meteorological Analysis





Results

TMY climate data

Temperature + precipitation

Solar radiation patterns

Discussion

Climate analysis shows consistently high temperatures and significant humidity throughout the year. Solar radiation levels are substantial, indicating strong renewable energy potential, but also contributing to internal heat gains.

Psychrometric Analysis

Results

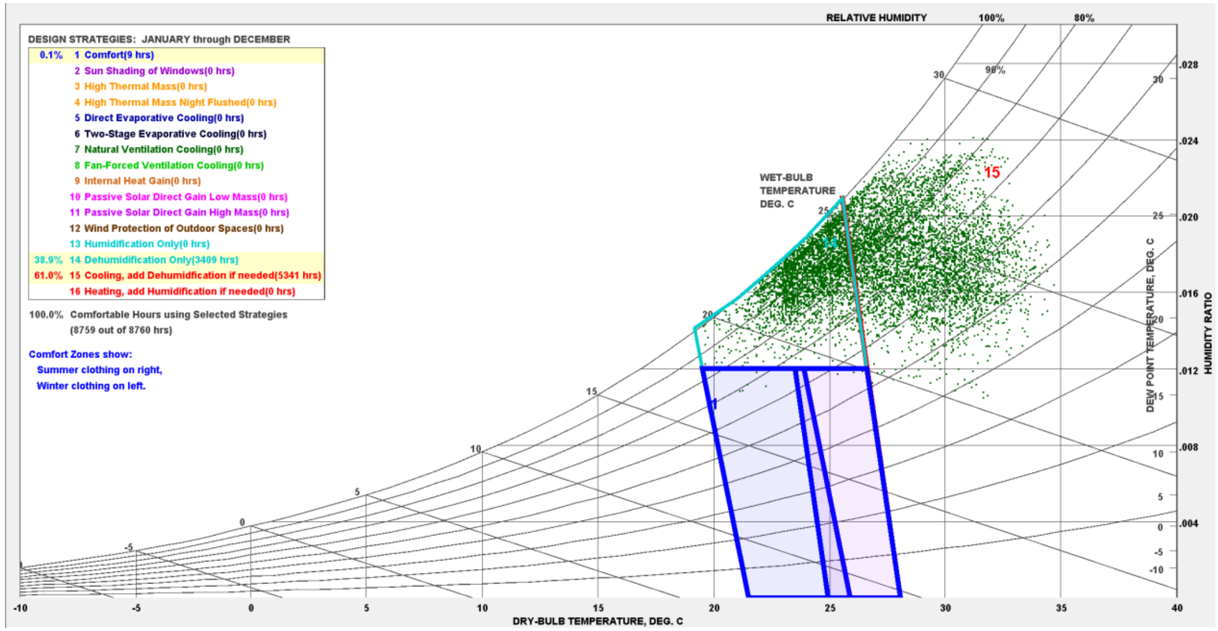
ASHRAE 55 (PMV)

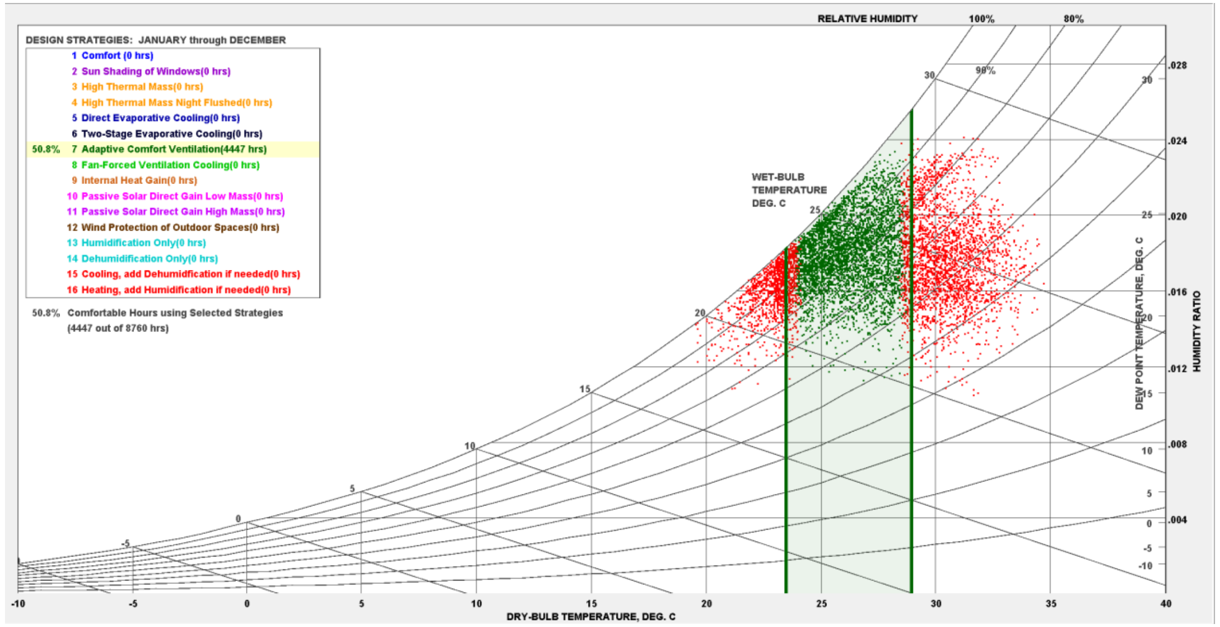
Adaptive comfort model

Strategy identification

Discussions

Thermal comfort was assessed using both PMV and adaptive comfort models. This dual approach captures both controlled indoor conditions and naturally ventilated scenarios, enabling the identification of appropriate passive and active strategies.





Thermal Comfort

Results

- 9 hours/year comfortable
- 3,409 hours (dehumidification)
- 4,447 hours (adaptive comfort)
- 5,341 hours need cooling

Discussion

The results reveal extreme thermal discomfort under standard conditions. Dehumidification significantly improves comfort, while adaptive strategies further extend acceptable conditions. However, the majority of time still requires mechanical cooling.

Ventilation & Healthcare Needs

Results

- Cross-ventilation
- Airflow control
- Humidity management
- Infection control

Discussion

Ventilation strategies must address both thermal comfort and clinical safety. Effective design includes directional airflow, high air-change rates, and humidity control to reduce infection risks while maintaining acceptable indoor conditions.

Key findings

- Climate exceeds comfort limits
- Energy system mismatch
- Storage limitations
- High cooling dependency

The findings highlight a fundamental mismatch between environmental conditions, building design, and energy infrastructure. Both thermal comfort and energy reliability remain constrained under current configurations.

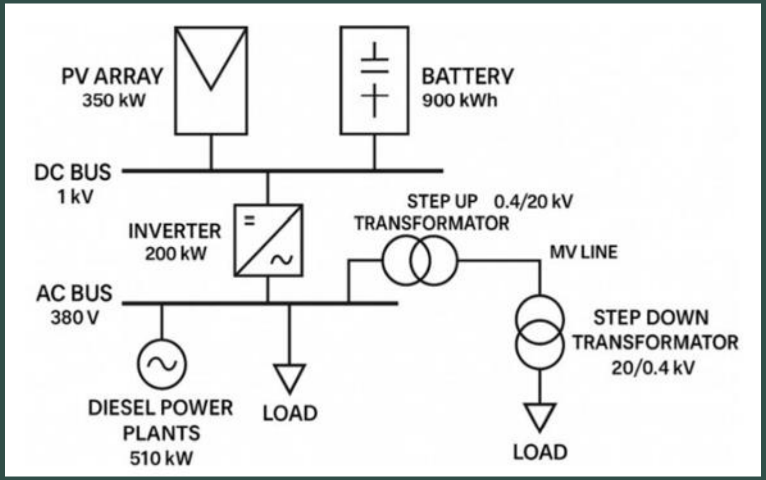
Design & Energy Implications

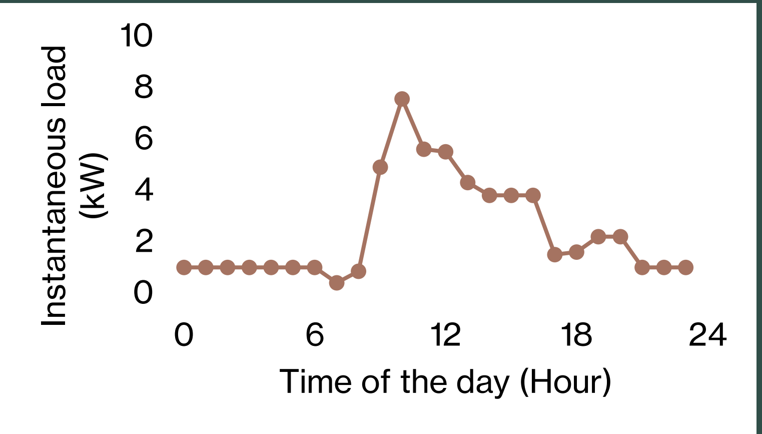
- Passive cooling first
- Hybrid system approach
- Load management
- Storage expansion

Priority should be given to passive design strategies such as shading, insulation, and ventilation to reduce cooling demand. These should be integrated with mechanical systems, alongside improved load scheduling and expanded energy storage capacity.

Energy System Analysis

The facility is connected to a hybrid island microgrid and also operates its own PV system. Energy demand peaks in the morning during clinical operations, creating challenges for matching supply with demand.





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

Solar PV Performance

Solar modelling indicates strong generation potential throughout the year. However, system performance is constrained by storage capacity and temporal mismatches between generation and demand.

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			

Conclusions

Hybrid strategies essential

Climate-responsive design critical

Supports resilient healthcare

Future research needed

Climate-responsive design combined with hybrid energy systems is essential for improving healthcare resilience in tropical island contexts. While this study provides a strong foundation, further research across multiple sites is needed to validate and extend these findings.

Authors





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