



Thermal Management of Photovoltaic Inverters: A Critical Review of Cooling Architectures, Climate Suitability, Reliability, And Field Deployment

Ahmed Arafat Khazaal Alkhalil

Energy Technologies, Istanbul Aydın University, Istanbul, Türkiye

ABSTRACT: Photovoltaic (PV) inverters are subject to a coupled thermal problem with losses of semiconductors as a part of the problem, but also the variability of the solar resources, ambient temperature, installation geometry, dust, humidity, and enclosure thermal inertia. Thermomechanical fatigue in power modules and degradation of capacitors, solder layers, bond wires, interfaces and auxiliary components are accelerated by elevated junction and heat-sink temperatures. Thermal management of power electronics has been extensively discussed, but the evidence is scattered if the design goal is a field-deployed PV inverter, running under a field climate and mission profile. This critical review, therefore, compiles and summarizes the literature in the inverter-specific and transferable power-electronics domain of natural and forced-air cooling, advanced finned heat sinks, liquid cold plate and microchannels, heat pipes and vapor chambers, two-phase and immersion methods, evaporative cooling, multi-mode thermal systems, and active thermal control. Special emphasis is placed on the boundary conditions of practical importance not usually covered in laboratory studies: cooling parasitic power, water usage, psychrometric limits, condensation, leakage, corrosion, fouling, maintainability, measurement uncertainty, and the variations in the sun that occur from day to day. A framework for selecting cooling technologies based on climate requirements is proposed for matching cooling technologies with hot-dry, hot-humid, temperate, dusty, water-stressed, and high-power-density operating environments. Based on the review it can be seen that there is no one best architecture. Simple forced air, high heat-flux liquid cooling (with risk of leakage and the need for pumping), vapor chambers (which offer high spreading rates without being the answer to the last heat-rejection barrier), and evaporative approaches can be very interesting in hot-dry climates if water use, psychrometric limits, and condensation are managed. Multi-mode systems might provide greater operating flexibility, but this flexibility must be offset by auxiliary-resource and maintenance penalties. The future research needs include standardization of the thermal metrics for inverters, comparative experiments under the same condition, direct flow and psychrometric measurements, long-term field tests, thermal-aware control, and co-optimization of reliability, cooling energy, water use, cost, and maintainability.

KEYWORDS: Photovoltaic inverter; thermal management; power electronics; heat sink; liquid cooling; evaporative cooling; hybrid cooling; thermal reliability; junction temperature; hot climate

Highlights

- PV-inverter cooling is considered as a problem dependent on climate and missions, and not as a typical electronic cooling problem.
- The following air, liquid, vapor-chamber, two-phase, evaporative, hybrid and active-thermal-control methods are compared on a common deployment-oriented basis.
- For hot-dry, hot-humid, temperate, dusty and water-stressed installations, a climate-cooling decision matrix is proposed.
- Key evidence gaps identified include: field validation, auxiliary cooling energy, water use, condensation, corrosion, and long-term reliability.

PV-inverter thermal management in the future should consider co-optimizing temperature, lifetime, efficiency, water, cost and maintainability.

1. INTRODUCTION

PV Inverters are the electrical conversion and grid-interfacing devices to integrate a variable solar energy source into an AC network. Their thermal environment is really quite complex: The input power changes in response to the irradiance; semiconductor losses vary with load and switching conditions; and the same weather that increases PV output also increases ambient and enclosure temperatures. Field measurements have demonstrated that ambient temperature, electrical loading, airflow and installation geometry all influence the temperature of the inverter, and reliability studies have consistently identified thermal stress

as a key factor in component degradation (Sorensen et al., 2013; Zhang et al., 2016; Hacke et al., 2018). Removing a fixed heat load is the problem, but controlling peak temperature and temperature cycling under a mission profile that varies from seconds to seasons is.

Thermal path from a semiconductor junction to the environment traverses different interfaces – die attach, substrate, baseplate or package, thermal interface material, heat spreader, heat sink or coolant, and finally air or coolant. The layers can each be a choke point. The thermo-mechanical stress caused by high junction temperature, repeated junction-temperature swings result in fatigue, and high enclosure temperature impacts DC-link capacitors, magnetic components, gate-driver electronics, connectors and fans. Therefore, inverter thermal management needs to be considered as a whole system reliability issue rather than a heat-sink issue only (Baker et al., 2014; Li et al., 2021; Ryu et al., 2022).

In the past, the amount of literature that has been created has grown quickly in the field of advanced cooling. In the case of broad power-electronics reviews, the air and liquid channels, phase change materials, immersion cooling, jet impingement, spray cooling, two-phase systems, and active thermal control are included in the list (Rahman et al., 2024; Rehman and Park, 2025). Research into automotive inverters has also contributed to advancements in SiC power modules, double-sided cooling, microchannels, vapor chambers, and highly-integrated cold plates (Abramushkina et al., 2024; Paul et al., 2024; Mu et al., 2025). These studies are very relevant for PV inverters, but they are different in duty cycles and constraints applied to the inverter as used in the automotive sector. In contrast, till date, the vast amount of PV cooling literature is focused on PV-module thermal management and not inverter thermal management (Dwivedi et al., 2020; Hamzat et al., 2021).

This provides a helpful but not fully developed middle ground. The principles of thermal performance discussed in general power electronics are applicable to PV inverters as well, but the selection of the technology must take into consideration the specific field requirements of solar applications: diurnal loading, hot equipment rooms, rooftop or outdoor environment, dust, humidity, intermittent ventilation, water shortage, and extended service intervals. A good solution for a laboratory heater at a given heat flux can be undesirable in a PV plant if it consumes a lot of pumping power, necessitates frequent water treatment, is difficult to maintain, or requires a sealed structure that would not fit into current commercial enclosures.

The second reason why I think there should be an inverter-specific review is because the field is evolving. Akgül (2025) directly investigated PV-inverter cooling by adding skived-fin heat sink with embedded vapor chamber under multi-heat-source conditions, and found that the maximum temperature and thermal resistance decreased with the use of skived-fin

heat sink with embedded vapor chamber. Concurrently, evaporative cooling of SiC MOSFETs has demonstrated that significant heat can be extracted from the device by evaporating water, using very little auxiliary power (Hong et al., 2025). Furthermore, machine-learning and data-driven reliability studies are shifting towards real-time temperature estimation along with reliability-aware operation (Mabutyana-Rabaza et al., 2026; Fan et al., 2026). The developments indicate that hardware, sensing, climate information and control will be more and more integrated in the future inverter cooling.

The aim of this review is thus to critically structure the existing evidence in relation to four questions: (i) which cooling mechanisms are technically feasible for PV inverters; (ii) what are the metrics to be used for comparing the different cooling mechanisms other than peak temperature; (iii) how do climate and site conditions influence the applicability of these technologies; (iv) what evidence is still missing for a proper use of these technologies on the field? The contribution is an approach to taxonomy and selection framework that relate to deployment rather than to individual devices or generic power electronics, and that complement the existing approach to individual device and generic power-electronics reviews..

2. REVIEW SCOPE AND SYNTHESIS APPROACH

This article will be a structured critical review instead of a formal PRISMA systematic review. The synthesis focuses on peer reviewed work related to PV-inverter thermal behaviour, reliability and mission profile applicable to PV-inverter systems, and applicable transferable investigations of power semiconductor & inverter cooling. Work from 2018 to September 2026 have been given priority, with some of the earlier foundational studies kept for establishing the behavior of field temperatures, the reliability of PV-inverters, evaporative PV cooling, and/or concepts for thermal management used broadly in the PV field. Any results that are published or otherwise publicly cited are synthesized; results from experimental data that have not been published, or dimensions of equipment, are intentionally omitted.

The combinations of keywords were chosen as the principal themes for the search combinations, and included the terms photovoltaic inverter, PV inverter, thermal management, junction temperature, reliability, heat sink, forced air, liquid cooling, cold plate, microchannel, vapor chamber, heat pipe, two-phase cooling, evaporative cooling, hybrid cooling, active thermal control, SiC MOSFET, IGBT, mission profile, and hot climate. The studies were categorized into five groups: (1) PV-inverter field/reliability evidence, (2) cooling hardware, (3) semiconductor packaging and heat spreading, (4) cooling that is climate sensitive, and (5) thermal-aware control and prediction.

The review intentionally does not address PV-Module cooling as a cooling for the inverter. PV-module studies are

only used if they yield transferable data or knowledge about evaporative process, water use or operation in hot climate. Similarly, automotive-inverter studies are incorporated when they explain the cooling for the high-heat-flux problems, small size and/or packaging considerations, or new thermal-

management techniques with regard to SiC. The separation is necessary because temperature reduction percentages can't directly be compared from device to device, if they have varying heat fluxes, thermal masses, sensor locations and boundary conditions.

Table 1. Position of the present review relative to selected prior reviews.

Reference	Primary scope	PV inverter focus	Climate / field focus	Gap left for this review
Khattak and Ali (2019)	Forced-air heat-sink geometries	No	Limited	Does not address inverter mission profiles or climate selection
Dwivedi et al. (2020)	PV-module cooling technologies	No (module focus)	Some	Thermal boundary is the PV module, not inverter power electronics
Hamzat et al. (2021)	PV/PVT cooling	No (module/PVT)	Some	Does not synthesize inverter packaging, reliability and cooling
Rahman et al. (2024)	Power-electronic converter thermal management	Broad converter focus	Limited	Strong technology breadth but not PV-specific climate deployment
Ibrahim et al. (2024)	Active thermal control	Converter/control focus	Limited	No physical cooling-selection framework
Rehman and Park (2025)	IGBT thermal management	Device/module focus	Limited	Not centered on PV-inverter field installation
Mabutyana-Rabaza et al. (2026)	ML for PV-inverter reliability	Yes	Partly	Data-centric; physical cooling architectures are outside its main scope

3. THERMAL STRESS IN PHOTOVOLTAIC INVERTERS

3.1 Heat generation and the thermal path

The losses in semiconductors are primarily conduction and switching losses. The relative contribution varies depending on current, switching frequency, gate drive, modulation, temperature and device technology for an IGBT or MOSFET. This heat is very concentrated at the semiconductor junction and must be conducted through the package to the ultimate heat-rejection surface. This path is of transient nature and not purely steady state so that the thermal capacitance and the time constants of the individual layers reflect the speed of the junction response to power cycling. Reduced order thermal models have been developed specifically for PV inverters, to capture this dynamic behavior and allow long mission-profile simulation (Sangwongwanich et al., 2020).

Thermal resistance $R_{th} = (T_{hot} - T_{cold})/Q$ is useful as a steady-state indicator and PV operation is often interpreted in this context. A steady-state heat-sink temperature reduction cooling technology can have significant swings in junction temperature during cloud transients or fast power ramps. On the other hand, thermal mass can mitigate short-term fluctuations even if long-term mean temperatures are moderately altered. Therefore, peak junction temperature, mean temperature, temperature swing, spatial non-uniformity and transient recovery should be taken into consideration.

3.2 Temperature cycling, failure mechanisms and lifetime

Thermal cycling causes multiple expansions and contractions to occur between materials with different CTE. In power modules it can lead to solder fatigue, bond-wire lift-off, interconnect degradation, substrate stress, and delamination of interfaces. Thus, online junction-temperature measurement and estimation methods are at the core of reliability assessment (Baker et al., 2014). For compact SiC devices, a smaller die size allows for high power density, but also a decrease in thermal inertia and an increase in the local heat flux, which requires increased demands of packaging and heat spreading (Mu et al., 2025; Abbaszada et al., 2025). PV mission-profile studies show that the representation of irradiance and temperature histories are important when making reliability predictions. Sangwongwanich et al. (2018) demonstrated that the mission-profile time resolution can have a significant impact on the estimated thermal damage, and Fogsgaard et al. (2022) presented a method for mission-profile simplification for PV-converter reliability analysis. Wang et al. (2020) correlated real-field mission profiles and PV-array configuration to inverter lifetime and cost-effectiveness, while Zhang et al. (2022) demonstrated the impact of the junction-temperature components on the different timescales on the lifetime evaluation. Ryu et al. (2022) also demonstrated that lifetime estimates vary with the definition of thermal loading. The location is also important:

research in different climatic zones and PV degradation conditions has shown that inverter reliability can significantly depend on environmental conditions (Gatla et al., 2022; Alavi et al., 2024; Anusuya and Vijayakumar, 2024). Thermal management thus alters the temperature at the moment and the distribution of thermal cycles over years.

Accelerated testing, complementary evidence. Afridi et al. (2023) performed long duration high temperature fixed and cyclic power stress tests on microinverters, demonstrating the utility of such tests with long durations and realistic loading conditions. This type of work is important because short cooling experiments can provide evidence of thermal capability but not alone can prove lifetime extension. A defensible reliability statement needs to be backed up with either long term field evidence or a validation of a mapping from measured temperature history to damage models.

3.3 Installation environment and climate

The thermal behavior of PV-inverter is very dependent on the installation conditions. Based on experimental data, Zhang et al. (2016) developed a model of heat-sink temperature as a

function of ambient temperature, power level, and wind speed, which illustrates the importance of considering heat rejection with respect to the local environment. The high inlet air temperature and recirculation of air may be experienced by indoor inverters installed in unconditioned rooms, while outdoor inverters may be affected by solar heating, dust, wind blown contaminants, and the large day-to-night swings. In the hot climate, there is high ambient temperature and the presence of the sun which means high electrical load with low temperature differences for air cooling.

If the weather's humid, the technology ranking changes. When relative humidity is high, the depression between the dry bulb and the wet bulb is small and the direct evaporative cooling is less; hot-dry climates supply a large wet-bulb depression and thus have a greater evaporative potential. However, water supply may be most limited in the very same dry areas. Dust causes an additional penalty through fouling of fins, filters, wet media and heat exchangers. Therefore, the suitability for a climate should not be based only on temperature, however, but on temperature, humidity, dust, water stress and maintenance capability.

4. COOLING ARCHITECTURES FOR PHOTOVOLTAIC INVERTERS

Table 2. Deployment-oriented taxonomy of inverter cooling approaches.

Approach	Dominant mechanism	Auxiliary demand	Key strengths	Main limitations	PV-inverter suitability
Natural air / passive fins	Natural convection + radiation	None	Simple, low maintenance	Low heat-flux capability; strong ambient dependence	Low/medium power, cool or ventilated sites
Forced air	Forced convection	Fan power	Low cost, mature, retrofit-friendly	Fan reliability, dust, noise, hot-inlet limitation	Broad use where inlet air is sufficiently cool
Advanced heat sink / vapor chamber	Conduction spreading + air rejection	Usually fan power only	Reduces hot spots and spreading resistance	Final heat rejection still air-limited	Compact inverters, multi-chip layouts
Liquid cold plate / microchannels	Forced liquid convection	Pump power	High heat capacity and heat-flux capability	Leakage, pump, pressure drop, service complexity	High power density, controlled installations
Two-phase / thermosyphon	Phase-change heat transport	Low to moderate	High heat-transfer coefficient; can reduce pumping	Working-fluid, sealing, orientation and integration limits	Emerging high-performance applications
Immersion spray / jet	Direct high-intensity heat transfer	Pump/compressor varies	Very high local heat removal	Complex enclosure, fluid compatibility, maintenance	Specialized high-heat-flux systems
Evaporative air cooling	Water evaporation cools inlet air	Fan/water circulation small	High value in hot-dry climates	Humidity dependence, water use, scaling	Hot-dry sites, especially retrofit pre-cooling

Approach	Dominant mechanism	Auxiliary demand	Key strengths	Main limitations	PV-inverter suitability
Hybrid / multi-mode cooling	Two or more complementary heat-removal paths	Depends on selected modes	Flexible, strong peak-temperature control	More components and controls	Sites where added complexity is justified by peak thermal stress
Active thermal control	Loss/operation manipulation	Control overhead	Reduces thermal cycling without hardware redesign	May increase losses or affect power quality	Complementary layer for any hardware cooling system

4.1 Natural convection and conventional forced-air cooling

Natural convection is mechanically attractive since it avoids the need for fans or pumps, but the convective heat-transfer coefficient, which is typically available in air, restricts the use of natural convection usually. It has a reduced performance in warm environment and if installation geometry doesn't allow buoyancy driven flow. It's generally still useful for low to moderate power density, especially for sites where maintenance access is not possible, but it does need more heat-sink area and thermal headroom.

Many commercial PV inverters still use the forced air-cooled design. The design variables (governing parameters) are fin spacing, fin height, base spreading resistance, pressure drop, fan curve, bypass leakage, recirculation and inlet temperature. Forced-flow heat sink reviews indicate that forced-flow heat sinks can be significantly altered in their thermal resistance with some modest geometric changes (Khattak and Ali, 2019). The most significant practical constraint, however, may be the inlet-air temperature in PV applications. A fan will not produce a high temperature driving force if the room or outside air temperature is high, but it will do so if the inlet temperature is low.

In addition, there are reliability interactions present in forced air. Fans have moving parts, filters become dirty, dust collects between fins and the flow field configuration changes as obstructions form. Therefore, it is not unlikely if the design that is optimized in the clean laboratory bench can be degraded quite a lot when it is already in service. It is, therefore, recommended that for field studies, pressure drop, fan operating point, filter condition and maintenance interval, as well as temperature reduction, be reported.

4.2 Advanced finned heat sinks, heat pipes, and vapor chambers

Advanced heat spreaders attack another portion of the thermal chain. Vapor chambers and heat pipes take advantage of an internal phase change to carry heat away from the localized heat source and can help to create increased temperature uniformity over the heat-sink base. Power-electronic integration with vapor-chamber cooling was analyzed by Chen et al. (2020) and more recent studies of SiC

have placed the vapor chamber nearer to the junction. The benefits of reducing short-time-constant thermal resistance through the near-junction vapour-chamber integration were demonstrated, showing significant decrease in the maximum junction temperature and the fluctuation of junction temperature as reported by Mu et al. (2025).

Akgül (2025) is particularly relevant to PV inverters since the cooled object was an inverter IGBT array. To evaluate the skived-fin heat sink with embedded vapor chambers under multi-heat-source conditions, a performance analysis of the proposed design was conducted and the results indicated that the maximum temperature was reduced by approximately 6.63 °C and the thermal resistance was reduced by approximately 16.64% under low fan power. The study reveals that the thermal hardware for PV is now starting to transition from the traditional extruded fin designs to an integrated spreading and convection design.

The key warning is that a vapor chamber will move heat around, but will not remove it from the system. The airside thermal resistance could still be the dominant factor if the final sink is air-cooled in a hot room. Vapor chambers are thus most useful when the source spreading is the limiting factor, when there is sufficient non-uniformity caused by multiple chips, or when footprint limits are a constraint and the base area cannot be simply increased.

4.3 Liquid cooling, cold plates, and microchannels

The volumetric heat capacity of liquid cooling is greater and generally has greater heat-transfer coefficients than those of air. This renders it appealing for high power density devices, and also for installations where there is already a coolant loop. Integrated liquid heat sinks for high power IGBTs were proven to be effective in reducing temperature (Pan et al., 2021), and optimized inverter cold plates could provide a compromise between temperature reduction, pressure drop, temperature uniformity, and manufacturability (Aviles et al., 2023). The ratio between the heat transfer and pumping cost (Kwon et al., 2024; Mazaheri and Mwesigye, 2025) is also continuously improved with more recent pin-fin and topology-optimized liquid heat sinks.

With PV inverters, the engineering issue is not if liquid cooling can remove heat, it can, rather it is "is the liquid

cooling's system penalty worth it?". Cost and failure modes include a pump, a reservoir or a heat exchanger, hoses and fittings, coolant management, leak containment and controls. Also, the parasitic power of the pump decreases "Net System Benefit". So liquid systems are most interesting when air cooling would use too much fan power or too large a heat-sink, when the enclosure temperature is very high, or when the thermal density is very high and the reliability margins cannot be achieved with air cooling.

Microchannels take this concept one step further by bringing a large wetted area near the heat source. They can offer outstanding heat transfer performance, but come with water quality, manufacturing, clogging and pressure-drop issues. If the solar installation is unattended, maintainability and fouling tolerance can be more critical than best case thermal resistance. Therefore, channel geometry should be optimized to minimize pumping energy during the life cycle and/or maximize serviceability, as well as minimum junction temperature.

4.4 Double-sided, direct, immersion, spray, and two-phase cooling

Packaging architectures which remove heat from both sides of the die are emerging to make the transition from Si IGBTs to SiC MOSFETs possible. Double-sided cooling can help reduce the thermal path length and the temperature non-uniformity, and low-inductance packaging can be achieved. There are recent SiC modules that have shown low thermal resistance and better distribution of temperature, but the fabrication and mechanical interface are more complicated than traditional single-sided modules (Abramushkina et al., 2024; Paul et al., 2024; Tan et al., 2024). As wide bandgap devices become more prevalent these concepts will likely move into the future high power PV inverters.

Two-phase systems involve not only sensible but also latent heat. In 2024, Lima Baschera et al. conducted an experimental performance assessment of a complete integrated two-phase cooling system for a 1200V, 100A IGBT inverter module and demonstrated its ability to provide good cooling performance at low coolant flow rates. Two-phase approaches thus lead to reduction in pumping requirements but introduce problems of choice of fluids, sealing, condenser design, control and long-term stability.

For extreme heat flux, very high local heat-transfer coefficients can be obtained with jet impingement, spray cooling and immersion. However, at present, the use of these devices in conventional PV inverters is restricted due to the complexity of the enclosure, compatibility of the dielectric fluid, aging of the fluid, contamination, and field maintenance. They can be considered advanced solutions for future compact or centralized converters, but not for short-term drop-in replacement of the conventional commercial string inverters.

4.5 Evaporative cooling

Evaporative cooling is the process of lowering air temperature or directly removing heat by the evaporation of water. The lower limit in the case of direct evaporative air cooling is related to the wet-bulb temperature at the air inlet and is hence greatly dependent on the climate. In all the literature reviewed on evaporative systems, the systems are found to be very suitable in hot-dry conditions and less suitable as the relative humidity increases (Haile et al., 2024; Ishugah et al., 2024). This psychrometric dependence is a characteristic feature that distinguishes it from ordinary forced air, and it is important to be included explicitly in the inverter studies.

PV-module literature has set the ground for the general feasibility of water-assisted cooling and evaporative cooling in hot climate (Alami, 2014; Bahaidarah et al., 2013; Moharram et al., 2013 and Nižetić et al., 2016). Although the heat source and geometry are different, these studies do not directly quantify inverter cooling, but show that the evaporation and water circulation is a good solar-site thermal resource. More directly, Hong et al. (2025) showed that SiC MOSFETs could be cooled by evaporative cooling by capillary water transport to a conventional aluminum heat sink. From their experiments they found that 42% of the total heat was removed by evaporation alone, and 89% was removed when a fan was used, giving them good evidence that evaporative heat removal could be important for power semiconductors.

The wet bulb depression potential is greatest in hot-dry areas at the time when conventional air cooling is most limited in its capability due to high dry-bulb temperatures, which is why PV inverters are so attractive in these areas. However there are also some disadvantages. Some issues that are introduced into the lifecycle include water use, scaling, biological growth, wet-media degradation, corrosion, carryover droplets, condensation risk, and water treatment. Thus, evaporative cooling should be assessed both thermally using the thermal effectiveness metric, $\epsilon_{\text{evap}} = (T_{\text{db,in}} - T_{\text{db,out}}) / (T_{\text{db,in}} - T_{\text{wb,in}})$, and in terms of the amount of water required per kWh of inverter energy processed or per kWh of cooling provided.

4.6 Multi-mode and hybrid cooling systems

Multi-mode cooling is appealing due to the varying dominant thermal bottleneck over varying loads, packaging, and climate. A low energy mechanism can account for the majority of the operating hours, with a second well-defined mechanism being triggered under increased thermal stress. Some of these examples mentioned in the literature elsewhere in the thermal-management field are: air plus liquid cold plates, heat pipes with forced convection, phase-change storage with convection, and staged passive-active operation. In their study, Coşkun and Çetkin (2023) demonstrated that

air and liquid modes can be used separately or together in a common cold-plate architecture, resulting in enhanced thermal performance and temperature uniformity. With PV Inverters, the design issue is not a specific combination of hardware but the question if additional modes can lower the thermal stress during the life cycle sufficiently to justify additional hardware and controls.

A multi-mode architecture is also an opportunity for reliability-aware control. Control logic may be used to switch all cooling hardware off when the heat-sink temperature, estimate of junction temperature, ambient conditions, predicted irradiance, fan or pump efficiency or remaining-useful-life indicators are suitable. The main issue is that it must be demonstrated that the extra hardware complexity results in a net lifecycle benefit. This includes auxiliary electricity, consumable resources (if applicable), maintenance burden and temperature reduction.

4.7 Active thermal control as a complementary layer

There are ways to relieve thermal stress without any physical cooling. Active thermal control varies converter parameters (such as switching frequency, modulation, power routing, gate control, etc.) to minimize peak temperatures or minimize temperature swings. A variety of device-, converter- and system-level techniques are summarized in recent reviews (Ibrahim et al., 2024). For instance, a gate-voltage based approach has shown the capability of semiconductor manipulation and lifetime improvement estimation under a typical profile (Chanekar et al., 2023).

Active thermal control is especially attractive in grid connected PV Inverters, as it can be added to existing heat rejection components. But it is not a cost-free process: lower switching frequency can impact on harmonic performance,

power redistribution can alter efficiency and intentional loss shaping can result in increased energy dissipation. Co-optimization, in other words, is therefore the most promising direction, as opposed to just thermal control, with reduced lifetime damage subject to grid-code, efficiency, acoustic, fan/pump, and power-quality constraints.

5. COMPARATIVE ASSESSMENT OF COOLING TECHNOLOGIES

5.1 Why temperature reduction alone is insufficient

One of the key issues in the literature is that different performance indicators are used that are not comparable. Some studies reference a maximum junction temperature, some a heat-sink temperature, some a case temperature, some a cold-plate temperature, and some a local thermocouple attached to a fin. Ambient, inlet air, coolant temperature or control day reference may be used. As a result, reported percentage reductions may not be accurate if the denominator and sensor location are not the same.

PV-inverter cooling studies should report at least the following: ambient dry-bulb temperature, relative humidity and wet-bulb temperature (where evaporation is involved), inlet-air or coolant temperature, inverter AC/DC loading, heat-sink or case temperature, junction temperature or a validated junction temperature estimator (where possible), airflow (and/or coolant flow), fan and pump power and the actual start/stop times. Irradiance and power should be time matched for field comparisons among days. If these variables are not present, a drop in temperature may be falsely interpreted as a cooling effect, when it is in reality due to decreased electrical loading or resultant of changing weather conditions.

Table 3. Recommended performance metrics for PV-inverter thermal-management studies.

Metric	Expression / unit	Why it matters	Minimum reporting requirement
Absolute temperature reduction	$\Delta T = T_{ref} - T_{cooled}$ (°C)	Direct thermal effect	Define same sensor location and matched reference
Thermal resistance	$R_{th} = (T_{hot} - T_{cold})/Q$ (K/W)	Normalizes heat load	State heat rate and hot/cold locations
Junction temperature swing	ΔT_j (°C)	Key fatigue driver	Use measured or validated estimator
Temperature uniformity	$T_{max} - T_{min}$ (°C)	Hot-spot and current-sharing risk	Report sensor/mesh positions
Cooling parasitic power	P_{aux} (W)	Net-energy penalty	Fan + pump + controls
Specific cooling energy	E_{aux} / E_{AC} (%)	Lifecycle efficiency	Integrate over test window
Water intensity	L/kWh or kg/h	Critical in dry climates	Measure make-up water and purge
Evaporative effectiveness	ε_{evap} (–)	Separates climate potential from hardware quality	Report dry-bulb, wet-bulb and RH

Metric	Expression / unit	Why it matters	Minimum reporting requirement
Transient time constant	min or s	Response to cloud/load changes	Record activation and recovery
Reliability proxy	damage index / lifetime model	Connects temperature to service value	State model and assumptions

5.2 Representative quantitative evidence

The quantitative literature has validated that various architectures address different thermal hot spots. Akgül (2025) enhanced the heat spreading and forced air performance in a PV inverter with vapor chambers. Pan et al. (2021) and Aviles et al. (2023) show the much higher heat-removal capability available with liquid cooling. The dual-medium operation is a flexible one as shown by

Coşkun and Çetkin (2023). Mu et al. (2025) has demonstrated the benefits of locational proximity of a phase-change spreading to a SiC junction, and Hong et al. (2025) has shown that a significant portion of semiconductor heat can be directly removed by evaporation. These results are not necessarily ordered by the amount of temperature reduction, as there are variations in heat flux, source geometry, coolant boundary, and sensor locations.

Table 4. Selected studies illustrating recent thermal-management directions relevant to PV inverters.

Study	Cooled object	Approach	Reported outcome	Strength	Transfer limitation
Zhang et al. (2016)	PV inverter	Field thermal modelling	Heat-sink temperature linked to ambient/load/wind	Real field data	Not a cooling intervention
Pan et al. (2021)	High-power IGBT	Integrated liquid heat sink	Strong liquid-cooling performance	Direct power-electronics relevance	Not PV field installation
Aviles et al. (2023)	Multilevel inverter switch	Optimized liquid heat sink	Thermal/pressure/cost trade-off	Manufacturability included	Laboratory/design study
Coşkun & Çetkin (2023)	Battery/electronic heater	Air + liquid hybrid cold plate	Hybrid improves temperature control/uniformity	Dual-mode architecture	Different source geometry
Lima Baschera et al. (2024)	1200-V IGBT inverter module	Two-phase cooling	Effective cooling at low flow	Real inverter module	Specialized loop
Akgül (2025)	PV-inverter IGBT array	Vapor chamber + skived fins	~6.63 °C lower max T _j ; ~16.64% lower R _{th}	PV-specific	Bench/multi-source boundary
Mu et al. (2025)	SiC power module	Near-junction vapor chamber	>33% lower max T _j ; 44% lower T _j fluctuation	Targets junction swing	Advanced packaging
Hong et al. (2025)	Discrete SiC MOSFET	Capillary evaporative cooling	42% heat removed without fan; 89% with fan	Very low auxiliary energy	Discrete device, controlled setup
Mazaheri & Mwesigye (2025)	Drive inverter IGBT	Topology-optimized liquid pin fins	Up to 8.1 °C max-temperature reduction in studied design	Energy-aware optimization	Automotive duty
Afridi et al. (2023)	PV microinverters	Accelerated thermal stress	15,000 h high-temperature test campaign	Long-duration reliability evidence	Not a cooling comparison

6. CLIMATE-ORIENTED COOLING-SELECTION FRAMEWORK

PV inverters are being installed all over the world, and cooling selection is often mentioned as if the boundary

conditions were the same everywhere. The maximum dry-bulb temperature, the typical relative humidity and wet-bulb depression at high PV output, the severity of dust/fouling and water availability should be the starting point of a practical

selection framework. It should then include inverter power density, enclosure/IP requirements, maintenance options available and value of downtime.

In hot-dry climates, a significant reduction may be obtained in the inlet temperature due to the effect of direct evaporative pre-cooling because the wet-bulb depression is high. However, water scarcity, mineral content, media maintenance and water-treatment requirements dominate its lifecycle feasibility. In hot humid climates evaporative potential is low, sealed liquid loops, large air-side heat exchanger, heat spreading, refrigerant/two-phase are more appealing. In dust-laden deserts, open airflow and wet media must be filtered and the dust must be cleaned from surfaces,

and sealed liquid systems can minimize dust entry at the expense of more hardware.

Simplicity is sometimes the better choice for temperate sites. A well-designed forced air system with an efficient heat sink can offer sufficient thermal margin for most of the year and active thermal control can help to decrease peak cycling without involving water or coolant. With decreasing air density, the heat transfer through the air is less effective, and the optimum design is for a larger fan or larger fins or liquid cooling at high altitudes. This means that 'best cooling technology' is a site-specific issue and not a universal ranking.

Table 5. Qualitative climate-cooling decision matrix for PV inverters (5 = highly suitable; 1 = generally weak fit).

Climate site /	Forced air	Vapor chamber + air	Liquid loop	Two-phase	Evaporative air	Hybrid multi-mode	Active thermal control
Hot-dry, water available	3	4	4	4	5	5	4
Hot-dry, water-stressed	3	4	4	4	2	2	5
Hot-humid	2	3	5	4	1	2	4
Temperate	5	4	3	3	2	2	4
Dusty desert	2	3	4	4	3	3	4
High power density	2	4	5	5	3	5	4
Remote / low maintenance	4	4	2	3	2	2	4

The matrix is intentionally qualitative. A real design should convert it into a multi-criteria decision process using site weather files, mission profiles, inverter loss models, cooling curves, water cost, auxiliary electricity price, and reliability value. The important point is methodological: cooling selection should be optimized against the local mission profile rather than a single rated operating point.

7. FIELD DEPLOYMENT, SAFETY, AND MAINTAINABILITY

7.1 Auxiliary energy and net benefit

Cooling consumes resources. Fan power increases with increase in pressure drop and flow rate; pumping power increases with flow rate and hydraulic resistance; water production or treatment may have an energy cost; and active thermal control can affect converter losses. A thermal design which would lower the junction temperature but require large auxiliary energy consumption may have little net energy benefit. It is therefore important to report in future studies the

gross thermal improvement as well as the net electrical effect, covering the same operating window.

It's the same with oversizing. A larger heat sink can mitigate fan power consumption, although it will increase the amount of materials and volume of the enclosure. Using a microchannel can reduce the junction temperature but can increase pump power. The use of hybrid operation with intensive mode near thermal limits can help to reduce the average value of auxiliary energy. This is not a single objective temperature minimisation problem, but rather a natural optimization problem.

7.2 Water, condensation, leakage, and corrosion

Explicit safety engineering is needed for water-based inverter cooling. Leaks must be routed away from energized equipment and systems should include secure fittings, strain relief, dry-run protection, water-level monitoring and leak detection. There is the risk of condensation: When a cooled surface crosses the local dew-point temperature, moisture will appear, even if the liquid circuit is absolutely dry. Dew-

point margin should therefore be included in the control logic, particularly in humid climate or for chilled water applications.

The compatibility of materials is also important. Thermal materials such as copper and aluminum are widely used; however galvanic corrosion may result if an electrolyte is present. Small channels can get plugged with mineral deposits and reservoirs and wet media can be fouled by biological growth. The key question is not whether water cooling works; it's how long it works at an affordable maintenance cost while using a real water chemistry.

7.3 Dust, fouling, and serviceability

Air-side thermal resistance is enhanced by dust which accumulates in fin passages or filters. Mineral scale can become deposited in evaporative media and small liquid channels can foul. Therefore field deployable designs should be tested following realistic fouling exposure, as well as clean. Geometry should be driven by serviceability, e.g. a slightly less compact exchanger that is easier to inspect and clean, might perform better over the life of the exchanger than a high-performing exchanger that is more difficult to service.

7.4 Instrumentation and uncertainty

The strength of thermal validation can only be as good as the measurement chain. The contact resistance and local non-uniformity may cause surface thermocouples to be biased, platform-reported temperatures may be taken from an internal sensor at a different thermal location, and electrical efficiency estimates may require calibrated and synchronized DC measurement and AC measurement. Temperature differences should not be inferred from the resolution of the instruments; in fact, when calculating differences, uncertainty should be propagated. Also time synchronization is crucial during switch experiments and matched day field comparisons.

8. RESEARCH GAPS AND FUTURE DIRECTIONS

Literature is well-developed in the area of thermal mechanisms, but remains limited in the field evidence of inverters. The most important gap is not another stand-alone demonstration of the effectiveness of a new heat sink; it is a consistent demonstration of the effectiveness of a cooling architecture on a PV inverter over a realistic mission profile with acceptable auxiliary energy, water, cost, and maintenance impacts.

Table 6. Priority research gaps for PV-inverter thermal management.

Gap	Why current evidence is insufficient	Recommended experiment / analysis	Decision value
Few same-condition comparisons	Different days/loads obscure technology effect	Baseline and selected cooling modes on synchronized repeated profiles	Separates mechanism contributions
Limited junction-temperature data	Heat-sink sensors may miss chip hot spots	Validated TSEP/observer + surface/coolant measurements	Links cooling to lifetime
Psychrometrics often omitted	Evaporative results are not transferable across climates	Measure T_db, RH, T_wb and evaporative effectiveness	Enables climate scaling
Flow rates unmeasured	Heat-transfer rate cannot be closed	Calibrated airflow and coolant-flow measurement	Supports energy balance and R_th
Auxiliary energy ignored	Net system benefit unknown	Fan/pump/control power integrated over time	Net-efficiency comparison
Water use rarely quantified	Dry-region feasibility unknown	Make-up, purge, evaporation, water quality	Water-energy trade-off
Short campaigns	Reliability/corrosion/fouling claims unsupported	Seasonal/annual field trials and accelerated contamination tests	Deployment confidence
Weak standardization	Cross-paper ranking unreliable	Common sensor locations, metrics and reporting template	Meta-analysis capability
Cooling and control studied separately	Misses adaptive operating opportunity	Joint thermal-hardware + predictive control experiments	Lower lifecycle resource use

Gap	Why current evidence is insufficient	Recommended experiment / analysis	Decision value
Economic models incomplete	Best thermal option may not be best lifecycle option	CAPEX + OPEX + water + energy + downtime + replacement	Bankable technology choice

8.1 Same-day and hardware-in-the-loop comparative testing

A good future experiment would be to repeatedly use the same inverter but change the cooling system from baseline to air-only, to liquid-only, and to hybrid, and maintain the same set of environmental conditions throughout the tests. If irradiance in the field cannot be controlled, the electrical profile can be reproduced with a hardware-in-the-loop or programmable DC-source test while a climatic chamber is used to control dry-bulb temperature and humidity. The laboratory ranking can then be confirmed by field trials. This two-stage protocol would greatly help causal attribution.

8.2 Digital twins and predictive thermal control

There is a roadmap to digital twins with reduced order thermal models or for data driven approaches that predict the inverter temperature from power, weather and cooling state. Instead, fan or pump instructions could be optimized before the heat sink would reach a thermal limit. Machine-learning reviews reveal that while the advancement in fault diagnosis and junction-temperature estimation is swift, validation of machine-learning algorithms under real operating conditions is also highlighted (Mabutyana-Rabaza et al., 2026). Unsupervised learning has also been applied to field-oriented data to detect the principal PV-inverter failure mechanisms and estimate the reliability based on plant operational data (Roy et al., 2024). The most useful next step is physics-based prediction that is verified by multiple inverter ratings and climates.

Optimization should be based on cost/damage over the lifecycle not only on temperature. An objective that includes semiconductor damage, capacitor temperature, fan/pump energy, water usage, noise and thermal reserve could be minimized by a controller. A natural predictive horizon can be provided by weather forecasts and PV power forecasts. Pre-cooling may be cost effective if a high-irradiance event is forecasted, and conversely, aggressive cooling may be undesirable if cloud is forecast since it would result in energy and water waste.

8.3 Wide-bandgap devices and packaging-level thermal management

SiC and GaN offer the potential for higher switching frequency and power density, but also introduce a new thermal design paradigm, characterized by smaller hot spots and more integrated packaging. Sintered interfaces, embedded vapor chambers, direct-to-package microfluidics, low-inductance interconnects and double-sided cooling are

likely to be more relevant to PV inverters. What needs to be avoided is a reliability trade in which a lower electrical loss is balanced by increased packaging stress and/or more challenging thermal cycling.

8.4 Standardized climate-aware reporting

The PV-inverter cooling paper should ideally contain a weather and boundary-condition block like that of the electrical ratings block in an inverter paper. These recommended fields are: site/climatic zone, indoor/outdoor location, enclosure volume/ventilation conditions, ambient dry-bulb temperature, ambient RH, wet-bulb temperature, solar radiation, wind velocity (if applicable) dust conditions, inverter loading, cooling-resource inputs. This would allow published thermal results to be used for design instead of only being a stand-alone demonstration.

9. CONCLUSIONS

PV-inverter thermal management is at the intersection of power-electronic cooling, PV mission profile, climate and reliability. Current evidence indicates that thermal stress is a significant reliability variable and that location, mission-profile resolution and environmental conditions have a significant impact on lifetime predictions. Therefore it is important to choose and analyze cooling technologies under real operating conditions that cause thermal stress on the inverter.

Although forced-air cooling is the basic type of cooling due to its simplicity and low cost, the thermal head room would be reduced in hot weather and the performance would be dependent on the status of dust and fan. Liquid cooling provides a high heat-removal capability and is suitable for high power density, but the pumps, leakage risk, water chemistry and service complexity must be justified. When spreading resistance and hot spots are important, vapor chambers and advanced heat spreaders are effective, and two-phase and direct cooling technologies provide additional benefit for compact, high-flux systems. Although evaporative cooling has the potential to directly harness the hot-dry climate, it has yet to be given due consideration in PV-inverter research, and water use, psychrometrics, and compatibility of materials over time must be quantified. More generally, multi-mode systems can use low energy operation during normal conditions, and use a more powerful secondary cooling system during peak thermal stress, if there is a justification for the additional complexity of the lifecycle.

The most critical change for the future is from the reduction of temperature at the component level, to lifecycle. A PV-inverter cooling study should be conducted at the same time considering temperature, thermal cycling, auxiliary energy, water, cost, maintenance, safety and field reliability. The field needs to be transitioned from stand-alone cooling demonstrations to bankable, design rules for thermal-management for real PV plants, through standardized metrics, synchronized comparative experiments, direct flow measurements, climate-aware reporting and predictive thermal-control.

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