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Energy efficient fan customer in her home, Bihar.
Source: Efficiency for Access

Landscape Assessment of Space Cooling Solutions in Rural sub-Saharan Africa and South Asia

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CONTEXT

This report maps the landscape of space cooling solutions that can be used in rural contexts in sub-Saharan Africa and South Asia, covering both passive and active solutions.

The objective is to provide a comprehensive overview of existing solutions, identify gaps, and propose context-specific approaches that can enhance thermal comfort and climate resilience for rural populations. The report focuses on the cooling needs and opportunities for human communities in rural areas and cuts across diverse building types such as homes, schools, healthcare facilities, and community spaces. While some of these space cooling solutions are applicable for animal welfare, those explicitly developed for this purpose have been excluded from this report.

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Efficiency for Access is a global coalition dedicated to advancing access to energy and affordable, energy efficient appliances in low-income countries. It is a catalyst for change, accelerating access to off- and weak-grid appliances to boost incomes, avoid carbon emissions, improve quality of life and support sustainable development. LEIA is jointly managed by Energy Saving Trust and CLASP, and funded by the UK government via the Transforming Energy Access platform and the IKEA Foundation.

This report is intended as a landscape mapping and does not provide technical evaluations or cost-benefit analyses of each solution. The mapping of solutions is not exhaustive and focuses on representative technologies and approaches rather than a complete catalogue. Additionally, while the report includes examples from both South Asia and sub-Saharan Africa, regional diversity within these areas means that not all solutions are universally applicable.

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GLOSSARY

- **Active cooling**: This refers to the use of mechanical systems, typically using electricity, to lower temperatures of a building or a device and maintain thermal comfort.

- **Embedded carbon**: This refers to the total greenhouse gas (GHG) emissions associated with the entire lifecycle of a material or product, from extractions and manufacturing to transport, installation, usage or operation and disposal.

- **Global Warming Potential (GWP)**: This is a measure developed to compare how much impact on global warming different gases have. It is a measure of how much energy the emission of one ton of gas will absorb over a given period, relative to the emission of one ton of carbon dioxide.

- **Pay-as-you-go (PAYGo)**: A financing model allowing customers to pay for appliances in instalments. When payments are missed, the appliance may be remotely disabled/locked.

- **Passive cooling**: This refers to non-mechanical strategies used to reduce indoor temperatures and enhance thermal comfort by harnessing natural processes like conduction, convection, insulation, radiation, ventilation and even landscaping to create airflow, shading and to effectively utilise thermal mass to control heat gain and promote heat loss.

- **Space cooling**: This refers to the process of creating a thermally comfortable indoor environment by regulating temperature, humidity, and air movement, ensuring occupants feel neutrally thermal satisfaction (neither too hot nor too cold).

- **Thermal comfort**: Thermal comfort refers to the state in which individuals feel neither too hot nor too cold within their indoor environment, achieved by regulating temperature, humidity, and air movement. Traditionally defined through engineering standards like ASHRAE 55, it involves six measurable factors — air temperature, relative humidity, air velocity, mean radiant temperature, clothing insulation, and metabolic rate — to determine comfort zones. However, contemporary understandings of thermal comfort go beyond technical metrics, recognising the influence of cultural norms, socioeconomic conditions, and local climate. It is now seen as both a physiological state and a lived experience shaped by access to cooling technologies, building design, and behavioural adaptations.

ABBREVIATIONS

AC	Alternate Current
ACC	Autoclaved aerated concrete
ACs	Air conditioners
BLDC	Brushless direct current
DC	Direct Current
EBA	Electrified business areas
EHS	Environmental, Health and Safety
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Hydrofluorocarbon
HFCFC	Hydrochlorofluorocarbon
IEC	Indirect evaporative cooler
MVC	Mechanical vapour compression
NIEC	Novel indirect evaporative cooler
PayGo	Pay-as-you-go
PCM	Phase-change materials
PFAS	Per- and Polyfluoroalkyl Substances
PM	Permanent magnet
PUF	Polyurethane foam
PV	Photovoltaic
R&D	Research and development
RCC	Reinforced concrete
SRI	Solar Reflectance Index
TR	Ton of refrigeration
XPS	Extruded Polystyrene

EXECUTIVE SUMMARY

Context

As global temperatures rise, rural communities in sub-Saharan Africa and South Asia face increasing risks from heat stress. These risks, compounded by intersecting challenges such as limited access to electricity, inadequate buildings and service infrastructure, and limited financial resources, exacerbate the vulnerability of these populations. Despite the growing urgency, efforts to expand space cooling efforts have largely focused on urban areas, leaving rural populations underserved and the landscape of solutions poorly understood in terms of availability, affordability and contextual applicability.

This study aims to support development actors, donors and policymakers to improve decision-making when designing and implementing space and thermal comfort cooling initiatives in rural areas.

Overview

The report maps a range of space cooling solutions applicable to rural areas, spanning from high-performing active solutions like off-grid air-conditioners and fans, to hybrid solutions such as active and passive evaporative cooling, and passive solutions including cool roofs and various types of insulation.

The report includes:

1. **Introduction** — presents the context and need for space cooling in rural areas.
2. **Understanding space cooling** — defines thermal comfort and its determinants, with reference to recognised global standards and expands to more people-centred, sensitive understandings of thermal comfort.
3. **Mapping of cooling solutions** — includes a subsection for each solution and aims to assess the key factors that impact their use and implementation in different geographies and use contexts by compiling each solution's technical characteristics, market maturity, indicative costs, geographic availability, benefits, and challenges. Case studies from sub-Saharan Africa and South Asia illustrate how these solutions have been implemented.
4. **Design values for space cooling** — proposes a value-based design approach for space cooling interventions.
5. **Conclusion** — summarises key findings and calls to action.

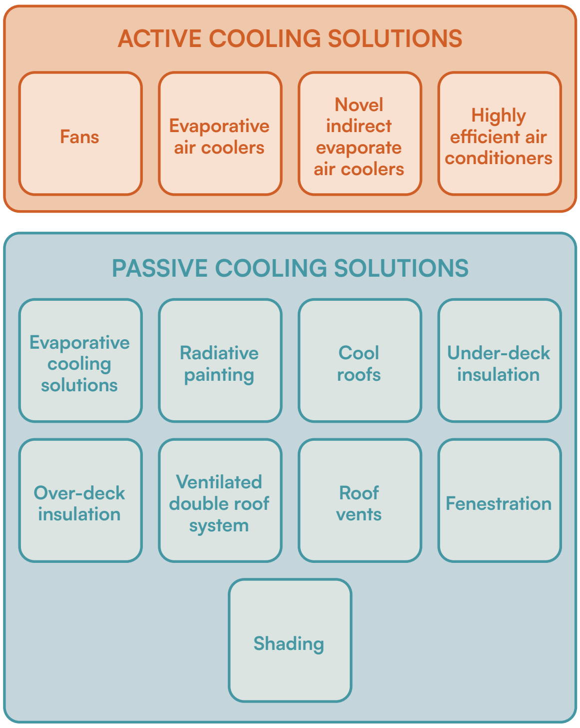


Figure 1. Diagram of mapped space cooling solutions

Assessing applicability

To support decision-making, the paper proposes an applicability assessment framework composed of seven criteria to support understanding of the different aspects and trade-offs to consider when designing or implementing an intervention for space cooling in rural areas. The analysed criteria and guiding questions for each, are the following:

- **Performance in different climates**: How suitable is the solution for either hot-dry or hot-humid climates?
- **Ease of implementation**: How complex is the implementation of the solution? Does it require the building to be refurbished? Does it require skilled workers or specialised technicians for installation?
- **Quality assurance and maintenance**: What are the main challenges regarding quality assurance which impact the scaling of this solution? Are the existing quality assurance standards applicable to the solution?
- **Ease of use**: Does the solution require complex user management? Does it require change of behaviour to be effective?
- **Supply chain resilience**: Does the solution use materials or components reliant on global supply chains? Does it use locally or regionally available materials?
- **Embedded greenhouse gas (GHG) emissions**: What is the embedded GHG emissions hot spot for the solution? How impactful are its embedded emissions in relation to other cooling solutions?
- **Environmental impact at end-of-life**: Does the solution produce e-waste or toxic/harmful chemicals when it reaches its end-of-life? Are there available recycling options for the materials and/or components?

Design framework

Cooling is not just a technical challenge, it is a design practice that needs tailored solutions per use case and requires us to negotiate between material and technology availability, climates, cultural expectations, individual and collective behaviours, and economic constraints. This report proposes a value-based design framework to improve design of space cooling interventions. Using this approach ensures that interventions are not simply technically feasible, but that they are also socially just, environmentally friendly, inclusive, and economically viable.

1. **Design for socio-cultural value** — Solutions should reflect local traditions and lifestyles, ensuring technologies are not only functional but culturally acceptable and co-developed with communities.
2. **Design for environmental value** — Solutions should minimise lifecycle emissions and waste, prioritise locally available and regenerative materials, and integrate a combination of passive and active solutions to enhance effectiveness, long-term sustainability and resilience.
3. **Design for inclusivity** — Solutions should be co-created with people who most affected by heat, ensuring they reflect diverse needs, empower the communities they serve through training and participation, and are economically viable either by being low-cost or through accessible financing and support for local livelihoods.

KEY FINDINGS AND RECOMMENDATIONS

1. **Integrate space cooling for rural communities into development and climate agendas**
   Space cooling is a critical adaptation need for people living in off- or weak-grid rural areas. Integrating interventions into broader climate and development strategies and aligning goals with climate resilience and energy access is essential to bridge the rural cooling gap.

2. **Implement human- and planet-centred design approaches to advance equitable and sustainable space cooling interventions**
   Designing for thermal comfort is not only a technical challenge. Value-based design frameworks that also prioritise socio-cultural relevance, environmental sustainability, inclusivity, and economic viability are critical.

3. **Consider passive cooling as foundational, and solar-powered active cooling appliances as complementary**
   Passive cooling should be prioritised to help meet cooling needs in rural settings, due to its cost-effectiveness and suitability for local contexts. Solar-powered active cooling appliances should be promoted to address residual cooling requirements where passive methods are insufficient, and in critical contexts such as in healthcare facilities, extreme heat and during heatwaves.

4. **Invest in Research & Development to improve affordability and performance of emerging technologies**
   Emerging technologies like highly efficient solar-powered air conditioners and evaporative coolers can be highly effective in providing thermal comfort in critical contexts but they require further innovation to reduce their cost and adapt them to rural settings.

5. **Promote cross-region knowledge transfer and adaptability of space cooling solutions**
   Passive cooling techniques such as using mosaics as a radiant barrier in India, show promise for cross-regional use. On the other hand, evaporative coolers, more widely available in on-grid settings in South Asia, have potential for uptake in off-grid hot-dry regions.

6. **Support local ecosystems for design, installation, maintenance and repair to enable sustainable job creation**
   To scale sustainable space cooling solutions effectively and sustainably, it is essential to build local capacity across the value chain — from masons and carpenters to manufacturers and architects.

7. **Support innovation and pilot projects to demonstrate traditional passive cooling techniques**
   Many passive solutions are rooted in traditional architectural techniques which have been displaced by standardised construction methods. There is potential for recovery and innovation of traditional passive cooling techniques to increase their potential for scale.

8. **Assess supply chain dependencies when designing cooling interventions**
   Many cooling solutions, particularly active ones, rely on global supply chains, which impacts their cost, availability and environmental impact. It is key to support and invest in local manufacturing of both passive and active cooling components.

9. **Create awareness campaigns and resources that provide clear guidance and support for integrating passive and active cooling solutions for implementers and end-users**
   Fans and evaporative coolers are often easier to install than passive cooling solutions. While they provide some thermal comfort, they can be more effective when used adequately and alongside passive cooling solutions. Awareness supports better choices in cooling system selection and installation.

10. **Expand quality assurance frameworks to ensure effectiveness and reliability of space cooling solutions**
    Quality assurance is a key challenge in scaling space cooling. Inadequate standards and quality control can lead to markets being flooded with low-quality products, hindering user adoption and trust. For passive cooling, the lack of rural-specific building codes limits adoption and impact.

Bamboo curtain on a home's windows, Indonesia.
Source: Getty Images

1. INTRODUCTION

Access to adequate space cooling (referring to the area inside any building) is a critical but often overlooked dimension of sustainable development and climate resilience in hot regions of the world. As global temperatures rise due to climate change, ensuring thermal comfort for all is not only a matter of convenience — it is crucial for communities to survive and prosper. Addressing this issue requires context-specific strategies that prioritise the safety and comfort of the most vulnerable.

Sustainable Energy for All (SEforAll) and the World Bank / ESMAP highlight three interconnected domains of cooling needs: (a) agriculture, food security, and nutrition; (b) healthcare; and (c) human safety and comfort[1]. While all three domains are crucial, this report focuses on the need for space cooling specifically for human safety and comfort in rural contexts, particularly in sub-Saharan Africa and South Asia, where the intersection of extreme heat, socio-economic and infrastructure challenges poses serious and growing threats to lives and livelihoods. In this context, cooling needs to be considered as crucial adaptation measure that requires urgent attention especially for rural communities who are often overlooked in this domain.

1. World Bank & SEforALL (2024). The Nexus of Energy and Cooling Access in Rural Areas. ESMAP Technical Report.

The growing need for space cooling in sub-Saharan Africa and South Asia

Heatwaves are increasing in frequency, duration and intensity worldwide and climate projections show that sub-Saharan Africa and South Asia will face some of the most acute impacts. In Africa, 2023 ranked amongst the top three warmest years based on 124 years of data and several countries, including Mali, United Republic of Tanzania, and Uganda, reported their warmest year on record[2]. In March and April 2024, communities across the Sahel and West Africa faced severe hardship as an extreme heatwave brought unprecedented temperatures, compounded by power outages and existing socio-economic challenges. In South Asia, heatwaves and humid heat stress are becoming more intense and frequent[3], with detrimental effects for under-served communities.

Simultaneously, across Africa and South Asia, cooling degree days[4] are three to four times higher than North America, but access to space cooling in rural settings is extremely limited.

One key limitation is the lack of access to electricity in rural areas — in 2023, 666 million people worldwide remained without electricity at the end of 2023 (nearly 565 million of whom were in sub-Saharan Africa), and 84 percent of these people were living in rural areas.[5]

Many households are challenged to afford even simple electric fans (especially when in off-or weak grid settings where they need to purchase power systems to provide the access to electricity that is required to power them) while only a minority of on-grid middle to high income households can afford higher-tier appliances such as air conditioners. In a business-as-usual scenario, these regions will experience the fastest growth in installed capacity of cooling equipment until 2050, which will require large investments in electricity generation and distribution infrastructure, and will result in higher electricity bills for end users.[6]

Health and safety risks in rural areas

To date, responses to extreme heat have predominantly targeted urban populations — for instance through urban heat action plans — leaving the cooling needs of rural populations largely overlooked. The consequences of inadequate access to space cooling in rural areas are wide-ranging and severe, exacerbating vulnerabilities. Meanwhile, the lack of space cooling disproportionately affects vulnerable groups, particularly those whose exposure is amplified by the nature of their work, or by limited infrastructure and services for the provision of electricity, water and sanitation.

In rural areas, vulnerable groups such as smallholder farmers, informal workers and micro and small business owners, women, children, the elderly, patients and staff in rural health centres are especially at risk. For example, agricultural workers — who comprise 49% and 43% of the population in sub-Saharan Africa and South Asia respectively[7] — often perform physical labour such as farming, and fetching water and firewood in the sun, with little to no shelter or opportunity to rest in cool environments. According to The Lancet, in 2023, heat exposure potentially led to the loss of 71 billion hours of agricultural work in Africa, and over 148 billion hours in Bangladesh, India, and Pakistan combined.

Women in rural households often face heightened risks due to gendered labour roles, unequal access to resources and the impact of exposure to excessive heat during pregnancy. Cooking with biomass or charcoal in poorly ventilated and overheated homes further exposes women to both heat and indoor air pollution. Research highlights how inadequate building materials and lack of insulation exacerbate indoor heat exposure — particularly dangerous for women who are pregnant or who spend a larger share of their time in the home.[8]

Children are also disproportionately affected by the lack of access to cooling. Studies show that cognitive performance and concentration decline significantly under high-temperature conditions, impacting learning outcomes in schools without cooling infrastructure.

Healthcare delivery is also under pressure: rural healthcare facilities that lack cooling cannot safely store temperature-sensitive medicines (and particularly vaccines) or provide a safe living environment for staff and patients. Globally, an estimated one billion people are served by healthcare facilities with unreliable or no electricity access. In South Asia and sub-Saharan Africa, 12% and 15% of healthcare facilities respectively have no access to any electricity[9].

2. World Meteorological Organisation (2024). State of the Climate in Africa 2023.
3. IPCC (2021). Working Group I contribution to the Sixth Assessment Report, Climate Change 2021: The Physical Science Basis.
4. A measure of the typical cooling load required based on local weather conditions.
5. IEA, IRENA, UNSD, World Bank, WHO. (2023). *Tracking SDG 7 | Progress Towards Sustainable Energy.* https://trackingsdg7.esmap.org/
6. UNEP (2023). Global Cooling Watch 2023: Keeping it Chill: How to meet cooling demands while cutting emissions
7. World Bank data recovered from the International Labour Organization database from 2023, Employment in agriculture (% of total employment) (modelled ILO estimate) — South Asia | Data.
8. Bonell, A. et al. (2023). An expert review of environmental heat exposure and stillbirth in the face of climate change: Clinical implications and priority issues.
9. World Health Organization, the World Bank, Sustainable Energy for All and the International Renewable Energy Agency (2023). Energizing health: accelerating electricity access in health-care facilities.

Specific challenges in off-grid settings

Space cooling needs are especially acute in rural areas that are completely off-grid or have unreliable electricity supply. The nexus of extreme heat and energy poverty leaves millions without the means to cool living spaces or protect health where passive methods are inadequate and active cooling is completely unavailable.

Rural populations also face systemic disadvantages: typically, lower incomes and fewer public or communal resources which make it more difficult to invest in sustainable space cooling solutions compared to their urban counterparts. Poor ventilation, inadequate building construction, and the lack of access to basic cooling appliances (exacerbated by lacking access or inability to pay for electricity) contribute to dangerously high indoor temperatures in homes, schools, healthcare facilities and workplaces — posing serious risks to human health and well-being.

According to *Chilling Prospects 2025*, over 309 million people living in poor rural areas of 77 countries analysed are at high risk due to limited access to sustainable cooling. This includes people who live in rural areas with hot climates, with limited access or no access to electricity, and who live in extreme poverty. sub-Saharan Africa and South Asia account for the majority of the global "cooling access gap." In 2024, 155 million people are at high risk in poor rural areas of sub-Saharan Africa, and almost 105 million in Central and Southern Asia[10]. In addition, in off-grid rural areas, electricity is provided by solar energy kits to an estimated 493 million people: who could benefit from cooling equipment like fans by upgrading their systems' capacity (Lighting Global/ESMAP et al. 2022). However, purchasing these higher tier systems is typically beyond the means of most rural households.

The need for context-specific solutions

Space cooling needs vary widely depending on factors such as geography, climate, building use, as well as socio-cultural aspects like the type of human activity, and the physiological ability to adapt (depending on factors like age and health state which affect body thermoregulation)[11]. In arid regions such as the Sahel, priority is often given to reducing daytime indoor temperatures in homes and healthcare facilities that lack thermal insulation. In contrast, humid areas like Bangladesh and coastal India require not only cooling but also dehumidification and improved air movement to reduce thermal discomfort and prevent heat-related illnesses.

Tailored, context-specific solutions — aligned with local conditions, infrastructure, financial resources and community needs — are essential to bridging the rural cooling gap and advancing broader goals for sustainable development and climate adaptation. Rapid advances in the efficiency, performance, and affordability of off-grid cooling appliances — such as fans and refrigerators — have significantly expanded the range of cooling services available in rural areas. While passive solutions can provide substantial benefits without electricity, active cooling technologies, including technologies powered by solar systems, are essential for more intensive needs and require further development and scaling to become widely accessible and affordable[12].

10. SEforALL (2025). Chilling Prospects: Tracking Sustainable Cooling for All 2025.
11. Navas-Martín, et al. (2024). Human adaptation to heat in the context of climate change: A conceptual framework — ScienceDirect.
12. Energy Sector Management Assistance Program (2024). The Nexus of Energy and Cooling Access in Rural Areas. ESMAP Technical Report.

SPACE COOLING NEEDS AND SOLUTIONS FOR RURAL FARMING COMMUNITIES

Extensive research insights are providing evidence on the effect of increasing heat on health and livelihoods of rural households. Excessive heat can result in cardio-respiratory and diarrhoeal diseases; thus, it is expected that there will be increased heat-related morbidity and mortality. For smallholder farmers and workers in these high-heat risk regions, tilling the land in extreme temperatures is affecting productivity as they cannot work long hours and efficiently, directly impacting on crop yield and by extension food security.

For such rural, farming communities, the ability to adapt to extreme heat is constrained by their socio-economic conditions that limit access to appropriate infrastructure. This, in turn, limits access to space cooling systems such as air conditioning or even more basic kinds of evaporative or fan-based cooling, which require electricity supplies. Additionally, living in poorly ventilated homes exacerbates the harmful effects of extreme heat.

While rural farming communities are employing strategies to adapt to these extreme conditions by altering working hours, seeking shade, or increasing water intake, these are often insufficient to prevent heat-related illness and productivity loss. It is key that cooling technologies, solutions and interventions are implemented which increase climate resilience of rural communities, particularly during heatwaves. These solutions, as further described in this report, must consider the socio-cultural needs (nature of their work and livelihoods) of such communities in sub-Saharan Africa and South Asia.

Muhammad Shehryar of Harness Energy educating community members in Pakistan about energy efficient fans.
Source: Harness Energy

Energy efficient fans at a store in Bangladesh.
Source: Efficiency for Access

2. UNDERSTANDING SPACE COOLING

Space cooling or thermal comfort cooling means to create a comfortable indoor environment by regulating temperature, humidity, and air movement, ensuring occupants feel neutrally thermal satisfaction (i.e. that they are neither too hot nor too cold). The perception of thermal satisfaction is influenced by diverse factors from biophysical to socio-cultural which vary across regions in the world and depend on local context. It is a critical aspect of building design, as maintaining thermal comfort can significantly impact productivity, health, and overall well-being. This is achieved through various strategies, including natural ventilation, insulation, shading, and the use of mechanical cooling systems like fans, evaporative coolers, or air conditioning.

DEFINITIONS OF THERMAL COMFORT

The definition of thermal comfort has changed from a narrow focus on engineering and technical standards with a universal (one-size fits all) approach, to a more sensitive understanding, that acknowledges social-cultural diversity, and the importance of variable local context.

TECHNICAL AND BIOPHYSICAL DEFINITIONS OF THERMAL COMFORT

Thermal comfort is commonly defined in engineering standards as the condition in which most people feel neither too hot nor too cold in a given environment. ASHRAE Standard 55 and the ESMAP Space Cooling Primer describe thermal comfort as the outcome of six measurable factors: air temperature, relative humidity, air velocity, mean radiant temperature, clothing insulation, and metabolic rate. These variables can be combined in models to identify "comfort zones" on psychrometric charts, which specify the ranges where the average person is expected to feel comfortable. This approach provides designers and engineers with clear parameters for building performance and HVAC operation and has shaped global guidelines for energy-efficient construction.

INCLUSIVE AND HUMAN-CENTRED DEFINITIONS OF THERMAL COMFORT

Today, social scientists and heat researchers no longer define thermal comfort using the above technical measurements alone. Comfort is also influenced by cultural expectations, daily routines, and social and economic conditions. Access to cooling technologies, the type of building materials used, and the design of homes and workplaces all play a role in how people experience and adapt to heat. In many rural and low-income settings, behavioural adjustments, localised design, and collective practices prove to be just as important as indoor air conditions in shaping comfort. This broader view recognises that comfort is not only physiological but also shaped by local context, resource availability, and patterns of inequality. In the context of climate change and rising energy demand, there is growing recognition that technical standards remain important, but they must be complemented by approaches that account for adaptation, equity, and sustainability, and stress the importance of cultural, climatic, and economic diversity in shaping comfort needs. This shift reflects a broader understanding of thermal comfort as both a measurable condition and a lived experience.

ASHRAE STANDARD 55: LIMITATIONS FOR SPACE COOLING IN RURAL AFRICA AND ASIA

The ASHRAE framework is widely recognised and has become the global benchmark for evaluating indoor environments, particularly in office and residential settings. The ASHRAE Standard 55 defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." It sets out the six key determinants presented in Table 1 that influence how people experience thermal comfort. These variables are used to establish "comfort zones" on psychrometric charts, which guide building design and HVAC system operation.

While ASHRAE standards are useful for providing clear and measurable parameters, they have important limitations. First, they reduce comfort to a set of physiological responses, overlooking cultural, behavioural, and contextual factors that shape how people adapt to heat. Second, the universal ranges established in these standards were developed through 20th century laboratory studies on narrowly defined populations, raising questions about their applicability across diverse geographies and demographic groups. Third, by focusing on indoor environments, the ASHRAE framework does not adequately address thermal comfort challenges in informal, rural, or outdoor settings where much of the world's population lives and works.

In rural areas of sub-Saharan Africa and South Asia, where electricity access is limited and buildings are often constructed with local, low-cost materials, the assumptions underpinning ASHRAE standards may not hold. People in these contexts frequently adapt to heat through behavioural strategies, localised building design, and community practices, which fall outside the narrow focus of technical standards. While ASHRAE 55 remains a critical reference for defining comfort in energy-efficient buildings, its relevance is constrained in rural settings. Broader, context-specific approaches are required to account for cultural expectations, adaptive behaviours, and resource limitations to ensure that definitions of thermal comfort reflect real-world conditions and support climate resilience.

2. UNDERSTANDING SPACE COOLING

Table 1. Determinants of thermal comfort as defined by ASHRAE 55

DETERMINANT	DESCRIPTION
Air temperature	Primary driver of sensible heat gain/loss affecting body heat balance.
Relative humidity	Influences evaporative heat loss; crucial role in warm-humid climatic zones.
Air velocity	Facilitates convective and evaporative cooling; vital in passive cooling design.
Mean radiant temperature	Contribution of surrounding surfaces to thermal perception.
Clothing insulation	Modifies heat exchange between the body and environment. Act as thermal resistance to heat flow.
Metabolic rate	Heat generated by physical activity; higher activity increases cooling need for an individual.

CLIMATIC CONDITIONS

Climatic conditions such as air temperature, relative humidity, and wind patterns, are key determinants of thermal implications and which solutions are viable to provide comfort. Using India as a case study, the table below presents the country's climatic zones, as defined by the Bureau of Energy Efficiency (BEE), under the Ministry of Power, Government of India[13], and the thermal comfort levels and cooling needs identified for each zone.

This table showcases the complexity of providing thermal comfort for rural populations in different climatic zones and contexts. These characteristics and their diversity can help better explain the specific local rural cooling solutions and their variable emphasis on locally appropriate architecture, building materials and passive and active cooling solutions.

Table 2. India's climatic zones, thermal comfort levels and cooling needs identified for each zone

CLIMATIC ZONE	TEMPERATURE RANGE (°C)	RANGE OF HUMIDITY (%)	KEY CHARACTERISTICS	EXPECTED THERMAL COMFORT RANGE	THERMAL IMPLICATIONS FOR RURAL POPULATIONS
Hot and dry	40—45 (summer), 10—25 (winter)	25-40	High diurnal temperature swings, low rainfall, arid conditions.	Indoor temp: 26—30°C; RH: 30—50%	High temperatures increase heat stress risks, so evaporative cooling is crucial. Limited electricity access influences reliance on passive cooling strategies such as shading, ventilation and roof materials, but increasing use of modern materials (e.g., concrete) increases the need for cooling.
Warm and humid	30—35 (summer), 20—30 (winter)	70—90	High humidity, monsoon influence, minimal diurnal variation.	Indoor temp: 26—29°C RH: <60%	High humidity reduces sweat evaporation, increasing discomfort and health risks. Ventilation, shading and dehumidification, and the use of fans is essential.
Composite	35—40 (summer), 5—15 (winter)	40—60	Seasonal extremes with hot summers and cold winters.	Indoor temp: 25—29°C (summer) RH: 40—60%	Seasonal temperature variations require adaptive cooling. Flexible design strategies combining shading, ventilation, insulation, shaded courtyards and high thermal mass are crucial.
Temperate	20—30 (year-round)	50—70	Moderate climate with minimal temperature fluctuations.	Indoor temp: 24—28°C; RH: 50—70%	Cooling requirements remain low, and indoor comfort can be effectively maintained through natural ventilation and ceiling fans. A strong reliance on passive cooling strategies further supports low energy consumption.
Cold	0—20 (summer), -5—10 (winter)	50—80	Cold winters, moderate summers, high humidity in winter.	Indoor temp: 20—22°C; Minimal air velocity; RH: 40—60%	Cooling is rarely needed; insulation retains warmth. Summer heat stress is minimal but requires ventilation to manage humidity.

13. Bureau of Energy Efficiency. (2024). *Energy Conservation and Sustainable Building Code 2024*. Government of India. https://beeindia.gov.in/sites/default/files/BEE_ECSBC_2024.pdf

IMPORTANCE OF ACCESS TO SPACE COOLING IN A HEATING CLIMATE — THE CASE OF SOUTH ASIA

In parts of South Asia — particularly northern and central India, and Pakistan — as well as across the Sahel in sub-Saharan Africa, summer temperatures can soar past 45°C. These aren't just uncomfortable numbers; they represent real threats to health, safety, and livelihoods. In Southeast Asia and coastal parts of equatorial Africa, the challenge isn't just the heat — it's the oppressive humidity that drives up heat stress, making the outdoors, and even indoor spaces, extremely uncomfortable.

In these regions and in extreme heating conditions, space cooling isn't a luxury — it's a lifeline. Without it, people face heatstroke, deteriorating health, reduced productivity, and, in extreme cases, death. Climate projections only heighten the urgency. Heatwaves across South Asia and sub-Saharan Africa are expected to grow in intensity and duration. According to the International Labour Organization, India alone could lose 5.8% of its annual working hours by 2030 due to heat stress — equal to 34 million full-time jobs, especially in sectors like agriculture and construction[14]. Similar vulnerabilities exist across Southeast Asia and the African continent, where a large share of the population works outdoors or in overcrowded, poorly ventilated conditions.

Demand for cooling is rising fast, fuelled by climate change, urbanisation, and rising incomes. Global energy use for space cooling has been growing by about 4% annually since 2000 — twice the rate of energy demand for water heating. In 2022 alone, it jumped more than 5% compared to the previous year. In India, one of the most heat-vulnerable countries in the world, access to space cooling is currently limited — an average Indian consumes four times lower energy than the global average (see Figure 2). Cooling demand has grown and is expected to continue to grow significantly over the next decades. Therefore, addressing efficiency and sustainability of cooling solutions holistically is also a climate mitigation imperative.

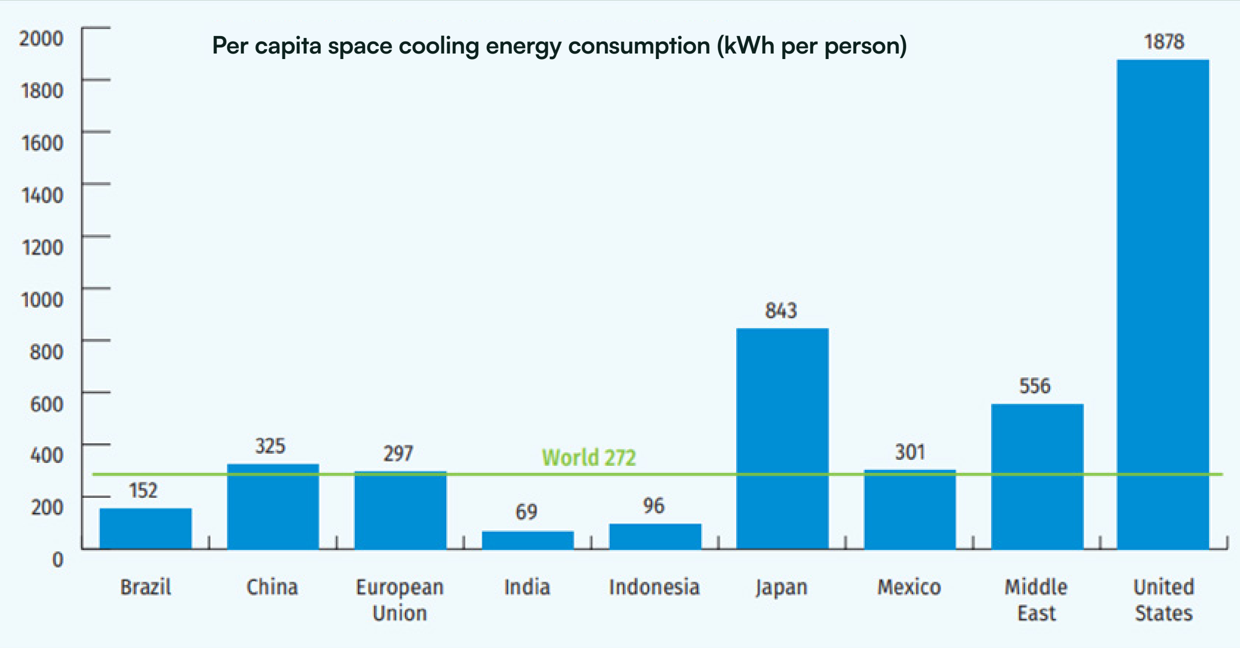


Figure 2. Per capita space cooling energy consumption. IEA (2018)[15].

14. International Labour Organization (2019). Working on a warmer planet: The impact of heat stress on labour productivity and decent work. International Labour Office, Geneva. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40dgreports/%40dcomm/%40publ/documents/publication/wcms_711919.pdf
15. IEA (2018). The Future of Cooling. https://www.iea.org/reports/the-future-of-cooling

Air conditioning unit outside a home, sub-Saharan Africa.
Source: Getty Images

3. MAPPING SPACE COOLING SOLUTIONS

Thermal conditions in rural settings can be improved by the appropriate selection of cooling solutions. In rural areas of sub-Saharan Africa and South Asia, which are largely defined by communities being off-grid or having low grid reliability, it is critical to first ensure that appropriate passive solutions are available and affordable to improve indoor thermal comfort. When passive cooling solutions are not viable or insufficient, such as due to extreme climatic conditions, these need to be complemented by active solutions to reach satisfactory thermal comfort levels.

3. MAPPING SPACE COOLING SOLUTIONS

This chapter maps a range of space cooling solutions which are available or applicable to rural areas (See figure 3) — focusing on off- and weak- grid solutions. It highlights their technical characteristics, market maturity, indicative costs, geographic availability, benefits, and presents case studies of implementation of some of these solutions in different areas within sub-Saharan Africa and South Asia. Additionally, an applicability assessment is proposed and conducted for the mapped solutions.

The proposed space cooling applicability assessment includes an analysis of seven criteria which aim to support stakeholders' understanding of the different aspects and potential trade-offs to consider when designing or implementing an intervention for space cooling in rural areas. The analysed criteria and guiding questions for each, are the following:

- **Performance in different climates**: How suitable is the solution for either hot-dry or hot-humid climates?
- **Ease of implementation**: How complex is the implementation of the solution? Does it require refurbishment of the building? Does it require skilled workers or specialised technicians for installation?
- **Quality assurance and maintenance**: What are the main challenges regarding quality assurance which impact the scaling of this solution? Are the existing quality assurance standards applicable to the solution?
- **Ease of use**: Does the solution require complex user management? Does it require behaviour change to be effective?
- **Supply chain resilience**: Does the solution use materials or components reliant on global supply chains? Does it use locally or regionally available materials?
- **Embedded greenhouse gas (GHG) emissions**: What is the embedded GHG emissions hot spot for the solution? How impactful are its embedded emissions in relation to other cooling solutions?
- **Environmental impact at end-of-life**: Does the solution produce e-waste or toxic/harmful chemicals when it reaches its end-of-life? Are there available recycling options for the materials and/or components?

This analysis aims to encompass all the mapped cooling solutions, both active and passive. However, there are some important considerations more applicable to specific solutions, such as the water use impact of evaporative cooling solutions which are included in the respective sections.

This report does not conduct a full life cycle assessment of each solution, where environmental impacts are evaluated through a recognised methodology, however, it is important to recognise that the environmental impacts of each solution- and the solar systems to power the active cooling- go beyond GHG emissions. For example, the manufacturing and transport of certain components or materials can have relevant impacts on water consumption or land use[16].

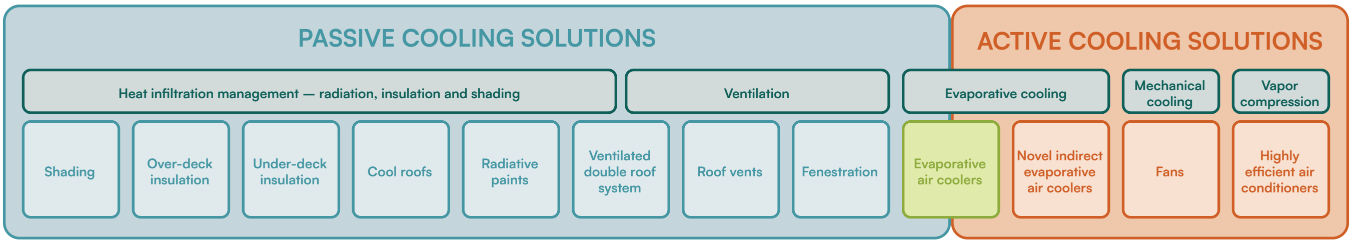


Figure 3. Diagram of mapped space cooling solutions in this report. Own elaboration based on SELCO Foundation's Access to Sustainable Cooling report.

3.1 Active cooling solutions

Active cooling solutions are often considered essential for delivering thermal comfort in rural areas of sub-Saharan Africa and South Asia, particularly where passive methods alone are insufficient.

These solutions require electricity input, and in rural settings, this often must be provided by stand-alone solar power systems or mini grids due to the lack of access to electricity grid or its unreliability.

16. Efficiency for Access. (2025). Designing for Sustainability: Blueprint for a Low-Carbon Cold Room.

3.1.1 OFF-GRID FANS

DESCRIPTION AND KEY INNOVATIONS

Solar-powered fans are among the most accessible and scalable active cooling solutions for off or unreliable grid rural areas in sub-Saharan Africa and Asia. These appliances enhance thermal comfort and have been shown to increase productivity by circulating air, which improves sweat evaporation and reducing perceived heat. While they do not lower air temperature directly, they are effective in many climate conditions without excessive humidity and extreme temperatures — particularly when paired with passive cooling strategies.

Fans typically come in three formats: 1. Table fans for small spaces, 2. Pedestal fans with adjustable height and oscillation, 3. Ceiling fans for larger rooms. Generally, these appliances are suitable for off-grid settings given their relatively low electricity consumption (typically between 5 — 60W) and the option to operate them intermittently[17].

The motor is a critical component determining the fans' energy consumption. Innovations in motor technology, particularly brushless direct current (BLDC) and permanent magnet (PM) motors, have significantly improved energy efficiency, reducing power consumption by up to 50%. These innovations have also improved the motors' reliability and repairability, but they substantially increase the appliances' upfront costs, impacting the price and affordability of the fans[18].

Advancements in blade design have further improved airflow efficiency by up to 15%[19]. These innovations collectively reduce the size and cost of the required solar power system, making fans more affordable and accessible for rural users.

MARKET MATURITY

Off-grid fans are the most mature and widely adopted solar appliance globally. Their relatively low cost, simplicity, and compatibility with small solar systems have driven widespread uptake, particularly in South Asia, which accounts for 80% of global off-grid fan sales as of end-2024[20]. In sub-Saharan Africa, adoption is growing — especially in West Africa, with Nigeria accounting for most of the uptake to date — but remains limited in East Africa, where demand is lower due to milder climates.

INDICATIVE COSTS

- **Price range**: USD 8—65. Depending on size, type, brand and location[21]. The cost of the solar system or battery storage is an additional consideration, with prices for small off-grid solar energy kits (to power these fans) generally starting from around USD 80.
- **DC motor premium**: BLDC fans are ~1.7x more expensive than AC motor fans but reduce total system cost due to lower energy needs and their increased longevity[22].
- **System integration**: Highly efficient fans reduce the size and cost of associated solar kits.

GEOGRAPHIC AVAILABILITY

The demand for fans is directly proportional to the relevant geographic and climatic conditions, with the greatest demand being in the hottest, most humid environments, often following seasonal patterns.

- **High availability**: South Asian countries like Bangladesh, India, and Pakistan account for 80% of global sales reported by GOGLA affiliates as of end-2024.
- **Emerging markets**: The fan market is growing in West Africa, particularly in Nigeria. This is potentially driven by its sweltering and humid climates, a relatively more developed solar off-grid market and supportive subsidy programmes[23].
- **Low availability**: In East Africa, fans are generally scarce. While some areas in the region have milder climates that limit demand, others, such as northern and coastal Kenya, experience scorching conditions. The low penetration of fans in these hotter areas highlights significant gaps in product availability.

KEY CHARACTERISTICS

- **Low energy consumption** when highly efficient motors are used, making them compatible with smaller solar systems and improving end-user affordability.
- **Cost-effective**: Affordable upfront and operational costs in comparison to other cooling appliances.
- **Health benefits**: Improved ventilation reduces indoor air pollution and respiratory risks[24].
- **Vector control**: Airflow deters mosquitoes, reducing malaria and dengue risk[25].

17. SEforAll, (2021). 'Raising Ambitions for Off-Grid Cooling Appliances'.
18. Efficiency for Access, (2023) , 'Tech Trends in Energy Access: Assessing the Off-Grid Fan Market'.
19. Efficiency for Access, (2021). 'Solar-Powered Fans Can Help Support Sustainable Futures'.
20. GOGLA, (2024) Insights from GOGLA's 2024 Sales and Impact Data — GOGLA.
21. Efficiency for Access, (2023). 'Tech Trends in Energy Access: Assessing the Off-Grid Fan Market'.
22. Efficiency for Access, (2021). 'Solar-Powered Fans Can Help Support Sustainable Futures'.
23. Ibid.
24. Efficiency for Access, (2024) 'Tech Trends in Energy Access: Assessing the Off-Grid Fan Market'.
25. Majo Carrasco-Tenezaca et al. (2023). 'Effect of Passive and Active Ventilation on Malaria Mosquito House Entry and Human Comfort: An Experimental Study in Rural Gambia'.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	Suited for both hot and dry, and hot and humid conditions. However, studies have shown they can provide appropriate cooling in air temperatures up to 35°C, and their effectiveness depends on humidity conditions.
Ease of implementation	Their ease of implementation is high, as they are solar stand-alone appliances and don't require any specific installation or building refurbishing to be used. However, it is important that sizing is fit for efficient performance.
Quality assurance and maintenance	Quality standards exist, but product quality across the off-grid fan market has been inconsistent, especially in unregulated markets. In South Asia, a lack of national regulations and industry standards for these products has resulted in an influx of low-quality products, affecting efficiency and performance. Efforts from international programmes are ongoing to improve quality assurance of solar appliances (See box on Quality assurance programmes for off-grid appliances).
Ease of use	Low complexity. Fans are common appliances and do not require complex user management for adequate use. In extreme heat conditions, users must be aware that fans can be detrimental and even increase risk of heat stress, particularly for people with impaired sweating abilities[26].
Supply chain resilience	Medium to low resilience to global supply chains. While some companies are working to localise the manufacturing of off-grid fans (see case study on Harness Energy), solar system components still heavily depend on global supply chains, making these solutions vulnerable to fluctuations in cost and material availability.
Embedded GHG emissions	Fans do not require refrigerants; their energy consumption is the lowest in comparison to the other active cooling solutions in this report and can be powered by solar systems in off-grid settings. The emissions hotspot is linked to their manufacturing resources, particularly the manufacturing of the solar system, as PV panels and batteries represent significant embedded GHG emissions[27].
Environmental impact at end-of-life	Fans and their associated solar systems are electromechanical appliances, and when they reach end-of-life, their disposal generates e-waste that is non-biodegradable and potentially toxic, especially components like batteries and solar PV panels. This can pose environmental, health and safety (EHS) risks when inadequately handled, and in rural areas of sub-Saharan Africa and South Asia, often e-waste is managed by an unregulated informal sector[28].

26. Jay et al. (2021). "Reducing the Health Effects of Hot Weather and Heat Extremes: From Personal Cooling Strategies to Green Cities."
27. Efficiency for Access. (2025). Designing for Sustainability: Blueprint for a Low-Carbon Cold Room.
28. ESMAP. (2024). Off-Grid Solar E-Waste Management Toolkit.

Men selling energy efficient fans in Bangladesh.
Source: Efficiency for Access

QUALITY ASSURANCE PROGRAMMES FOR OFF-GRID COOLING APPLIANCES

Quality assurance is a critical market barrier or catalyst for off-grid solar appliances, including space cooling appliances. Being an emerging market with lack of national standards, the off-grid appliance markets have products with varying degrees of quality and durability. This is particularly true for off-grid fans, which are a relatively simple appliance, low-quality products are commonly available in the South Asian market. This has a significant impact to low-income end-users, for whom purchasing such an appliance is a major investment, and harms the reputation of off-grid solar products.

Addressing this, and other quality assurance challenges, requires robust testing frameworks, improved lab capabilities, and collaboration with manufacturers to enhance design and performance. Currently, there are global initiatives that work to support setting and compliance of quality assurance standards are key to create an enabling environment of high-quality off-grid appliances. Two examples are:

- Verasol, an Efficiency for Access programme, supports the off-grid solar sector by setting quality assurance standards, testing energy-efficient appliances, promoting durable products and adopting harmonised policies, which instil confidence in reliable, high-performance off-grid solar appliances reaching consumers.
- The United for Efficiency (U4E) Model Regulation Guidelines for Energy-Efficient Ceiling Fans developed by UNEP define energy efficiency criteria for fans, helping prevent the influx of inefficient products and aligning off-grid standards with grid-connected markets. These guidelines can also inform donor and government incentives. The core efficiency metric — service value (airflow per power input) — is central to U4E standards, with minimum thresholds based on blade size. The levels defined in U4E guidelines translate efficiency potential into concrete regulatory requirements and provide manufacturers with clear design targets and help ensure that smart subsidies go further to maximize impact. Robust quality assurance standards and programmes improve affordability by decreasing the unit economics for the manufacture of off-grid fans (and other appliances) manufacturing.

A fast-moving ceiling fan, Bangladesh.
Source: Appography

CASE STUDY

Figure 4. Off-grid fan end-user in Pakistan. Source: Harness Energy

Pakistan

HARNESS ENERGY

Harness Energy, a company located in Pakistan, developed a super-efficient rechargeable fan using BLDC motor technology, helping to significantly improve cooling solutions for off- and weak- grid areas in the country. With support from the Efficiency for Access Research and Development Fund[29], the company developed and manufactured a fan that uses only 20W — half the average power consumption of similar products — while still delivering high airflow, which is essential for consumers[30]. Harness Energy managed to locally manufacture 60-65% of fan components and pilot a product approximately 18% cheaper than similar imported models[31]. An R&D grant enabled Harness Energy to transition from being a solar distributor to an off-grid appliance manufacturer, helping to address the need for appropriate and reliable cooling appliances for use in Pakistan's hot climate.

3.1.2 OFF-GRID EVAPORATIVE AIR COOLERS

DESCRIPTION AND KEY INNOVATIONS

Off-grid evaporative air coolers — also known as swamp or desert coolers — offer a step up from the simple fan, which is a low-energy, climate-appropriate solution for space cooling in hot, dry regions with low-humidity environments. These systems cool air by using a mechanical fan to draw it through water-saturated pads made from materials such as sand, charcoal, or hessian fibre[32]. As the air passes through the wet medium, it loses heat through evaporation, resulting in a cooler airflow into the living space. The most common evaporative air coolers are direct evaporative air coolers where there is direct contact between water and air. An added cooling effect can be generated by adding ice or icepacks into the water reservoir, thereby further reducing the temperature of the air that is produced by the cooler. These all generally have simple designs, and lower cost and efficiency than more novel types (see section 3.1.3). However, their limitation lies in increased humidity of the cooled environment, which can lead to discomfort, and excessive moisture can promote growth of mould and dust which have harmful health effects[33].

The key innovation in this evaporative air coolers lies in the integration of energy-efficient motors (such as DC or BLDC motors) and the optimisation of water management systems to minimise water consumption. Advances in cooler pad materials and designs have enhanced air-cooling efficiency and improved moisture control, while solar-powered systems provide a sustainable energy source, making them suitable for rural areas without grid access. There are also options to use the evaporative cooling effect without any power source (see section 3.2.6).

Energy efficient fan in Sindh, Pakistan.
Source: Harness Energy

29. Efficiency for Access Research and Development Fund — Cooling Call 2019.
30. Efficiency for Access (2021). A Sustainable Solution for Pakistan's Off-grid Cooling Challenge.
31. Ibid.
32. Woven fabric made of strong, coarse, natural fibres, typically from the jute plant. Usually used for sacks.
33. Kapilan, N., Isloor, A. M., & Karinka, S. (2023). A comprehensive review on evaporative cooling systems.

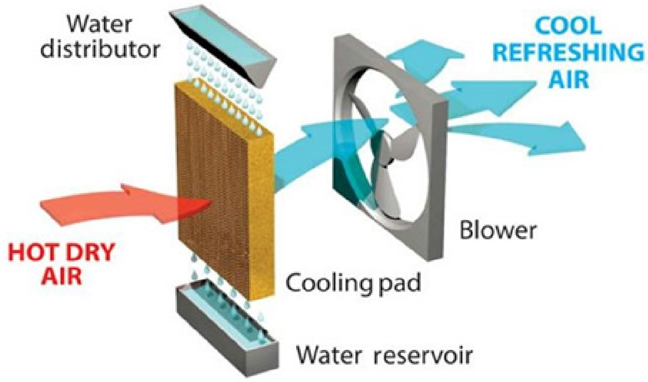


Figure 5. a) Evaporative cooling effect diagram. Source: Ishugah, T (2024). b) Solar-powered evaporative cooler. Source: Vankool

PREVALENCE OF SOLUTIONS AND MARKET MATURITY

While off-grid evaporative coolers are less mature than fans, their adoption is growing steadily in regions with hot and dry climates. Historically used for food preservation, these systems are increasingly being adapted for space cooling. Their reliance on locally available materials and compatibility with solar power make them particularly suitable for rural deployment.

In South Asia, commercial markets for these appliances exists and are expanding as on-grid alternatives to expensive and power-hungry air conditioners, with some companies partnering with local solar distributors to offer integrated cooling solutions. These appliances — even the on-grid versions — are less common in sub-Saharan Africa but there is market potential particularly in arid or semi-arid areas where air conditioning is not a viable option due to high energy demand, high cost and unreliable or non-existent electricity grid supply.

INDICATIVE COST

The cost of off-grid evaporative air coolers depends on their size. Smaller, desktop sized units start at USD 30, while room size units typically range from USD 100 to 500, depending on the size, brand, and features.

The cost of the solar system or battery storage is an additional consideration, with prices for small off-grid solar energy kits (to power desktop off-grid evaporative coolers) generally starting from around USD 100.

34. Kapilan, N., Isloor, A. M., & Karinka, S. (2023). A comprehensive review on evaporative cooling systems.

GEOGRAPHIC AVAILABILITY

Evaporative coolers are best suited to hot-dry climates with low humidity. In regions with this type of climate in South Asia, air coolers for on-grid use are available in the market, whereas in sub-Saharan Africa they are not common. However, there is high potential for market growth in both South-Asian and sub-Saharan African countries.

KEY CHARACTERISTICS

- **Energy efficiency**: Significantly lower power consumption than Air Conditioners (ACs)[34]; some models operate without any electricity (see passive section).
- **Affordability**: Lower upfront and operational costs than ACs, however they are still high-cost appliances for low-income groups which is a barrier for scaling their use.
- **Sustainability**: Requires potable water (which is often not available in off-grid communities) instead of refrigerants. If the manufacturing of the appliance uses locally sourced materials, this can reduce environmental impact further.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	Best suited for hot-dry climates with low humidity. These need a steady supply of water, which is a limitation for water-scarce regions. Due to this, it's crucial that manufacturers innovate in water management technologies, such as water recycling systems.
Ease of implementation	Ease of implementation is high, as they are solar stand-alone appliances and don't require any specific installation nor building refurbishing. However, it is important that sizing is fit for efficient performance.
Quality assurance and maintenance	As the market for off-grid evaporative coolers is very nascent, there are no energy efficiency or quality standards specific to these appliances, increasing the risk of purchasing low-quality products, affecting efficiency, performance and durability. Moreover, evaporative coolers are susceptible to microbial contamination when poor quality water sources are used or maintenance is inadequate, potentially posing health risks. Studies have found that there is a lack of manufacturing standards and user guidance to ensure the safety of these appliances[35].
Ease of use	Medium complexity. They require adequate user management for operation and maintenance. Users need to pour water relatively frequently into the water reservoir, and it's important that the water reservoir chambers and cooling pads are maintained properly to prevent bacteria growth.
Supply chain resilience	Medium to low resilience to global supply chains. Most of the components of the cooler can be manufactured locally or regionally. Although cooling pads are many times imported, the use locally available materials like natural fibres can be used as substitute[36]. However, solar system components still heavily depend on global supply chains, making these solutions vulnerable to fluctuations in cost and material availability.
Embedded GHG emissions	Evaporative coolers do not require refrigerants; their energy consumption is significantly lower than ACs and can be powered by solar systems in off-grid settings. The emissions hotspot is linked to their manufacturing resources, particularly the manufacturing of the solar system, as PV panels and batteries represent significant embedded GHG emissions[37].
Environmental impact at end-of-life	Like fans, these appliances and the required solar systems disposal at their end-of-life produces e-waste which can be toxic and is not biodegradable — particularly for batteries and solar PV panels. This can pose EHS risks when inadequately handled, and in rural areas of sub-Saharan Africa and South Asia, often e-waste is managed by an unregulated informal sector[38].

35. Stefaniak, Ł., Szczęśniak, S., Walaszczyk, J., Rajski, K., Piekarska, K., & Danielewicz, J. (2025). Challenges and future directions in evaporative cooling: Balancing sustainable cooling with microbial safety.
36. Kapilan, N., Isloor, A. M., & Karinka, S. (2023). A comprehensive review on evaporative cooling systems.
37. Efficiency for Access. (2025). *Designing for Sustainability: Blueprint for a Low-Carbon Cold Room.* https://efficiencyforaccess.org/publications/designing-for-sustainability-blueprint-for-a-low-carbon-cold-room/
38. ESMAP. (2024). Off-Grid Solar E-Waste Management Toolkit.

Evaporative air cooler, Thailand.
Source: kckate16

3.1.3 NOVEL INDIRECT EVAPORATIVE AIR COOLERS

DESCRIPTION AND KEY INNOVATIONS

While conventional evaporative air coolers offer a low-energy alternative to air conditioning, they face significant limitations — particularly related to their low effectivity in humid climates, water efficiency, and system complexity, which lead to significant maintenance issues. Indirect evaporative coolers (IECs) aim to overcome these barriers by creating a physical separation between the working and supply air streams, enabling cooling without adding moisture to the indoor environment.

Most of the innovations in IECs rely on complex multilayer barriers — composed of hydrophilic and hydrophobic membranes bonded together — to separate the dry and wet channels of the heat exchanger. These are difficult to manufacture, prone to microbial contamination, and inefficient in heat transfer. These challenges have limited their scalability and commercial viability.

To help address this, the Novel Indirect Evaporative Cooler (NIEC) introduces a simplified, highly efficient design[39].

- An aluminium foil heat exchanger replaces multilayer barrier. This material improves thermal conductivity, is locally available, and reduces the weight and cost of the system in comparison to other IECs.
- External humidification eliminates internal water spraying, reducing potential for contamination and need for constant maintenance.
- A double component system (heat exchanger + humidifier) makes the unit modular, low-cost, and easy to operate. See Figure 5.

The system operates by using a fan to draw hot air into the dry channels of a heat exchanger. Simultaneously, working air passes through the external humidifier, where it mixes with a fine water mist, cooling the air to match the system's wet-bulb temperature and saturating it with moisture. This cooled, humid air then flows through the wet channels of the heat exchanger, absorbing heat from the dry channels via orthogonal exchange. As a result, the incoming hot air is cooled before entering the indoor space. The working air, now slightly warmer and less humid, is funnelled outside the system.

SOLUTION MATURITY AND MARKET POTENTIAL

Although not yet implemented in rural areas, the NIEC is already undergoing field testing (technology readiness level 8+). A 5 TR[40] unit has been successfully deployed at Northumbria University's data centre, maintaining indoor temperatures of 22°C even under high thermal loads.

39. Jamil, M. A., et al (2024). Machine learning-based process design of a novel sustainable cooling system.
40. Ton of Refrigeration, unit for measuring capacity of air conditioning systems, sometimes written as rton and is equal to 12,000 BTUs (British thermal units) per hour.

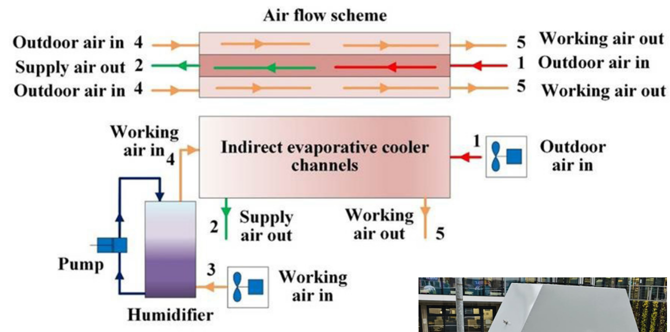


Figure 6. a) Source: Jamil, M et al (2024). b) NIEC at pilot site in Northumbria University. Source: Dr. Muhammad Wakil Shazad.

The NIEC's modular design, low water use, and refrigerant-free operation make it highly promising for use in rural areas — particularly in the hot-dry and semi-arid regions of sub-Saharan Africa and South Asia.

INDICATIVE COST

Although the NIEC is not currently available for purchase, the estimated retail costs are the following:

- **One TR unit**: USD 200—250
- **Five TR commercial units**: USD 1,000 — 1,300

The manufacturer has estimated energy savings of up to 65% when comparing to conventional ACs, directly improving end user affordability, especially in cost-sensitive developing regions.

KEY CHARACTERISTICS

- **Energy savings**: Up to 65% reduction compared to conventional ACs.
- **Modular and plug-and-play**: Easily integrated into existing infrastructure or used as a standalone.
- **Environmentally friendly**: No chemical pollutants, recyclable components, and minimal water usage.
- **Wide application**: Suitable for homes, schools, healthcare facilities, data centres, markets, and community facilities

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	Best suited for hot-dry climates with low humidity. In hot-humid areas, it can serve as a supplementary system to ACs (See Case study: Implementation of NIEC at Data Centre) or be customised for improved performance. It uses less water in comparison to traditional evaporative coolers, making it better suited for water-scarce regions.
Ease of implementation	The NIEC should be easy to implement when they become available for purchase, as they are solar standalone appliances and don't require any specific installation or building refurbishment. However, adequate sizing is key for efficient performance.
Quality assurance and maintenance	NIEC is a nascent technology and has not yet obtained certifications. Obtaining region-specific certifications is essential for market entry and consumer trust. In comparison to direct evaporative air coolers, NIECs have eliminated the possibility of microbial contamination by using an external humidifier (no cooling pads). This should also reduce the need for constant maintenance.
Ease of use	Medium complexity. NIEC requires users to restock water, although restock frequency should be lower to common evaporative coolers due to its efficient use of water.
Supply chain resilience	Low resilience to global supply chains. At present, NIEC is not commercially available, and its production relies on specific subcontracted facilities. The manufacturers plan to generate local manufacturing partnerships, although components will rely on global supply chain networks. Solar systems components significantly rely on global supply chains, making these solutions susceptible to variable costs and availability of materials and components.
Embedded GHG emissions	NIECs do not require refrigerants; their energy consumption is lower than ACs and is forecast to come from solar generation. Its embedded emissions hotspot are the resources required during their manufacturing, particularly of the solar system since PV panels and batteries represent[41]. While this is a nascent technology, localisation of materials and manufacturing would lower its embedded emissions.
Environmental impact at the product's end-of-life	Like other active cooling solutions, these appliances and the required solar systems disposal at their end-of-life produces e-waste, which can be toxic and is not biodegradable — particularly for batteries. When poorly managed, this can pose health, environmental and safety (EHS) risk. In rural areas of sub-Saharan Africa and South Asia, e-waste is often handled by an unregulated informal sector, which struggles to manage these risks[42].

41. Efficiency for Access. (2025). *Designing for Sustainability: Blueprint for a Low-Carbon Cold Room.*
42. ESMAP. (2024). *Off-Grid Solar E-Waste Management Toolkit.*

Evaporative air cooler.
Source: Getty Images

CASE STUDY

Installed NIEC at Northumbria University Data Centre.
Source: Northumbria University S2Cool project

Newcastle, United Kingdom

IMPLEMENTING NIEC AT A DATA CENTRE

Although the NIEC has not been tested in a rural setting, a 5 TR NIEC unit was deployed at Northumbria University to cool a high-load data centre. The system kept indoor temperature stable at 22°C, lowering it from the data centre's internal temperature of 35°C, caused by continuous serve and digital infrastructure operation. NIEC achieved a coefficient performance of 15—18, which amounts to three to four times higher than that of conventional vapor-compression-based air conditioners typically used in data centre environments. The success of this pilot demonstrates the potential of NIECs to help transform cooling strategies in energy-intensive environments.

Another innovative feature of the NIEC is its ability to integrate with existing mechanical vapour compression (MVC) chillers for AC systems as a pre-cooler, simplifying the transition to more sustainable solutions by enhancing overall energy efficiency by 45-50%. In the hybrid NIEC+MVC design, the NIEC manages most of the temperature reduction, significantly boosting overall efficiency.

The optimisation of the NIEC design for use in combination with MVC systems, as well as fine-tuning of operational parameters, has yet to be fully explored and is part of a UK-funded project called S2Cool[43].

43. Northumbria University News. (2024). Innovative project receives £2.8 million to develop energy-efficient cooling solutions to combat extreme heat.
44. Green Cooling Initiative (2025). Climate- and environmentally friendly solar cooling technology solutions.

3.1.4 HIGHLY EFFICIENT OFF-GRID AIR CONDITIONERS

DESCRIPTION AND KEY INNOVATIONS

Off-grid highly efficient air conditioners (ACs) are advanced cooling systems that use a refrigerant's vapour compression cycle (heat transfer medium) to extract heat from an indoor space and release it outside. ACs typically include four main components: the compressor, condenser (outside the building), expansion device, and evaporator (indoor unit). In off-grid settings, a solar system and energy storage would also be required to power the appliance.

Key innovations include:

- DC inverter compressors that adjust power consumption based on cooling demand, reducing energy use by 30—50%, compared to traditional alternate current units.
- Solar-powered ACs are connected to solar systems in three main ways: through grid-tied hybrid systems, off-grid day-use systems, and full off-grid systems designed for 24/7 operation. Each configuration meets different usage patterns and energy autonomy requirements. Table 3 shows key features of these three configurations.
- Phase-change materials (PCMs) for thermal energy storage, enabling cooling during non-solar hours.
- Low-GWP refrigerants such as R-32, R-290 (propane), which reduce environmental impact compared to most used refrigerants like R410A, and other HFCs with high GWP[44].

Technician washes outdoor air conditioning unit, Ghana.
Source: Roger Yebuah

3. MAPPING SPACE COOLING SOLUTIONS

Table 3. Types of solar energy systems for air conditioners.

TYPE	POWER SOURCE	IDEAL USE	GRID CONNECTION	BATTERY BACKUP	SURPLUS ENERGY TO GRID
On-grid model	PV & grid	General use with grid access	Yes	No	Yes
Off-grid day model	PV & battery (optional grid)	Day-use spaces (e.g. offices)	Optional	Yes (for short storage)	Optional
Off-grid night model	PV & extended battery (optional grid)	24/7 use (e.g. homes, healthcare facilities)	Optional	Yes (long autonomy)	Optional

Table 4. Comparison of refrigerants' GWP and other key characteristics.

REFRIGERANT	TYPICAL CHARGE (KG)	GWP (AR5)**	CO_2-EQUIVALENT EMISSIONS (KG)	KEY CHARACTERISTICS
R22 (HCFC)	0.9 — 1.2	1810	1,629 — 2,172	High GWP; phased out in many countries.
R410A (HFC)	0.8 — 1.1	2088	1,670 — 2,297	Common but with high GWP; blends complicate recycling.
R32	0.5 — 0.7	677	339 — 474	Lower GWP; single-component gas.
R290 (Propane)	0.15 — 0.25	3	0.45 — 0.75	Very low GWP; flammable but efficient.

Off-grid air conditioner.
Source: Roger Yebuah

These systems are high-load appliances and particularly suited for critical services such as space cooling for healthcare, education, and small-scale commercial use in rural areas. The following figure shows an example of a diagram and technical data for a high-efficient solar powered AC with an alternate current compressor and using R290.

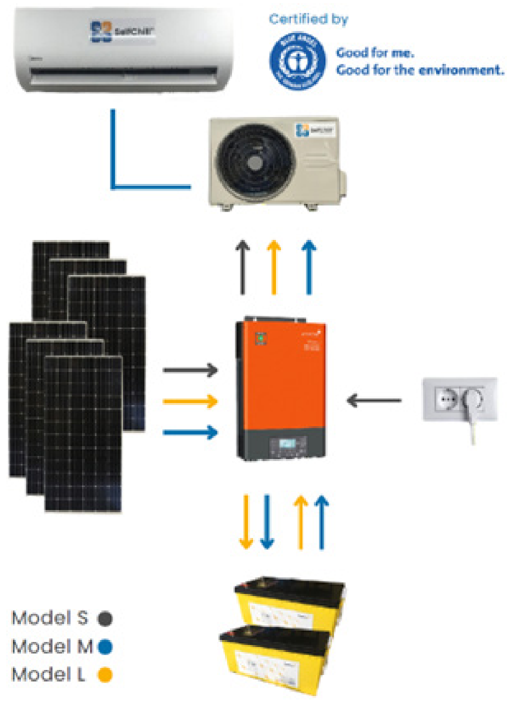


Figure 7. Highly efficient AC. Source: SelfChill/Solar Cooling Engineering GmbH

SOLUTION MATURITY AND MARKET POTENTIAL

Since highly efficient ACs are highly expensive, high-load appliances, there has been little uptake in rural households, businesses, or public settings[45]. However, demand is expected to increase in South Asia and some countries in sub-Saharan Africa such as Nigeria.

INDICATIVE COST

- **Unit cost**: USD 500—2,000 per standard room (approximately 30m^2), depending on size, features, and solar compatibility.
- **System cost (with solar + battery)**: Higher upfront investment, but lower long-term operating costs.
- **Cost drivers**: Inverter technology, refrigerant type, battery capacity, and installation can increase initial costs (when compared to traditional ACs), but they also result in long-term energy savings.

45. SEforAll. (2021). Raising Ambitions for Off-grid Cooling Appliances.

GEOGRAPHIC AVAILABILITY

Currently, highly efficient off-grid air conditioners have low commercial availability. However, they can be found in South Asia (India, Pakistan, Nepal).

In these regions, the adoption of solar-powered air conditioning systems is expected to increase as the demand for cooling solutions rises due to rising temperatures.

Air conditioning unit outside a home, sub-Saharan Africa.
Source: Getty Images

KEY CHARACTERISTICS

- **Energy efficiency**: Lower power consumption than traditional ACs enables use with smaller solar systems.
- **Sustainability**: Using low-GWP refrigerants and renewable energy reduces the appliance's environmental impact.
- **Scalability**: Modular systems can be adapted to different building sizes and energy setups.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	Suited for both hot-dry and hot-humid climates. ACs provide cooling in extreme climate conditions regardless of humidity, making this appliance critical for certain conditions and settings.
Ease of implementation	Ease of implementation is medium. The lack of trained local installation partners who can deliver, configure, and service these systems at the last mile is a major barrier in scaling off-grid AC systems. The most widely commercially available AC systems, including solar-compatible appliances, are optimised for standard room sizes (approximately 30m^2) or commercial buildings. However, many off-grid households and micro-enterprises operate in small, low-ceilinged buildings that require a much lower cooling capacity. There is a clear need for ultra-efficient, low-wattage AC units (e.g., 300—500W) that can operate using minimal solar power and are appropriately sized for smaller rooms.
Quality assurance and maintenance	As the market for off-grid evaporative coolers is very nascent, there are no energy efficiency or quality standards specific to these appliances, increasing the risk of purchasing low-quality products, affecting efficiency, performance and durability. As these units use advanced technology, regular maintenance and occasional repairs may require skilled technicians, which can be a challenge in remote areas, and potentially reduce system reliability and user trust. When using natural refrigerants like R290 (propane), safety regulations must be followed because of its high flammability (classified as A3). These requirements vary depending on the size of the room. Rooms that are smaller than 20m2 have strict regulations when using this refrigerant, making its use a challenge in rural dwellings with a smaller footprint.
Ease of use	Medium complexity. For ACs to provide adequate cooling and operate efficiently, the room to be cooled must be highly insulated. While this is a building issue, it can also be a challenge when end-users are unaware of the importance of closing windows and doors.
Supply chain resilience	Low resilience to global supply chains. Both the ACs and the solar system components heavily depend on global supply chains, making these solutions vulnerable to fluctuations in cost and material availability
Embedded GHG emissions	The environmental impact of off-grid ACs which use low-GWP refrigerants is significantly lower than traditional ACs. ACs' higher energy consumption (which requires a larger solar system) and the manufacturing complexity of the appliance results in a larger embedded than other cooling technologies mapped in this report.
Environmental impact at end-of-life	The disposal of incumbent, high GWP refrigerants require adequate and professional recovery and handling to avoid harmful leaks to the environment. However, this form of disposal is seldom available in countries in sub-Saharan Africa and South Asia. Another benefit of low-GWP refrigerants such as R290 is that it does not require complex treatment during disposal to avoid environmental harm. At the end of their life, AC units and solar systems generate e-waste, which can be toxic and non-biodegradable — especially batteries. The challenges are described in previous sections.

Figure 8. a) Interior of a refurbished classroom showcasing solar-powered AC units, fans and under-deck roof insulation.
Source: SELCO Foundation

Ahmedabad, India

THERMAL COMFORT AT A SCHOOL FOR MIGRANT CHILDREN

SELCO Foundation, in partnership with Navrachit Trust and Mahila Housing SEWA Trust, implemented integrated passive and active cooling solutions at a school at Ahmedabad which serves 60 students from the nearby migrant slum community.

The school's building was originally constructed using high thermal conductivity materials like metal sheets, with the structure absorbing and retaining heat, making indoor temperatures extremely high. Ventilation was minimal, with only two small windows offering little relief in a hot and dry climate where summer temperatures can range between 35 — 50°C.

These types of spaces are commonly built under various government and NGO initiatives (temporary or tent schools) — they are highly vulnerable to damage during the monsoon season, lack basic structural stability, and have inadequate sanitation — resulting in inappropriate spaces for children to learn and play.

To help address this challenge, a mix of passive and active cooling solutions was implemented:

- **Material and insulation**: The building envelope was upgraded using low thermal conductivity wall panels and insulated polyurethane foam (PUF) panels for roofing.
- **Design of fenestration and orientation**: Windows with aluminum-insulated frames were reoriented to face north and positioned for cross ventilation, enhancing indoor air circulation and reducing heat gains.
- **Integrating energy efficient appliances and solar-powered solutions**: A rooftop canopy of solar PV modules offered additional shading while generating clean energy. On the active cooling front, a 3 TR air conditioning unit with thermal backup by Inficold India Pvt Ltd was installed to provide consistent cooling during high ambient temperatures. Moreover, the number of fans was optimised from six to four, thanks to improved passive design.

Following the intervention, indoor temperatures, which had exceed 35°C in the summer, consistently dropped to 24—26°C, a significant improvement over previous conditions. The passive strategies alone contributed to a temperature reduction of 4—5°C, minimising reliance on active cooling. This not only improved energy efficiency, but also reduced operational costs. The optimised environment helped improve students' comfort, focus, and attendance, creating a safe and thermally comfortable learning space for the children. The case demonstrates how integrated passive and active cooling strategies can help transform vulnerable educational infrastructure into climate-resilient, energy-efficient spaces.

Exterior of school after implementation of active and passive cooling solutions.
Source: SELCO Foundation

3.2 Passive cooling solutions

Passive cooling solutions are the foundation of sustainable thermal comfort — particularly in rural and off-grid settings where energy access is limited and affordability is a key concern. Unlike active systems that rely on electricity or mechanical components, passive cooling leverages building design, materials, and natural ventilation to reduce indoor temperatures and improve comfort.

Integrating passive cooling should be the first step in any space cooling strategy. These measures are often low-cost, locally sourced, and environmentally sustainable. When implemented effectively, they reduce the need for active cooling and lower energy consumption if active cooling is still needed. Therefore, the effective use of passive cooling solutions is key to providing thermal comfort in rural areas of sub-Saharan Africa and South-Asia.

In many cases, passive cooling solutions are considered from the design stage of a building. For example, a key design feature is the orientation of the building with respect to sun and prevalent wind. In this chapter, we focus on passive solutions which could be implemented in existing buildings as part of refurbishment programmes.

The proposed solutions consider the type of materials or construction types which are prevalent in rural areas in sub-Saharan Africa and South Asia. In hot climates, roofs are typically made of corrugated metal sheets or flat reinforced concrete (RCC) slabs, so the solutions explored in this chapter are designed for these structures.

This section explores a range of passive cooling techniques and solutions, with a focus on their relevance for rural housing, workspaces, educational institutions, and public infrastructure.

3.2.1 REFLECTIVE PAINT FOR METAL ROOFS

DESCRIPTION

This is a high-impact, low-technology solution appropriate for metal sheet roofs which are common in rural dwellings. It involves applying a white paint with a high Solar Reflectance Index (SRI) to the exterior surface of the metal roof. The paint contains pigments that are highly effective at reflecting the sun's visible and near-infrared radiation, preventing the metal from absorbing heat. Even a simple, high-quality white exterior paint can significantly outperform a bare or dark-coloured metal sheet. Moreover, this paint can help extend the lifetime of metal sheet roofs by providing protection against environmental damage such as rusting.

Reflective paints are universally applicable. They are ideal for residential homes, schools, healthcare facilities, and community markets with metal roofs. In schools, it can make afternoon classes tolerable, helping to improve student concentration and attendance.

INDICATIVE COSTS

The cost of reflective paints is low in comparison to other passive cooling solutions. They cost approximately USD 2 — 5 per m^2, including labour costs. The cost is highly dependent on the quality and durability of the paint. It is one of the most cost-effective retrofit options available.

Figure 9. a) Installation of reflective paint on roof. Source: Cool Roofers Senegal/Clean Cooling Collaborative b) Diagram of the reflectance effect of reflective paint. Source: Kimberly Magerl (2023).

AVAILABILITY & LOCAL KNOWLEDGE

Reflective paints are widely available, however there is a lack of awareness of their impact for thermal comfort in many areas of sub-Saharan Africa and South Asia.

International organisations have aimed to scale up this solution through programmes such as the 'Million Cool Roofs Challenge'. The Challenge — an initiative under the Clean Cooling Collaborative (formerly K-CEP), Global Cool Cities Alliance, Sustainable Energy for All (SEforALL), and Nesta Challenges — awarded grants across the world to test different approaches and models to scaling up cool roofs in their countries. The winning team installed cool roofs on 70 buildings across 15 cities in Indonesia, including low-cost housing units, schools, factories and an orphanage, estimating that more than 10,00 people will benefit. Moreover, the measured reduction of indoor temperatures ranged from 3°C at a school to 10°C at a factory[46]. The challenge also funded a project in Kenya, where reflective coatings were implemented in housing and public buildings in informal settings of Nairobi. The implementers state the pilot was successful and helped influence the inclusion of passive cooling in Kenya's National Cooling Plan[47].

KEY CHARACTERISTICS

- **Immediate Impact**: Can reduce indoor temperatures by a range of 3-7°C. In low-income dwellings with low ceilings, where heat radiation of metal roofing during peak solar hour increases the roof's temperature, the impact of reflective paints can be even more significant.
- **Low cost**: Affordable for a wide range of households and institutions.
- **Light weight**: Adds no structural load to the roof.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	This solution is suitable for both hot-dry and hot-humid climates.
Ease of implementation	Medium to high ease of implementation. Local painters can use reflective paint with minimal training using brushes or rollers. Only proper surface preparation (cleaning, de-rusting) is required to ensure paint adhesion and longevity.
Quality assurance and maintenance	As they represent a simple solution, the market is flooded with low-quality paints that have poor reflectivity and durability. Quality and efficiency standards are nascent globally[48]. The paint's effectiveness decreases as it gets dirty or peels. It requires re-application every three — five years, representing a recurring maintenance cost.
Ease of use	Medium to low complexity. Reflective paints require no user management but since dust build up decreases its effectiveness, these paints require regular additional cleaning compared to a roof that uses conventional paints.
Supply chain resilience	High resilience to supply chains. Reflective paints are widely available, while specialised coatings offer the best performance, standard white industrial or exterior-grade paint is available in almost every market.
Embedded GHG emissions	Very low embedded GHG emissions, although some chemical-based paints or coating — potentially including PFAS[49] — have higher embedded emissions during their manufacturing and end-of-life. This requires further assessment.
Environmental impact at end-of-life	Some chemical-based paints are likely to contain nano-particles or PFAS (coiled as eternal pollutants due to their very lengthy degradation) and thus specialised disposal is required. Promoters of the solution should ensure the environmental impact of the materials used.

46. SEforAll (2022). Million Cool Roofs Challenge: Local Champions for a Global Movement.
47. TDMA (nd). How titanium dioxide is helping to keep Kenyan homes cool — TDMA.
48. APEC Energy Working Group (2020). Coordinating Standards for Cool Roof Testing and Performance.
49. PFAS (per-and poly fluoroalkyl substances) is a chemical family consisting of at least 5,000 individual substances. They are sometimes referred to as 'forever chemicals' because of their persistence in the environment.

3.2.2 COOL ROOFS

DESCRIPTION

Flat Reinforced Concrete (RCC) slabs are the standard for permanent construction across South Asia and urban sub-Saharan Africa. Their key thermal characteristic is high thermal mass: they absorb solar heat slowly throughout the day and continue to radiate it into the living space long after sunset, making nights uncomfortable.

A cool roof surface's goal is to prevent the roof's concrete thermal mass from absorbing heat in the first place. There are different techniques that can be used in concrete slab roofing:

- **China mosaic / broken tile roofing**: A traditional and highly durable technique, popular in Western India. It involves embedding pieces of broken white ceramic tiles or glazed pottery into a cement mortar bed over the RCC slab. The white, glossy surface is highly reflective and the air pockets in the mortar add a small insulating effect.
- **Limewash**: A very low-cost, traditional method of applying a thick coat of slaked lime to the roof. Lime is naturally white and reflective.
- **Reflective paint**: Modern elastomeric or acrylic-based white coatings can also be used, like the solution for metal roofs.

INDICATIVE COSTS

- **Limewash**: Very low (< USD 1 per m²).
- **Reflective paint**: Low (USD 3 — 6 per m²).
- **China mosaic**: Moderate (USD 10 — 15 per m²), with a higher proportion of the cost being skilled labour.

AVAILABILITY & LOCAL KNOWLEDGE

Lime is widely available. Broken tiles for mosaic are often an industrial waste product, making it a circular economy solution. The technique requires skilled masons, but this knowledge is well-established in many parts of South Asia.

Applying reflective paint to the roof.

Source: Getty Images

KEY CHARACTERISTICS

- **High durability (Mosaic)**: A China mosaic roof can last for decades with no maintenance.
- **Waterproofing**: Both mosaic and modern coatings improve the concrete slab's waterproofing. This is crucial benefit of cool roofs as RCC roofing typically experiences leaks.
- **Prevents night-time heat radiation**: This is the most significant benefit for concrete roofs, leading to much cooler and more comfortable nights.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	This solution is suitable for both hot-dry and hot-humid climates.
Ease of implementation	Medium ease of implementation. Limewash and China mosaic require skilled masons, who may not be available in all regions. This knowledge is well-established in many parts of South Asia and has potential to be transferred to other regions.
Quality assurance and maintenance	The assessment for the reflective paints and coatings for concrete slab roofing is the same as that used in reflective paints for metal roofing. Quality and efficiency standards are nascent globally[50]. Repainting or re-coating is needed every three — five years. Limewash coating erodes and must be reapplied annually, typically after the monsoon season.
Ease of use	Medium to low complexity. Cool roofs require no user management but since dust build up decreases its effectiveness, additional cleaning is required when compared to a regular roof.
Supply chain resilience	High resilience to supply chains. The assessment for the reflective paints for concrete slab roofing are equal to the reflective paints for metal roofing. China mosaic roofing and limewash are materials available locally and are usually construction waste in the focus regions of this report. This makes them cooling solutions which are non-reliant on global supply chains.
Embedded GHG emissions	Cool roofs have low embedded GHG emissions in comparison to other cooling solutions, particularly when using locally available materials and if limewash and China mosaics are waste from other constructions. Despite that, some chemical-based coatings — potentially including PFAS — have higher embedded emissions during their manufacturing and end-of-life. This requires further assessment.
Environmental impact at end-of-life	The environmental impact of disposing China mosaic or limewash is negligible. Some specialised paints are likely to contain nanoparticles or PFAS (coiled as eternal pollutants due to their very lengthy degradation) and thus specialised disposal is required. Promoters of the solution should ensure environmental innocuity of the materials used.

50. APEC Energy Working Group (2020). Coordinating Standards for Cool Roof Testing and Performance.

Applying reflective paint to a roof.
Source: Getty Images

CASE STUDY

Figure 10. Masons installing China mosaic on a roof in India.

Source: Mansi Shah demonstration project

Ahmedabad, India

CHINA MOSAIC COOL ROOFS

In Ahmedabad, India, a city with a hot-dry climate, China mosaic roofing is a standard feature on countless residential and institutional buildings. A typical family home with a concrete roof experiences indoor temperatures that remain high until 2-3 AM. An identical home with a China mosaic roof will see its indoor temperature start to drop shortly after sunset, making sleeping conditions significantly better and reducing the need for fans or air coolers.

Figure 11. a) Diagram of an under-deck insulation effect. Source: Aerolam Insulations. b) Installed under-deck insulation at dwelling in Myanmar. Source: Geres.

This insulation barriers are adequate for homes, healthcare facilities, and classrooms where occupants spend significant time directly under the roof. In hot-humid climates, this is particularly crucial to reduce the "oppressive" feeling of radiant heat.

INDICATIVE COSTS

Its costs are low to moderate when comparing to other passive cooling solutions. It ranges from USD 3 — 8 per m^2. Costs are lowest when using locally sourced materials and highest when using imported, certified radiant barrier products.

3.2.3 UNDER-DECK INSULATION WITH A RADIANT BARRIER

DESCRIPTION

This solution is fit for metal sheet roofs which are common in rural dwellings. It tackles the heat that is absorbed by the metal sheet by blocking it from radiating downwards. This barrier should be installed below the metal roof with an essential air gap of at least 25-50mm. The most effective low-cost material for this is a radiant barrier — a thin sheet of reflective material like aluminium foil. This can be laminated onto kraft paper, bubble wrap, or woven polypropylene fabric for strength. Such barriers are also commercially available in some countries in sub-Saharan Africa[51] and South Asia.

KEY CHARACTERISTICS

- **Highly effective**: Can block up to 95% of downward radiant heat transfer.
- **Works well with other solutions**: The radiative barrier can be combined with reflective paint or additional insulation for maximum effect.
- **Light weight**: Adds minimal structural load.
- **Sound insulation**: Provides some sound insulation from rain noise on the metal roof.

51. The Cool Roof — Decra Roofing Systems Kenya.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	This solution is suitable for both hot-dry and hot-humid climates.
Ease of implementation	Implementation requires skilled workers to build the structure and install the insulation material. Local artisans can easily be trained to fix a simple timber or bamboo sub-frame and attach the barrier.
Quality assurance and maintenance	No quality standards specific to its implementation in rural buildings. Quality assurance of this solution is key for the fire rating of the insulation as fire hazard are a critical and often overlooked concern. Besides this, quality assurance must be reviewed case by case as it requires a structure and proper installation of the material. If insulation is not properly installed, the material can tear, and the air gap can become a nesting place for rodents or insects.
Ease of use	Low complexity. This type of solution does not require user management. However, it is key that users are aware of the quality assurance issues.
Supply chain resilience	High resilience to global supply chains. Basic aluminium foil is widely available. Woven polypropylene fabric is also widely available.
Embedded GHG emissions	Low embedded GHG emissions in comparison to other cooling solutions, particularly when regionally available materials are used. There is potential for substitution of the woven propylene fabric with natural fibres to decrease the solution's environmental impact further.
Environmental impact at end-of-life	The environmental impact of the materials of this solution is low. Aluminium and polypropylene fabric can be relatively easily recycled.

Under deck insulation.
Source: Getty Images

3.2.4 OVER-DECK INSULATION

DESCRIPTION

This solution can be implemented in RCC slab roofs. Insulated over-deck systems involve adding a dedicated insulating layer on top of the concrete slab's waterproofing membrane. Its purpose is to prevent the concrete slabs from absorbing heat. This is critical as in highly temperate conditions these types of roofs absorb and store solar heat throughout the day and release it into indoor spaces well into the night, making sleeping conditions uncomfortable. There are different techniques to achieve this type of insulation:

- **Inverted earthen pots**: An Indian traditional, low-cost technique where inverted clay pots are laid across the roof, and the gaps are filled with sand or broken brick aggregate before a final screed is applied. The trapped air inside the pots acts as an excellent insulator.
- **Prefabricated panels**: Modern solutions include laying extruded polystyrene (XPS) insulation boards, expanded cork panels, or lightweight autoclaved aerated concrete (AAC) blocks, on the roof, covered by a protective cement screed or tiles.
- **Rooftop garden (Green roof)**: A layer of soil and vegetation provides excellent insulation through shading and evaporative cooling. This requires a robust waterproofing layer, a drainage layer, filter fabric, soil, and plants.

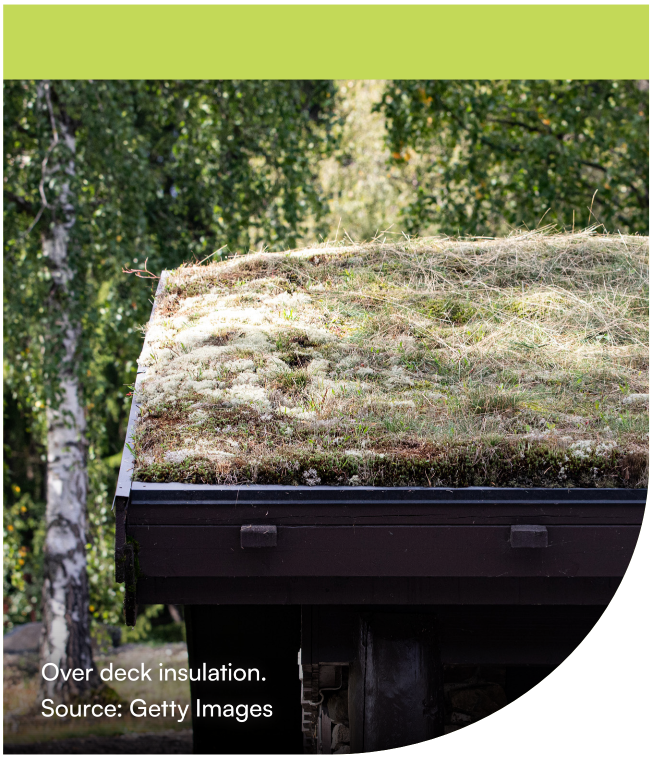
Figure 12. Installation of inverted earthen pots in India. Source: Mansi Shah demonstration project

INDICATIVE COSTS

- **Inverted pots**: Low to moderate (USD 8 — 12 per m²).
- **Prefabricated panels**: Moderate to high (USD 15 — 30 per m²).
- **Green roof**: High (USD 40 — 80 per m²).

AVAILABILITY & LOCAL KNOWLEDGE

Earthen pots are locally made and their use for insulation is traditional in India and other countries of South Asia. Insulation boards are industrial products, less available in rural areas. However, cork or wooden panels can be more widely available. On the other hand, some green roof components such as drainage mats are specialised.



Over deck insulation.
Source: Getty Images

KEY CHARACTERISTICS

- **Excellent insulation properties**: Provides a very high level of thermal resistance.
- **Protects structure**: Shields the primary roof structure and waterproofing membrane from UV radiation and thermal stress, extending its life.
- **Usable space (Green roof)**: Creates valuable recreational or agricultural space.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	This solution is suitable for both hot-dry and hot-humid climates. There needs to be detailed care of insulation and waterproofing when it is used in climates with heavy rains (monsoons).
Ease of implementation	Low ease of implementation. The weight of these solutions adds a significant structural load, which must be accounted for in the building's design. This makes it a difficult retrofit for many low-cost buildings. Their implementation requires skilled workers to install the types of different insulation.
Quality assurance and maintenance	No quality standards specific to its implementation in rural buildings. Quality assurance of the installation of prefabricated panels and green roofs is critical as these systems also work as waterproofing insulation and can affect the building's structure.
Ease of use	Low complexity. This type of solution does not require user management. However, it is key that users are aware of the quality assurance issues.
Supply chain resilience	High to medium resilience to global supply chains. Earthen pots are locally made, making them an easily available solution. Insulation boards are industrial products are less available in rural areas, while green roof components (drainage mats, etc.) are specialised and manufactured in specific regions.
Embedded GHG emissions	Low embedded GHG emissions in comparison to other cooling solutions, especially when using locally available materials like inverted earthen pots. If the prefabricated panels are used, the embedded GHG emissions are higher given the resources required for the manufacturing process.
Environmental impact at end-of-life	The environmental impact of disposing earthen pots is negligible, although the materials used for the prefabricated panels include chemicals are complex to recycle and more so in rural areas. Therefore, specialised disposal of this solution is required.

Bio-climatic design of an electrified business area using Nubian vault construction in Mali.
Source: Geres

A clay-tile filler slab roof used in a home in an informal settlement.
Source: SELCO Foundation

Ahmedabad, India

CLIMATE RESPONSIVE, HOME-BASED PRODUCTIVE WORKSPACES

The city of Ahmedabad has a hot semi-arid climate typology with dry summers and temperatures exceeding 40°C. Housing in informal settlements are ad-hoc structures built that have limited natural light, ventilation and other climate responsive strategies. Apart from the indoor heat stress conditions that these structures create, the rapid urbanisation and haphazard settlements contribute to urban flooding in monsoons. In 2022, in partnership between Mahila Housing SEWA Trust and SELCO Foundation, four climate-responsive houses were built for home-based women entrepreneurs in two informal settlements in Ahmedabad, India.

Regarding over-deck insulation strategies, the project used filler slab roofing technique using clay tiles, which is like using inverted clay pots, which was key to waterproofing the houses during the monsoon season.

The key strategies used to implement a climate-responsive, and people-centred architectural perspective were:

1. **Efficient spatial design**: Considering the linear profile of the individual plots (ranging from 450 to 800 sq.ft.) and a wall-to-wall row housing configuration (commonly found in urban informal settlements), cross ventilation was allowed through linearly placed door openings in the East-West direction. Rooms were placed with kitchens and living areas receiving the most natural light and ventilation with bedrooms and bathrooms towards the rear. Raised plinth avoids backflow of storm water drainage into the houses.

2. **Material and insulation**: One house utilised polyurethane foam (PUF) panel roofing for under-deck insulation. Additionally, cool roofs — such as those coated with white reflective paint or fitted with white tiles — are used on reinforced concrete (RCC) buildings to reduce heat transfer into indoor spaces.

3. **Efficient fenestration design**: To improve natural light and ventilation in small-footprint homes, the designs included roof ventilators (see section 3.2.8) and openings above doors and windows at lintel level. Ventilators were also integrated between the rooms to allow light to permeate.

4. **Integrating energy efficient appliances and solar energy solutions**: Energy -efficient lights and ceiling fans were incorporated. Exhaust fans in kitchens provide ventilation that helps to reduce indoor air pollution while cooking.

5. **Optimising the functionality of spaces**: Living rooms and bedrooms of these houses are often designed as multi-purpose spaces with storage and workstations to accommodate home-based livelihood activities.

6. **Adaptability to local social contexts — urban communities with focus on traditional, cultural and aspirational values**: RCC roof slabs are aspirational in these communities, to allow the addition of more floors to the house based on future requirements. Therefore, using RCC is key in designs, and worked on thermal insulation solutions for this type of roofing as described above.

One of the women who benefitted from the renewed houses said, “It’s so hot outside, but now my house is cool. I don’t have to worry about water entering my house during monsoons anymore, because my house is raised now.” Dipikaben, Tailor, Ahmedabad

3.2.5 VENTILATED DOUBLE ROOF SYSTEM

DESCRIPTION

A ventilated double roof system is a passive cooling strategy for buildings in hot-dry and hot-humid climates. This system was designed modernising traditional techniques of ventilated roofs. The system is not a single material, but a synergistic assembly of three key components.

1. **Outer layer (Radiant barrier)**: The first line of defence is a lightweight, pre-painted aluminium sheet roof to reflect heat as described in section 3.2.1. This can be complemented by an under-deck insulation barrier such as that described in section 3.2.3. Its primary function is to act as a radiant barrier, significantly reducing the amount of heat absorbed by the building envelope.

2. **Middle layer (Ventilated air gap)**: This is the critical component. An air gap, or attic space, is created between the outer metal roof and the inner ceiling. This space is cross-ventilated through openings on opposite sides of the building. As the metal roof heats up, the air in the gap also heats, rises, and is carried away by natural convection and wind (the stack effect). This process evacuates the absorbed heat before it can be conducted or radiated to the space below.

3. **Inner layer (Insulated ceiling)**: The final barrier is a false ceiling made out of plywood. While five millimetres of plywood offers modest insulation, its primary role is to block radiant heat from the hot underside of the metal roof from reaching the occupants. It acts as a "shield against the diffusion of heat" from the attic. Its low thermal conductivity is significantly better than that of a solid concrete slab, preventing the ceiling from becoming a large, hot thermal mass radiating heat downwards throughout the evening. In both hot and cold climatic conditions, an additional layer of insulation — made out of glass wool or bio-based materials — can be added to this layer to provide additional thermal comfort. The absence of thermal insulation hampers thermal comfort and the energy efficiency of active cooling both in cold and hot climates.

Figure 13. a) Ventilated double roof system with under-deck radiant barrier. b) Ventilated double roof system with reflective paint as radiant barrier (non-visible). Both implemented in rural settings in Myanmar.

Roof vents on a steel roof.
Source: Getty Images

INDICATIVE COSTS

Use cases provide cost estimates for two implementation examples:

MATERIAL	COST IN BOUCLE DU MOUHOUN, BURKINA FASO / M² (INCL. LABOUR)	COST IN CHIN STATE, MYANMAR / M²
Metal roofing	9 USD	13 USD
False ceiling, (5mm, plywood)	22 USD	7 USD (incl. ridging sheet)
Labour	NA	4 USD
Total system cost/m² (excl. main structure)	31 USD	24 USD

* Note: These costs are specific to the sites of the use cases.

Additional costs would need to be considered for roof structures and soffits (roof overhangs). The latter is not a requirement but could help improve the efficiency and durability of the solution.

The cost to implement this solution will vary significantly based on global commodity prices (steel, aluminium), logistics to the site, and local labour costs. However, a key economic benefit is that the lightweight nature of this system may help make the cost of foundations cheaper compared to a heavy concrete roof.

AVAILABILITY AND LOCAL KNOWLEDGE

The solutions use industrial materials, such as sheeting, steel profiles, and plywood. While these not "local" in the way that earth or stone are, they are widely available through commercial supply chains across Africa, Asia, and Latin America.

The concept of a ventilated roof is deeply rooted in traditional architecture worldwide. Thatched roofs, traditionally made with straw or reeds, inherently create a thick, ventilated insulating layer. This modern system applies the same scientific principle using more durable, industrial materials.

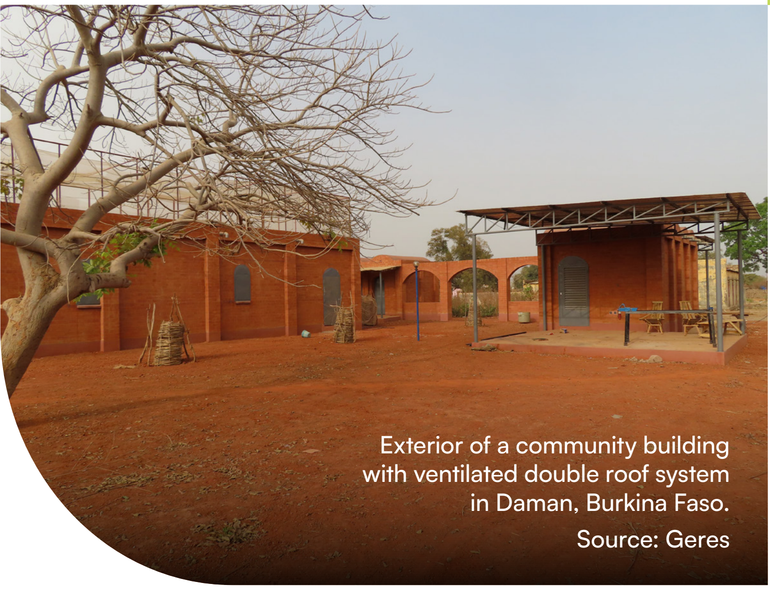
KEY CHARACTERISTICS

- **Improved thermal comfort**: By tackling all three modes of heat transfer (reflecting radiation, absorbing the convection generated heat, and resisting conduction), this system significantly lowers ceiling temperatures and reduces the mean radiant temperature of the indoor space, which is critical for human comfort.
- **Energy efficiency**: This solution significantly reduces or eliminates the need for active cooling.
- **Lightweight construction**: This reduces the load on walls and foundations, saving materials and money.
- **Moisture control**: In humid climates, the constant ventilation helps to prevent moisture buildup, condensation, and mould growth in the roof assembly.
- **Acoustic damping**: Rain on a single metal roof can be noisy. The insulated false ceiling provides a crucial acoustic buffer, improving the comfort of occupants.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	This solution is very effective in hot-dry climates as it reflects intense, direct solar radiation and venting the resulting heat load. Ventilated double roof systems are also effective in hot-humid climates. While reflectivity is still important, the ventilation component becomes even more critical for managing humidity and preventing the oppressive buildup of heat.
Ease of implementation	Low ease of implementation as it requires a specific roofing structure. Proper installation is crucial — seams in the metal roofing must be perfectly waterproof, and ventilation openings must be correctly sized and placed to ensure effective airflow without allowing the ingress of rain. This requires a higher skill level than traditional roofing.
Quality assurance and maintenance	No quality standards specific to its implementation in rural buildings. Quality assurance of the installation is critical as these systems also work as waterproofing insulation and can affect the building's structure. Moreover, the ventilated double roof system requires the radiant barrier to be maintained as described in the reflective painting section.
Ease of use	Low complexity. This type of solution does not require user management. However, it is key that users are aware of the quality assurance issues.
Supply chain resilience	High to medium resilience to supply chains. Metal sheeting, steel profiles, and plywood are industrial materials. While not local in the way that earth or stone are, these materials are widely available through commercial supply chains across sub-Saharan Africa and South-Asia. Depending on the radiant barrier material, it can be sourced regionally or depends on imported materials.
Embedded GHG emissions	Low embedded GHG emissions in comparison to other cooling solutions, especially when using locally available materials.
Environmental impact at end-of-life	The environmental impact of disposing the materials of this solution is relatively low. However, when using specialised chemical-based coatings for the radiative barrier, the issues described in the reflective paintings section apply.

Roof vents.
Source: Getty Images


Exterior of a community building with ventilated double roof system in Daman, Burkina Faso.
Source: Geres

Moro Moro, Mali and Daman, Burkina Faso

IMPLEMENTING VENTILATED DOUBLE-ROOF SYSTEMS IN COMMERCIAL AND COMMUNITY BUILDINGS (HOT-DRY CLIMATE)

Geres, a development NGO working in Europe, Africa and Asia to improve living conditions and combat climate change and its impacts, successfully implemented this system across a range of commercial and community buildings (Electrified Business Areas, EBAs), including a restaurant/leisure block, a bakery, juice production units, and mixed-service industrial blocks. The design was part of an integrated bioclimatic strategy that included thick laterite block walls and optimized window placement. The stated goal was to create a comfortable and economically viable activity hub with minimal reliance on external energy inputs, and the roof system was central to achieving this.

Chin State, Myanmar

RETROFITTING RURAL HOUSES (HUMID SUBTROPICAL, DRY WINTER CLIMATE)

In a region experiencing warm and humid summers and cool winters (down to 0°C at night), houses in rural areas can be highly energy inefficient. Some houses are constructed with metal sheet roofs and timber walls, while others use metal corrugated sheets for both roofing and walling. Most timber houses are old and had a lot of air gaps as the timber materials had shrunk with age and due to improper construction. Geres explored a variety of solutions useful for both warm and cold seasons, among which ceiling improvement, but also targeting walls and floor, using as much as possible local materials (mostly beams and plywood). Masons and carpenters were trained beforehand on actual pilot construction sites to ensure the use of appropriate techniques. Likewise, retailers of construction materials were involved, to guarantee future availability of materials not found pre-project, such as glass wool or some types of flooring. Inhabitants of the retrofitted houses have been surveyed pre and post project, and all of them cite significant improvements in their comfort and health, especially for particularly vulnerable individuals such as children and the elderly.

The methodology is currently reproduced in other parts of the country.


Installation of under-deck insulation at a rural household in Myanmar.
Source: Geres

3.2.6 EVAPORATIVE COOLING

DESCRIPTION

The evaporative cooling effect can also be a passive solution when it uses natural air flow (due to wind or pressure changes) to draw warm air through water-saturated pads, as described in Section 3.1.2. There are different methods to hone the evaporative cooling effect in a passive manner:

- **Evaporative shades**: By cross-ventilating buildings and covering windows with water-saturated shades the evaporative cooling effect allows cooler air to enter the room. Vetiver shades are the most common in India. Water-saturated shades reduce heat infiltration as they also shade the room. Adequate window placement is key to allow for cross-ventilation.

- **Passive downdraft evaporative coolers**: Towers that use gravity force to move air down and through the saturated material which cools the air before it naturally flows down in the building[52]. These were integral to traditional architecture in the Middle East, North Africa, and North India and Pakistan.

Evaporative cooling is particularly efficient in hot-dry climates where low humidity allows for better evaporation. However, they have high potential to provide thermal comfort when designed adequately.

Studies regarding evaporative charcoal and zero-energy brick coolers in Kenya, where charcoal and sand are used to retain water, showed that a temperature differential between the ambient air (outside) and inside the evaporatively cooled room can range from 5°C and 16°C depending on the season and time of day[53].

While most uses of passive evaporative coolers sub-Saharan Africa have been focused on cooling and preserving food, there is potential for the application of similar techniques and materials for space cooling. In Kenya, for example, an evaporative charcoal cooler designed for food storage, has been adequately modified with structural reinforcement to withstand harsh weather conditions. The walls made from fibre glass are not only durable, but have also transformed the unit into a structure that can be adapted to house people (Fig 14.a)

Figure 14.a) Evaporative cooler for food storage installed in Kenya. Source: Prof. Jane Ambuko. b) Vetiver evaporative shades. Source: Rayush Naturals

INDICATIVE COST

The cost of the different described evaporative cooling solutions varies significantly:

- Evaporative shades are low-cost and range from USD 20 — 50

- Passive downdraft evaporative coolers require architectural modifications to buildings, their cost will depend on materials and labour, reaching ranges of thousands of USD.

KEY CHARACTERISTICS

- **Energy efficiency**: Its use can significantly reduce or eliminate the need for active cooling.

- **Local materials**: Using locally available materials to build evaporative coolers makes them well-suited for rural areas and helps keep their embedded greenhouse gas (GHG) emissions low.

- **Improved indoor air quality**: All the passive evaporative cooling solutions require increased air ventilation, which improves indoor air quality.

- **Water management**: Water requirements and its management is a key consideration of evaporative coolers.

52. TERI (2021). Thermal Comfort prescription for Cooling dominated Indian residential buildings.
53. Ambuko et al (2016). Cold chain management in horticultural crops value chains: options for smallholder farmers in Africa.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	Best suited for hot-dry climates with low humidity. They need a steady supply of water, which is a limitation for water-scarce region. It is important for manufacturers to innovate in water management technologies, such as water recycling systems.
Ease of implementation	Varying ease of implementation. Covering windows with water-saturated materials has easy implementation, while modifying dwellings to make use of passive downdraft coolers has high difficulty and cost.
Quality assurance and maintenance	No quality standards specific to its implementation in rural buildings. They require high maintenance, as humid environments are good places for germs and viruses, frequent cleaning is important to maintain the humid pads clean and long-lasting. Many new systems of passive downdraft evaporative coolers have built-in filters to decrease the possibility of mould.
Ease of use	High complexity. They require adequate user management for operation and maintenance. Users need to pour water relatively frequently into the water reservoir, and it is important that the cooling pads are cleaned and maintained properly to prevent bacteria growth.
Supply chain resilience	The possibility of locally available materials to fabricate the evaporative coolers makes them non-reliant on global supply chains.
Embedded GHG emissions	The embedded GHG emissions is very low, particularly when they use local materials and water is efficiently managed.
Environmental impact at end-of-life	The environmental impact of disposing the materials of passive evaporative coolers is negligible.


Evaporative air cooler.
Source: Getty Images

3.2.7 FENESTRATION

DESCRIPTION

TECHNIQUES

Effective fenestration design is essential for enabling cross-ventilation and regulating indoor temperatures. Key techniques include:

- **Strategic placement and sizing**: Windows and openings should be positioned on opposite or adjacent walls to facilitate cross-ventilation. In hot-dry climates, smaller openings reduce heat gain, while in hot-humid climates, larger openings enhance airflow.
- **Height variation**: Placing openings at different heights (e.g., low inlets and high outlets) promotes the stack effect, drawing warm air upward and out. The use of clerestories, which are narrow windows placed towards top of the wall close to the roofline is an option to enable passive ventilation.

PRODUCTS

- **Lattice windows or Jaali (India)**: In hot and dry regions, windows and ventilators need to be smaller and shaded to ensure reduced heat gain and hot air movements. Lattice windows or screens allow air to circulate while protecting the buildings from sunlight and heat gain.
- **Windows with micro-ventilation**: These windows are designed to allow controlled airflow even when closed, using small vents or adjustable openings. They are particularly useful in areas where security, dust, or insects are concerns. Micro-ventilation features can be integrated into standard window frames and are increasingly available in both urban and rural markets.
- **Window films**: Reflective solar control films applied to surfaces of glass windows providing a range of benefits such as solar control, thermal insulation and UV protection, and ultimately enhancing passive cooling. Studies have found that window films can reduce indoor temperatures between 2 and 5°C, lowering cooling costs and improving indoor comfort[54]. Their effectiveness depends on the type of film, its adequate installation, and location of fenestration.

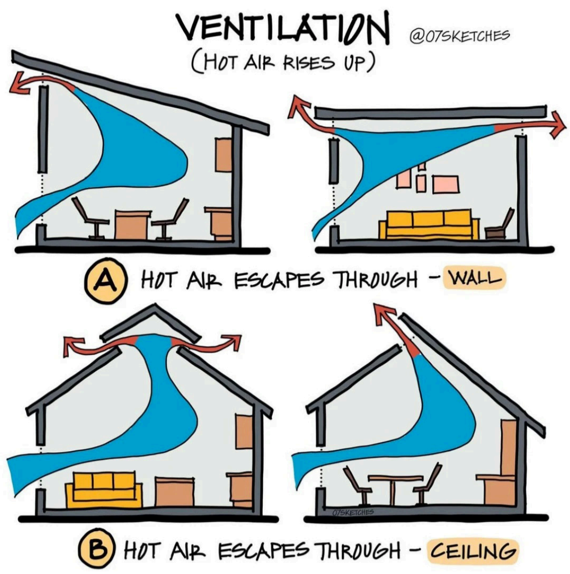


Figure 15. a) Diagram showcasing adequate placing of windows to facilitate ventilation. Source: 07sketches.
b) Example of passive design facilitating micro-ventilation in Electrified Business Area buildings in Mali. Source: Geres

54. Pereira et al. (2022). Performance of Solar Control Films on Building Glazing: A Literature Review.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	For hot-dry climates, lattice windows and smaller window openings are the best suitable fenestration solutions to reduce heat gain. In hot-humid climates, larger operable windows in opposite walls for cross-ventilation and operable windows with micro-ventilation to protect from rain or insects. Window films are suitable for both hot-dry and hot-humid climates.
Ease of implementation	Low ease of implementation. Some of these solutions such as strategic placing and sizing of windows or adding lattice windows require significant refurbishment. Windows with micro-ventilation are relatively easier to implement as they can be installed in existing openings.
Quality assurance and maintenance	No quality standards specific to its implementation in rural buildings. Material quality and appropriateness, such as corrosion-resistant metals in humid zones are important. Adequate design and installation are also key considerations. These solutions do not require complex or very frequent maintenance.
Ease of use	Security concerns, dust, or insects may discourage users from opening windows, which could affect this technology's ability to cool houses.
Supply chain	Medium to high resilience to supply chains. The materials to manufacture these solutions are generally available in local or regional supply chains. However, the lattice windows may be less available in certain regions, and micro-ventilation windows or window films are not commercially available in sub-Saharan Africa or South-Asia.
Embedded GHG emissions	Low embedded GHG emissions in comparison to other cooling solutions, especially when using locally available materials.
Environmental impact at end-of-life	The environmental impact of disposing the materials for the fenestration solutions is low when compared to other cooling solutions. Some materials such as steel or aluminium can be recycled, and their processes are relatively established and cost-effective.

Fenestration.
Source: Getty Images

The exterior of a climate- adaptive labour room implemented in Meghalaya, India to improve last-mile healthcare access.
Source: SELCO foundation

Meghalaya, India

CLIMATE ADAPTIVE LABOUR ROOMS IN MEGHALAYA, INDIA

Meghalaya, in the North-Eastern Region of India, has a humid, subtropical climate, where summers are hot and humid, winters are cool and there is ample rainfall during monsoons. In this area, the SELCO Foundation partnered with National Health Mission to design and implement climate-adaptive and energy efficient labour rooms. These were co-developed with state health officials, medical officers, district level engineers and community members, to be integrated with health sub centres that cater to last-mile communities.

The designed labour rooms used the following fenestrations:

a. **Strategic placement of clerestory windows**: Operable clerestory windows were placed above the lintel level, enabling privacy in the procedure rooms while ensuring appropriate cross ventilation in summer months. In the winter months, these windows can be used to let light into the rooms without losing heat. Shuttered units help maximise the window openings.

b. **Shading**: Efficient fixed overhang shading systems were implemented at the windows (typically called chajjas). See section 3.2.9 for more details on shading solutions.

However, the design went beyond that, taking a climate-responsive and people-centred architectural perspective. To achieve this, the following strategies were used:

1. **Efficient spatial design**: Compact building structures designed with the disaster context in mind — i.e. earthquakes and landslides. Heavy rainfalls informed the sloped roofing to allow water to flow during heavy monsoons. Guidelines were established to ensure health facilities are in low-risk areas, with safe housing, reliable access to essential services, strong connectivity to the villages they serve, and optimal natural light — maximising sunlight in winter and providing adequate shading in summer. Sites were also decided based on ample access to wind throughout the year. Verandas were added to further layer the building with insulating volumes and shaded areas.

2. **Material and insulation**:
    a. **Roofing**: A ventilated double roof system was implemented (see section 3.2.5). This roofing system, featuring an external roofing sheet with low thermal conductivity and a false ceiling, provides efficient thermal insulation in cold and heat-stressed regions. The roof canopy also helps protect the building from damage during extreme rainfall.

    b. **Walling**: Lightweight, autoclaved aerated concrete (ACC) blocks, which have much lower thermal conductivity than regular concrete or bricks, are used for walling. This replaced the normally used brick or concrete blocks that did not provide as much thermal insulation.

3. **Integrating energy efficient appliances and solar energy solutions:** Some labour rooms and procedure rooms were equipped with efficient wall-mounted radiant heaters, as well as energy-efficient fans for maintaining stable temperatures and ensuring thermal comfort for newborns. These were integrated with a solar PV system with lithium battery storage.

A mother who delivered at the labour room said, "'The facility has all the amenities, hence I decided to deliver my baby here. The baby warmer keeps the baby warm after delivery', highlighting how reliable, climate adaptive health facilities can strengthen last mile healthcare access.

3.2.8 ROOF VENTS

DESCRIPTION OF THE SOLUTION

Roof vents generate passive ventilation by leveraging natural forces — primarily wind pressure and thermal buoyancy (stack effect) — to move air without consuming electrical energy. This creates a pressure differential, actively drawing hot and moist air out of a building's roof space or attic.

It is key that these solutions are only used in combination with the ventilated double roof system (see section 3.2.5), to facilitate air flows. Ideally, these systems should be turned off during the warmest hours and started only when temperatures drop, which is typically at night.

The systems examined fall into two main categories based on their function.

EXHAUST-ONLY SYSTEMS (ATTIC & DUCT VENTILATION)

These systems are designed to create negative pressure at the termination of a duct or attic space, actively pulling hot, moist, or stale air out of the building. This is an indirect cooling method, as it reduces the heat load on the space below (in the case of attics) or ensures the proper functioning of a specific duct (like a chimney or bathroom vent).

- **Wind-powered roof vents**: These devices use a spinning rotor with vanes to create a consistent updraft. Made of aluminium or galvanized steel, the typical vent design features a rigid, riveted internal structure and air-foil curved vanes with rolled edges designed to deflect water. The turbine's head spins on permanently lubricated upper and lower ball bearings, necessitating limited maintenance.
- **Static extractors**: These devices have no moving parts. They rely on their fixed aerodynamic shape to use passing wind to create a low-pressure zone above the duct opening, which encourages a steady exhaust flow.

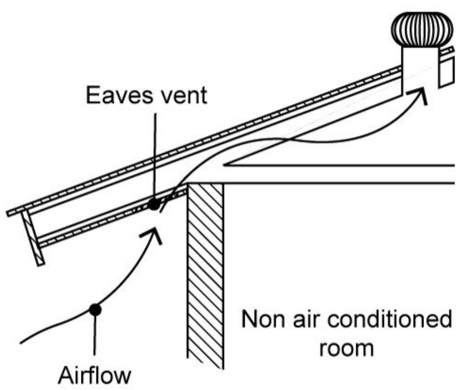


Figure 16.Diagram on use of roof vents and importance of airflow in the eaves vent. Source: Adapted from Yourhome — Australia's guide to environmentally sustainable homes.

BALANCED INTAKE & EXHAUST SYSTEMS (DIRECT SPACE VENTILATION)

This advanced strategy uses a single roof-mounted unit to both supply fresh air into and pipe stale air out of an occupied space.

- **Top-down ventilators**: This system works by capturing wind at roof level and directing it down into the building through a compartmentalised shaft. Its key advantage is that its external louvers capture wind from any direction. The windward side acts as an intake, while a negative pressure (suction) zone is created on the leeward side, which pulls warm, stale air up and out through a separate internal quadrant. This creates a full ventilation cycle — fresh air in, stale air out — without relying on open windows.

INDICATIVE COSTS

- **Exhaust-only systems**: These products exist in a large variety of sizes, shapes and quality. Prices can therefore range from 20 USD for household systems, to around 400 USD for larger/industrial sized exhausts.
- **Balanced intake & exhaust systems**: These systems are more complex in design and are therefore more expensive.

AVAILABILITY & LOCAL KNOWLEDGE

These are engineered, manufactured systems. Their availability depends on regional distribution networks, but they can be manufactured by local producers in many countries in sub-Saharan Africa and South Asia.

The simplest designs can be installed by skilled craftspeople with experience in the construction of metal roofing, whereas more complex systems might require a specifically trained workforce. In any case, installation challenge lies in proper positioning of the system on the roof to maximise air flow and tightness to avoid leakage in rainy conditions.

KEY CHARACTERISTICS

- **Energy-free operation**: The primary benefit is that all systems run on wind power, requiring zero electricity.
- **Improved air quality & thermal comfort**: These systems continuously remove stale, moist, or polluted air from spaces, and, for some systems, replace it with fresh air.
- **Low to no maintenance required**: Static extractors have no moving parts. Turbine vents use permanently lubricated bearings.
- **Night-time cooling**: The balanced intake/exhaust systems are particularly effective for "free cooling," helping purge a building of stored heat overnight.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	This solution is highly effective in all climates with high wind. Wind dependency is a limitation of these systems. In places where seasonal winds can carry significant amounts of particles or dust such as the Harmattan season in Sahelian countries, there is a high risk of indoor pollution, requiring an air-filtration system which could t be costly and need additional maintenance.
Ease of implementation	Ease of implementation is medium to low, especially when modifications to roofing are needed. The simplest designs can be installed by skilled craftspeople with experience in metal roofing construction, whereas more complex systems may require a specifically trained workforce. In any case, installation challenges lie in the proper positioning of the system on the roof to maximise air flow and avoid leakage in rainy conditions.
Quality assurance and maintenance	There are no quality standards that govern its implementation in rural buildings. Quality assurance of the installation is critical as these systems are part of the building structure. Maintenance of the turbines is seldom needed but when it is, the edges of the turbine vanes are sharp and can cause injury if they are handled improperly.
Ease of use	Adequate use is key, as this solution should be used mostly or even only at night, when the air outside is cooler than the one inside. Otherwise, if a building already has some energy efficiency features to prevent heat entering, it could have a detrimental effect on indoor air temperature. Therefore, only systems that can be turned off during the warmest hours of the day should be used. If outside air is dusty or polluted, it could create indoor air pollution.
Supply chain resilience	Medium resilience to supply chains. Their availability depends on regional manufacturing and distribution networks as they require specialised manufacturing usually using aluminium or galvanised steel. However, they should feasibly be manufactured by local producers in many countries of sub-Saharan Africa and South Asia.
Embedded GHG emissions	Low embedded GHG emissions in comparison to other cooling solutions, especially when using locally available materials.
Environmental impact at end-of-life	The environmental impact of disposing the materials for roof vents is low when comparing to other cooling solutions. If the materials used are galvanised steel or aluminium, their recycling processes are relatively established and cost-effective.

Roof vents on the exterior of a roof.
Source: Getty Images

3.2.9 SHADING

DESCRIPTION OF THE SOLUTIONS

Shading products are essential passive cooling solutions that reduce solar heat gain by blocking or filtering sunlight before it enters indoor spaces. By minimising direct solar radiation, these systems help maintain cooler indoor temperatures, reduce glare, and reduce the need for mechanical cooling. Shading can be integrated into buildings and other structures through both external and internal elements, with each offering unique benefits depending on climate, orientation, and building use. This report presents different shading solutions that are relevant to rural areas, categorised in built shading and green shading:

BUILT SHADING

Fixed overhangs and awnings

- Horizontal projections above windows that block high-angle summer sun while allowing low-angle winter sun (Chhajja in India).
- Effective on south-facing facades in the northern hemisphere and north-facing in the southern hemisphere.
- The projection factor (depth-to-height ratio) determines shading effectiveness and should be optimised for local solar paths.

External louvres and blinds

- Adjustable or fixed slats that block direct sunlight while allowing airflow and views.
- Louvres (horizontal or vertical slats) can be made of wood, bamboo, metal, and are effective for year-round shading.
- The adjustability allows for precise regulation of sunlight while providing natural ventilation and simultaneously reducing the need for artificial cooling system[55].
- Research shows that louvres can be designed to optimise daylight penetration while minimising glare, creating a more pleasant indoor environment[56].

Light shelves

- These are reflective horizontal surfaces above windows that shade the lower part while reflecting daylight deeper into the room. When they are adequately designed, they can decrease heat gain of the indoor space[57].
- They are particularly useful in workspaces. By reflecting sunlight onto the ceiling and allowing it to diffuse throughout the interior, they enhance daylight penetration while reducing direct glare[58].

Recessed windows and shaded setbacks

- Architectural design strategies that use the building envelope to create self-shading. They reduce direct solar exposure and enhance façade performance

55. Iqbal, W., et al. (2025). Optimizing Energy Efficiency: Louver Systems for Sustainable Building Design.
56. Lim, T., Seog Yim, W., and Kim, D. (2020). Evaluation of Daylight and Cooling Performance of Shading Devices in Residential Buildings in South Korea.
57. Masoud, S., et al. (2024). A Review of Factors Affecting the Lighting Performance of Light Shelves and Controlling Solar Heat Gain.
58. Idem.

Shaded exterior of a home.
Source: Getty Images

GREEN SHADING

Vegetative shading

- Use of trees, shrubs, and green walls to shade building walls, facades and windows.
- Can reduce surrounding air temperatures by up to 5°C and improve microclimates.

Trellises and pergolas

- Structures supporting climbing plants or shading screens that create dappled shade.
- These allow ventilation while reducing heat gain and enhancing outdoor comfort.

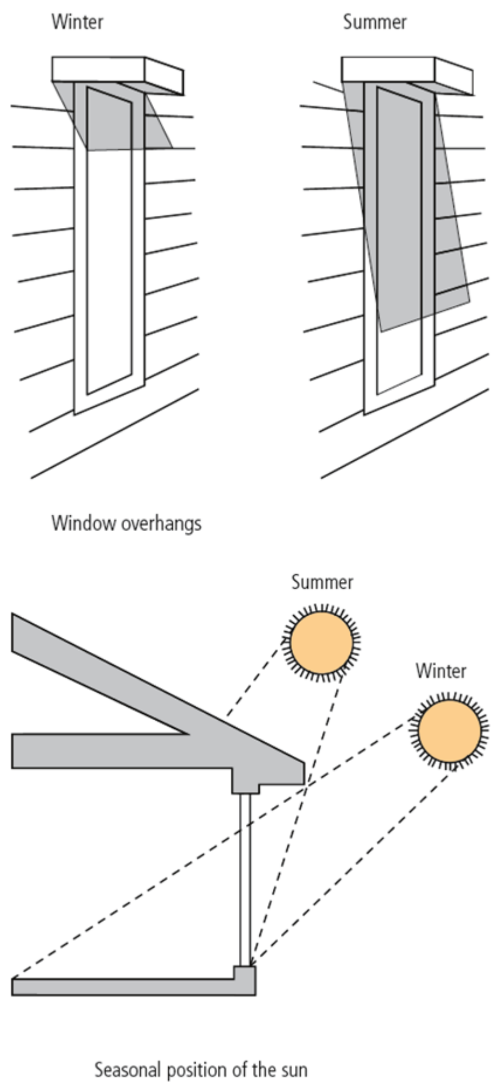


Figure 17. Diagram showcasing shading by overhangs and awnings. Source: Oluwafemi, A.

59. Perez-Carramiñana, C., et al. Influence of Sun Shading Devices on Energy Efficiency, Thermal Comfort and Lighting Comfort in a Warm Semi-Arid Dry Mediterranean Climate.
60. Armson, D. Stringer, P. and Ennos, A.R. (2012). The effect of tree shade and grass on surface and globe temperatures in an urban area.
61. Jewel, Rakibul and Habibur, (2022). An investigation on the impact of shading devices on energy consumption of commercial buildings in the contexts of subtropical climate.

INDICATIVE COSTS

Costs of the described shading products will vary according to the implemented solution, context and material used. Evidence is lacking on indicative costs for these materials in sub-Saharan Africa and South-Asia.

KEY CHARACTERISTICS

- **Indoor temperature reduction**: Although these depend on many factors, studies in the Mediterranean have shown that external louvres can reduce peak indoor temperatures by 2.6 — 5°C under specific conditions and adequate user management[59]. Other studies have shown that vegetative shading can lower surrounding air temperatures by up to 5°C[60].
- **Energy efficiency**: Given lower indoor temperatures, buildings require reduced active cooling when shading solutions are adequately implemented. A study in a hot-humid climate (Bangladesh) recorded a 7% reduction in annual energy consumption by applying shading strategies[61].
- **Impacts to natural light utilisation**: If adequately implemented and used, shading devices can optimise natural light while reducing glare. However, other times there is a trade-off between having adequate natural lighting and shading windows to prevent heat gain.
- **Urban heat island mitigation**: Vegetative and reflective shading reduces local temperatures.
- Implementation of green shading has multiple co-benefits on top of increased thermal comfort, such as improvement of air quality and biodiversity.

SPACE COOLING APPLICABILITY ASSESSMENT

CRITERIA	ASSESSMENT
Performance in different climates	In hot-humid climates it is essential to shade all openings and walls year-round, and it's recommended to shade roofs. In hot-dry climates, it is suggested to use adjustable shade screens or overhangs, so that people can change shading when needed. Covering open areas (terraces or courtyards) next to main living areas with vegetation or pergolas is also important to help cool air.
Ease of implementation	Ease of implementation is medium to low. It is low when the dwelling needs structural modifications to install a particular type of shading to windows (e.g. overhands, awnings and shaded setbacks). However, while a secure water supply is required to water vegetation, implementation of vegetative shading and blinds is relatively simple.
Quality assurance and maintenance	Standardised quality assurance of these solutions is not applied currently, and inconsistency and lack of enforcement of building codes hinders its scalability.
Ease of use	Some of the shading solutions would not require user management. However, some require proper user management to be effective, such as closing blinds and louvres during daytime to avoid heat absorption of buildings.
Supply chain resilience	High to medium resilience to global supply chains.
Embedded GHG emissions	Low embedded GHG emissions in comparison to other cooling solutions, especially when using locally available materials.
Environmental impact at end-of-life	The environmental impact of disposing shading products is low when comparing to other cooling solutions.

Green shading.
Source: Getty Images

Outside air conditioner.
Source: Getty Images

4. DESIGN FRAMEWORK FOR SPACE COOLING: PROPOSED APPROACH

4.1 Beyond technical fixes: designing for people and planet

In sub-Saharan Africa and South Asia, the gap between the demand for space cooling and the actual provision of thermal comfort in rural areas reflects more than technological gaps. It reflects design frameworks that have historically prioritised imported standards, energy-intensive technologies, and urban middle-class markets, while neglecting the vulnerabilities and lived realities of rural populations.

What design values for space cooling can deliver climate justice, inclusion and equitable access in rural areas? Contemporary frameworks for design thinking call for an integrated approach that addresses the technological, socio-cultural, environmental, democratic and financial or economic elements of cooling. This report highlights the real and present threats from heat risks for communities living in predominantly off- or weak-grid rural areas and presents a diverse portfolio of highly applicable space cooling solutions. Furthermore, this report provides a new assessment framework to draw on when designing cooling technologies, products, solutions or interventions. These examples demonstrate that space cooling design solutions can be participatory, context-sensitive, and inclusive.

Cooling is not a universal technical challenge; it is a design practice. Designing space cooling technologies requires us to negotiate between material and technology availability, climates, cultural expectations, individual and collective behaviours, and economic constraints. Cooling is not just an enclosure that can be filled with passive or active cooling solutions. It is a space in which people's relationships to each other, to their environments, livelihoods, technologies and ideas of comfort intersect

Taking a human and planet-centred perspective to design means placing empathy and sustainability at the core of design. It means asking:

- What does heat exposure feel like in this community?
- What are its impacts, and what forms of cooling relief already exist?
- How can access to cooling be improved with minimal greenhouse gas emissions, economic burden, and waste generation?

This approach emphasises the co-creation and adaptation of solutions to specific socio-economic and ecological contexts.

4.2 Design framework for space cooling

A value-based approach to the design of space cooling means working to ensure that solutions or interventions are not simply technically feasible but that they are also socially just, environmentally friendly, democratically inclusive, and economically viable.

Together, they support design that is locally rooted, adaptive, and just.

1. **Design for socio-cultural value**
   Passive or active cooling solutions — from the design of a window to the design of a fan, evaporative cooler or air-conditioning unit — are not abstract technical options but socio-technical practices that will directly shape how people live, work, and heal. For example, a sloped roof in a humid climate not only sheds monsoon rain, but also alters how indoor air circulates; lattice windows in drylands combine shading with cultural aesthetics of privacy. Taking a value-centred approach to designing space cooling situates design in socio-cultural norms and encourages collaboration with local builders and users.

2. **Design for environmental value**
   Aligning space cooling design with environmental values, can reduce emissions, minimise e-waste, and promote regenerative materials and practices. Designing for environmental values might involve working with a diversity of traditions and practices, from the use of localised building materials traditions to new technologies adapted for off-grid use. Passive measures can often form the foundation of rural cooling frameworks — from roof treatments and insulation to shaded courtyards and ventilated double-roof systems. By embedding passive cooling measures first, long-term carbon savings can be locked in. Active systems, such as solar-powered fans or evaporative coolers, can then be added to meet specific needs, particularly in health, education, or high-heat occupational settings. Designing across this continuum requires balancing affordability, energy access, and long-term resilience.

3. **Design for inclusivity**

   The management or reduction of heat stress involves reaching a state of thermal comfort. However, comfort is not defined only by indoor air temperature but also by humidity, airflow, radiant heat, clothing, and daily work or activity rhythms. Comfort is multifaceted. For agricultural workers, shaded rest spaces during peak heat hours may matter more than air-conditioned interiors. For children in schools, improved ventilation may be crucial for concentration and to realise the potential academic benefits of educational investments from governments and families. For health facilities, reliable cooling ensures both safe medicine storage and effective patient recovery. Inclusive processes ensure that cooling design is co-created with those most exposed to heat. Training and empowering people within communities can foster agency, trust, and intergenerational justice.

   Effective passive cooling depends not only on the final outcomes, but also on the skills of masons, carpenters, contractors, and manufacturers who often work in rural and informal contexts. It also depends on financiers, civil society organisations, innovators, and government representatives who set priorities, provide resources and produce appliances and essential components. Training and capacity-building must extend across this chain: from artisans who can implement passive measures, to bankers who can enable inclusive financing through subsidies or low-interest loans.

4.3 Examples of and lessons from best-practice design

Key examples from the practices in this report demonstrate how cooling design can be participatory, context-sensitive, and inclusive:

- **Training and capacity-building**: Local masons, carpenters, fabricators, and architects should be trained to integrate passive and active cooling into rural housing, schools, and healthcare facilities. In addition, financiers and government officials must be engaged to create inclusive loan and subsidy schemes. This expands the circle of design actors and aligns technical knowledge with lived needs, greening jobs and upskilling stakeholders with the skills and capacities to build and deliver resilient and socially just climate adaptation solutions.

- **Climate-responsive design choices**: Building orientation, roof form, and fenestration design should be adapted to climate realities — for example, sloped roofs in humid regions to shed rainfall and increase ventilation, or lattice windows in hot-dry zones to filter light and airflow.

- **Cultural and social adaptivity**: Projects should consider cultural context where design echoes traditional home layouts, marrying cultural continuity with materials and techniques that improve thermal comfort and energy efficiency.

- **Inclusive and universal design**: Barrier-free features can ensure that elders, people with disabilities, and other vulnerable groups could access and benefit from cooler, more comfortable spaces.

- **Demonstration projects**: Pilot projects including the ones included in this report: climate-adaptive labour rooms co-designed with health workers in Meghalaya; home-based workspaces for women entrepreneurs upgraded with passive cooling in Ahmedabad; and the redesign and refurbishment of schools for migrant children to improve student focus and wellbeing. These visible, lived examples helped build trust and encourage uptake.

- **Financial and social value**: By showing how passive design lowers long-term costs (energy bills, health expenses, productivity loss), projects reframe cooling as not only a technical intervention but also a livelihood and justice issue.

4.4 Barriers and challenges to adoption

Despite the existence of promising solutions, valued-oriented approaches to the design of space cooling remain nascent. Several systemic barriers were highlighted across this report:

- **Awareness gaps**. Many policymakers, practitioners, and end-users lack knowledge of how basic design choices affect thermal comfort. Misinformation often drives households to prioritise low-cost but thermally inadequate or low-quality, inefficient options.
- **Institutional limits**. Building codes are difficult to enforce or translate into small-plot and informal settings, while policies for green or climate-smart buildings are often perceived as elitist.
- **Financial exclusion**. High upfront costs for passive measures remain prohibitive without accessible financing. In rural contexts, inclusive financial instruments are scarce, and the importance of cooling is rarely understood by local banks or credit providers.
- **Erosion of localised practices**. Traditional cooling strategies such as thatched roofs or courtyards have been displaced by cheap, standardised construction methods, undermining local thermal resilience.
- **Lack of demonstration projects**. Without visible, accessible examples of cooler homes, schools, or healthcare facilities, trust in passive or integrated solutions remains limited.

4.5 Towards design justice in space cooling

The evidence suggests that designing for thermal comfort in rural sub-Saharan Africa and South Asia is not only a matter of better technologies, but of prioritising design for adaptation and climate justice. Human and planet-centred approaches remind us that design must start with people, their bodies, and their environments. Designing for heat resilience means designing not only cooler buildings, but also cooler futures: futures in which comfort, dignity, and survival are accessible to all.

By combining these perspectives, design frameworks can move beyond universal checklists and towards adaptive, situated, and just practices. These should include:

- Cooling solutions that respect local traditions, behaviours and practices while introducing new materials, techniques and technologies;
- Focusing on solutions to real-life problems and priorities faced by communities living in these settings;
- Financial mechanisms that expand access equitably rather than deepen exclusion;
- And infrastructures that enhance resilience to heat without imposing extractive or environmentally harmful models.


Under deck insulation.
Source: Getty Images

5. CONCLUSION

Space cooling is a critical adaptation need for rural communities living in off- or weak-grid areas, particularly for most vulnerable groups who face compounded challenges due to limited access to electricity, low levels of income, and inadequate infrastructure. This report mapped the most promising solutions to address these needs. While these solutions show strong potential, most are not yet widely used in sub-Saharan Africa and South Asia.

Scaling access to space cooling is constrained by awareness gaps, institutional limitations, and financial and technical barriers. Addressing these constraints is complex. Many solutions are most effective when implemented together; for example, combining a cool roof and adequate fenestration with an off-grid fan for periods when passive measures alone cannot ensure thermal comfort. Moreover, addressing this challenge goes beyond technical fixes, thermal comfort is deeply connected to how people interact with their environments and livelihoods.

Innovative approaches, such as the value-based framework proposed in this report, which prioritises socio-cultural relevance, environmental sustainability, inclusivity, and economic viability, are essential. Creating an enabling environment will require further research to assess cost-effectiveness and context-specific applicability, as well as additional R&D to advance technology readiness and commercial adaptation of traditional techniques. Finally, pilot projects are needed to demonstrate impact, understand users' needs and involve their views in design.

Access to adequate space cooling and thermal comfort can be lifesaving and it enables healthy and productive environments which ensure wellbeing. It is crucial that space cooling for most vulnerable communities advances as a priority for policymakers, development actors and donors.


Man working on a roof, India.
Source: Getty Images

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Man sitting in front of his energy efficient fan at home, Bangladesh.
Source: Efficiency for Access

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