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**THERMAL MANAGEMENT AT THE ENERGY WATER ENVIRONMENT NEXUS:  
FROM PHOTOTHERMAL MATERIALS AND BUILDING ENVELOPES TO  
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**ABSTRACT**

*Thermal phenomena sit at the heart of today's most important sustainability challenges, producing clean water, maintaining healthy indoor climates, valorizing biomass, and balancing increasingly variable power grids. This review synthesizes state-of-the-art advances across materials, devices, buildings, and energy systems to outline an integrated research agenda for the energy–water–environment nexus. We highlight photothermal platforms for desalination and wastewater treatment, including macroporous three-dimensional MXene architectures with high broadband absorption and near-complete contaminant rejection, a nature-inspired “suspended” evaporator that resists salt accumulation even in 15–20 wt% brines, and scaling-mitigating slippery membranes for robust membrane distillation (Lan, Wood, & Yuen, 2019), (Zhao et al., 2019), (Islam et al., 2020). For the built environment, we analyze optimization of phase-change Trombe walls, localized solid-state humidity pumping, evidence-based thermal comfort indices, and holistic multi-objective design of net-zero energy housing in the tropics (Zhang et al., 2022; Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021), (Luo et al., 2021; Mani et al., 2023). On the supply side, we assess rapid load transitions in solid-oxide-fuel-cell–gas-turbine hybrids, optimization-driven power-flow management, and thermal-pollution constraints on water-cooled generation (Staiger, Laschewski, & Matzarakis, 2019), (Zhu et al., 2021; Li, Hua, Tu, & Wang, 2019). Finally, we connect circular carbon strategies torrefaction and biochar to both energy quality and environmental remediation (Karanikola, Boo, Rolf, & Elimelech, 2018), (Miara et al., 2018). We conclude with cross-cutting gaps in durability, field validation, and multi-scale modeling, and propose harmonized metrics and standardized protocols to accelerate translation. All citations derive from the user-provided corpus.*

**Keywords:** photothermal desalination; membrane distillation; thermal comfort and indices; net-zero energy buildings; SOFC-GT hybrids; torrefaction and biochar; optimal power flow

**1. INTRODUCTION**

Thermal management links multiple decarbonization levers: efficient water purification, adaptive buildings and wearables, low-carbon fuels and materials, and fast, flexible power systems. Recent studies demonstrate major performance gains from salt-resistant solar evaporators and macroporous MXene photothermal foams to solid-state humidity control and underwater thermoelectric skins while grid-facing work advances rapid load control in hybrid fuel-cell–turbine plants and optimization frameworks that co-minimize losses, costs, and emissions (Zhao et al., 2019), (Lan, Wood, & Yuen, 2019), (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021), (Jung et al., 2022), (Staiger, Laschewski, & Matzarakis, 2019), (Zhu et al., 2021). At the same time, thermal externalities such as riverine heat

pollution and scaling/fouling at high salinity remain pervasive barriers to reliability and cost-effective operation (Islam et al., 2020), (Li, Hua, Tu, & Wang, 2019).

This review builds upon the provided literature set to (i) map core mechanisms and governing parameters across materials-to-systems scales; (ii) extract quantitative benchmarks; and (iii) identify research gaps whose closure would enable deployment. We deliberately bridge domains water treatment, buildings and human biometeorology, conversion/storage, and circular carbon because solutions increasingly depend on co-design across sectors (Lan, Wood, & Yuen, 2019), (Zhao et al., 2019), (Zhang et al., 2022), (Luo et al., 2021), (Karanikola, Boo, Rolf, & Elimelech, 2018), (Miara et al., 2018).

## 2. PHOTOTHERMAL AND THERMAL-SEPARATION PLATFORMS FOR HIGH-SALINITY WATER

Macroporous 3D MXene architectures. Transforming 2D MXenes into 3D open networks yields  $\approx 98\%$  broadband solar absorption and superb photothermal conversion, enabling evaporation rates of  $1.41 \text{ kg m}^{-2} \text{ h}^{-1}$  at 1 sun ( $7.49$  at 5 suns) with near-complete rejection of dyes and metal ions (Lan, Wood, & Yuen, 2019). Hydrophilicity and capillarity within the macroporous foam sustain water supply and minimize thermal losses (Lan, Wood, & Yuen, 2019).

Suspended hydrophobic-frame evaporators. Inspired by water striders, a hydrophobic frame supports a thin film of feed directly beneath the surface, stabilizing submergence depth across salinities and maintaining high fluxes  $1.45$  and  $1.35 \text{ kg m}^{-2} \text{ h}^{-1}$  in 15 and 20 wt% NaCl without salt accumulation up to saturation (Zhao et al., 2019). Confining a thin water layer on a hydrophilic absorber both enhances energy utilization and prevents fouling (Zhao et al., 2019).

Scaling-mitigating membranes for MD. Engineered “slippery” PVDF membranes (silica-grafted, fluoroalkylsilane-coated) lower surface energy and delay gypsum deposition during direct-contact membrane distillation on hypersaline brines, stabilizing flux and enabling higher recovery (Islam et al., 2020). Such surfaces directly target the inorganic scaling chokepoint that limits thermal desalination under high water recovery (Islam et al., 2020).

Mechanistic synthesis. All three strategies reduce parasitic losses at the water–heat interface while resisting performance decay from salt crystallization. MXene foams focus on optical-to-thermal conversion and wicking (Lan, Wood, & Yuen, 2019); suspended frames achieve geometric salt-avoidance and isothermal thin-film operation (Zhao et al., 2019); slippery membranes chemically neutralize nucleation/adhesion (Islam et al., 2020). Future head-to-head benchmarking should normalize for solar intensity, feed chemistry (ionic strength, multivalent species), and recovery target, reporting both initial and 100-hour stability metrics (Zhao et al., 2019), (Lan, Wood, & Yuen, 2019), (Islam et al., 2020).

Selain normalisasi tersebut, pelaporan sebaiknya juga memasukkan neraca energi rinci (efisiensi antarmuka vs. kehilangan konduksi/konveksi), konsumsi energi spesifik setara ( $\text{kWh m}^{-3}$ ) untuk perbandingan lintas platform surya–MD, serta kurva “retensi-rejeksi” (fluks dan penolakan garam/pewarna/ion logam) sepanjang uji 100 jam. Deskriptor fouling yang kuantitatif—mis. waktu induksi kristalisasi, laju pertumbuhan kerak semu, dan perubahan sudut kontak—akan memudahkan pemetaan kondisi operasi aman pada brine multivalen pekat. Skala-up wajib melaporkan kerapatan kemasan modul, stabilitas mekanik di lingkungan luar ruang (angin, percikan garam), dan kemudahan *rinse/regeneration* tanpa penurunan kinerja yang berarti, untuk memastikan relevansi menuju implementasi lapangan (Zhao et al., 2019), (Lan, Wood, & Yuen, 2019), (Islam et al., 2020).

**Table 1.** Solar-thermal separation platforms for hypersaline feeds (illustrative benchmarks)

Approach	Core mechanism	Brine/scaling performance	Peak performance (reported)	Core materials	Ref.
3D macroporous MXene foam	Broadband absorption with capillary water supply, minimized conduction losses	Near-complete dye/ion rejection; no fouling reported under tests	1.41 kg m <sup>-2</sup> h <sup>-1</sup> @ 1 sun; 7.49 @ 5 suns; up to 94.2% efficiency	MXene-coated melamine foam	(Lan, Wood, & Yuen, 2019)
Suspended evaporator (hydrophobic frame + hydrophilic absorber)	Thin-film confinement under water surface; salt-resistant geometry	No salt accumulation to saturation in 15–20 wt% NaCl	1.45 (15%) and 1.35 kg m <sup>-2</sup> h <sup>-1</sup> @ 1 sun	Hydrophobic frame, hydrophilic absorber, insulation	(Zhao et al., 2019)
Slippery MD membrane	Low-energy surface suppresses gypsum nucleation/adhesion	Substantial delay of CaSO <sub>4</sub> scaling; stabilized flux at high recovery	Sustained desalination on hypersaline industrial brines	PVDF + silica nanoparticles + fluoroalkylsilane	(Islam et al., 2020)

### 3. THERMAL MANAGEMENT IN BUILDINGS AND LOCALIZED ENVIRONMENTS

Phase-change Trombe walls. Coupled TRNSYS–GenOpt studies identify interacting parameters (vent area, PCM melting points, wall and air-gap thickness, sun-shade length) that jointly minimize annual loads; optimal settings cut total building load by ≈7.6% vs. a traditional Trombe reference and ≈13.5% vs. an optimized reference, respectively (Zhang et al., 2022). Multi-temperature PCM layering (≈16.5 °C and ≈27.75 °C) widens operating envelopes (Zhang et al., 2022).

Localized solid-state humidity pumping. A compact device combining thermoelectric coolers and silica-gel coatings transfers moisture without refrigerants or liquid handling, achieving 0.61 g W<sup>-1</sup> h<sup>-1</sup> (28.38 g h<sup>-1</sup>) and enabling precise, small-zone humidity control beyond bulky desiccant or condensing systems (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021). Such systems match emerging “right-sized” micro-comfort strategies for occupant-centric control (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021).

Evidence-based thermal indices. Among 165 indices, only four (UTCI, PT\_J, PET, SET\*) satisfy full human energy-budget traceability and suitability for urban/regional planning and heat-health applications, providing a defensible bridge between physics and perception (Luo et al., 2021). This is critical for designing low-energy comfort strategies and for evaluating “free-running” buildings under heat stress (Luo et al., 2021).

Net-zero energy housing in the tropics. A two-phase, multi-objective optimization that balances social (comfort/daylighting), environmental (energy efficiency), and financial (LCC) goals shows rooftop PV can close the energy balance for landed homes, whereas tall apartments require façade-integrated PV; a 25-floor H-shaped case can power ~19 floors (Mani et al., 2023). Sensitivity analysis reveals variables that jointly improve comfort and efficiency rather than trading off (Mani et al., 2023).

**Table 2.** Building and micro-climate thermal strategies: variables, tools, and gains

Application	Key variables optimized	Reported benefits	Modeling/Toolchain	Context/Climate	Ref.
PCM Trombe wall	Air gap, shading length, wall thickness, vent area, dual-PCM melting points	-7.56% vs traditional; -13.52% vs reference annual load	TRNSYS + GenOpt	Temperate/continental scenarios	(Zhang et al., 2022)
Local humidity pump	TEC power, silica-gel area/placement, heat-sink design	0.61 g W <sup>-1</sup> h <sup>-1</sup> ; precise localized control; no refrigerants	Experimental prototype	Wide ambient range; localized spaces	(Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021)
Thermal indices in planning	Full energy-budget models with active control representation	Validated indices (UTCI, PT_J, PET, SET*) for policy and design	Model appraisal	Urban biometeorology	(Luo et al., 2021)
Net-zero housing	Daylighting & natural cooling vs LCC & energy	NZEB feasible for landed homes; façade PV boosts apartments	Multi-objective optimization	Tropical (Singapore)	(Mani et al., 2023)

**4. WEARABLES AND UNDERWATER THERMOREGULATION/ENERGY HARVESTING**

A soft, stretchable thermoelectric “skin” demonstrates dual functionality: harvesting energy from the ocean–body temperature gradient and actively heating/cooling to prevent underwater hypo/hyperthermia (Jung et al., 2022). Elastic conformity improves heat transfer at the skin–device interface, raising power density relative to prior stretchable TE devices; integration into a neoprene dry suit shows multi-sensor self-powering and closed-loop temperature regulation (Jung et al., 2022). This platform illustrates “thermal human–device co-design” that complements building-scale strategies with personal micro-climate control (Jung et al., 2022), (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021).

**5. GRID-RESPONSIVE THERMAL–ELECTROCHEMICAL CONVERSION**

Hybrid SOFC–gas-turbine (SOFC-GT) systems combine high efficiency and low carbon intensity with the potential for fast ramping. A hardware-in-the-loop co-simulation using NETL’s Hyper facility and INL’s grid simulator achieved a ~50% load step in 10 s by simultaneously ramping SOFC and GT power while actively managing anode fuel, cathode air flow, and inlet temperature to protect the stack without violating operability constraints (Staiger, Laschewski, & Matzarakis, 2019). The experiment revealed non-linear couplings that motivate adaptive control design for autonomous operation under high VRE penetration (Staiger, Laschewski, & Matzarakis, 2019). Complementarily, a Harris Hawks Optimization (HHO) metaheuristic for optimal power flow reduces losses (~9.84%) and emissions (~26.2%) with distributed generation placement, benchmarking favorably against several AI optimizers (Zhu et al., 2021). Together, these works connect plant-level dynamics with system-level

dispatch that explicitly prices thermal constraints (Staiger, Laschewski, & Matzarakis, 2019), (Zhu et al., 2021).

**Table 3.** Energy systems and circular carbon: key results and implications

System/Process	Objective	Key result	Scale/Method	Implication for decarbonization	Ref.
SOFC-GT hybrid	Fast grid response with stack protection	~50% load change in 10 s without violating constraints	Hardware-based cyber-physical co-simulation	Firm, efficient, flexible low-carbon capacity	(Staiger, Laschewski, & Matzarakis, 2019)
OPF with HHO	Minimize fuel cost, losses, emissions	Losses -9.8355%; emissions -26.2% with DG	IEEE 30-bus benchmark; MATLAB	AI-assisted trade-offs under constraints	(Zhu et al., 2021)
Torrefaction	Upgrade biomass energy density & handling	~30% energy content; 18–19→20–24 MJ kg <sup>-1</sup> ; 1–3% w.b. moisture	↑ Reactor design concepts; moving bed favored	Dense, hydrophobic, grindable bioenergy feedstock	(Karanikola, Boo, Rolf, & Elimelech, 2018)
Biochar from lignocellulose	Production, modification, and applications	Versatile adsorbent; activation improves pollutant removal; decentralized production supports circularity	Comprehensive review	Coupled waste management & remediation co-benefits	(Miara et al., 2018)
Thermal pollution in rivers	Quantify heat-effluent impacts on power	High-resolution modeling shows heterogeneous plant impacts; recirculating cooling reduces pollution	Basin-scale simulations (Mississippi)	Co-plan cooling tech & regulation for reliability	(Li, Hua, Tu, & Wang, 2019)

## 6. CIRCULAR CARBON: TORREFACTION AND BIOCHAR

Thermal pretreatment at  $\approx 300$  °C devolatilizes biomass to a hydrophobic, brittle, energy-dense solid (torrefied) with improved storage and grindability; moving-bed reactors offer operational simplicity and uniform products, and gas-recycle concepts enhance efficiency (Karanikola, Boo, Rolf, & Elimelech, 2018). In parallel, lignocellulosic biochar produced via pyrolysis and often modified/activated serves as a low-cost adsorbent and soil amendment with broad remediation potential; decentralized, closed-loop production aligns with circular bioeconomy and waste-

management aims (Miara et al., 2018). Together, these pathways convert low-value residues into functional thermal–environmental materials and fuels that support the same water and grid systems examined above (Miara et al., 2018), (Karantikola, Boo, Rolf, & Elimelech, 2018), (Islam et al., 2020).

## 7. CROSS-CUTTING CHALLENGES AND RESEARCH GAPS

1. Durability at scale. Anti-fouling evaporators and slippery membranes need long-duration trials under realistic multivalent, organic-laden brines and cyclic operation (Zhao et al., 2019), (Islam et al., 2020).
2. Standardized metrics. Reported evaporation rates and efficiencies should be normalized by solar flux, ambient wind/humidity, recovery, and brine chemistry; MD studies should standardize supersaturation history and shear (Zhao et al., 2019), (Lan, Wood, & Yuen, 2019), (Islam et al., 2020).
3. Human-centric outcomes. Building controls and personal thermoregulation must map physics to perception using validated indices (UTCI, PT<sub>J</sub>, PET, SET\*) and measure health outcomes during heat waves (Luo et al., 2021), (Jung et al., 2022), (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021).
4. Co-optimization under constraints. Multi-objective building design and OPF must incorporate thermal limitations (e.g., stack temperatures, cooling-water limits) with explicit reliability objectives and policy constraints (Mani et al., 2023), (Zhu et al., 2021), (Staiger, Laschewski, & Matzarakis, 2019), (Li, Hua, Tu, & Wang, 2019).
5. Circularity and LCA. For torrefaction and biochar, harmonize LCA boundaries, quantify net carbon benefits (including avoided pollution remediation), and integrate with local waste streams and energy needs (Karantikola, Boo, Rolf, & Elimelech, 2018), (Miara et al., 2018).
6. Field-ready integration. Demonstrate end-to-end systems: e.g., biochar-assisted pretreatment upstream of MD for hypersaline produced water; building-integrated photothermal panels coupled to PCM storage; and hybrid SOFC-GT plants dispatched by optimization algorithms that respect cooling-water constraints (Miara et al., 2018), (Islam et al., 2020), (Zhao et al., 2019), (Zhang et al., 2022), (Zhu et al., 2021), (Staiger, Laschewski, & Matzarakis, 2019), (Li, Hua, Tu, & Wang, 2019).

## 8. RESEARCH OUTLOOK AND FRAMEWORK

We propose a common framework for thermal solutions at the nexus:

- Mechanisms → Metrics: Link dominant transport mechanisms (optical absorption, capillary wicking, nucleation energy, PCM latent storage, TE heat pumping, stack thermal inertia) to standardized metrics (e.g.,  $\eta_{\text{solar}}$ ,  $g\ W^{-1}\ h^{-1}$  humidity transfer, °C SET\* at equal metabolic rates,  $\Delta P$  ramp in s at bounded  $T_{\text{inlet}}$ ) (Lan, Wood, & Yuen, 2019), (Zhao et al., 2019), (Islam et al., 2020), (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021), (Luo et al., 2021), (Staiger, Laschewski, & Matzarakis, 2019).
- Benchtop → Field: Progress from controlled-chemistry brines and chamber tests to pilots with variable feeds and weather, reporting stability, maintainability, and cost per m<sup>3</sup> or kWh (Zhao et al., 2019), (Lan, Wood, & Yuen, 2019), (Islam et al., 2020), (Mani et al., 2023).
- Unit → System: Embed device-level models into building or grid co-simulation loops (e.g., TRNSYS/GenOpt for envelopes; cyber-physical labs for hybrids), enforcing physical operability and safety (Zhang et al., 2022), (Staiger, Laschewski, & Matzarakis, 2019).
- Optimization with Accountability: Use multi-objective optimizers (HHO and beyond) but tie solutions to interpretable sensitivities and policy-relevant constraints (water discharge temperatures, reliability metrics) (Zhu et al., 2021), (Li, Hua, Tu, & Wang, 2019).

## 9. CONCLUSIONS

Across water, buildings, and power systems, thermal science offers compact, material-efficient, and grid-supportive pathways to sustainability. Photothermal evaporation and scaling-resistant membranes push hypersaline treatment toward practical operation; PCM-enhanced envelopes, localized humidity pumps, and validated comfort indices realign buildings around people rather than loads; and hybrid SOFC-GTs plus optimization-aware dispatch deliver fast, efficient flexibility for high-VRE grids (Lan, Wood, & Yuen, 2019), (Zhao et al., 2019), (Islam et al., 2020), (Zhang et al., 2022), (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021), (Luo et al., 2021), (Staiger, Laschewski, & Matzarakis, 2019), (Zhu et al., 2021). Circular carbon strategies torrefaction and biochar upgrade biomass into durable energy and environmental assets (Karanikola, Boo, Rolf, & Elimelech, 2018), (Miara et al., 2018). Yet durability, standardized benchmarking, and system-level integration remain decisive gaps. Priorities include multi-ion, long-duration brine testing; heat-health impact trials; adaptive control for hybrid plants; and LCAs that capture whole-system co-benefits, especially where water and electricity systems are tightly coupled (Islam et al., 2020), (Luo et al., 2021), (Staiger, Laschewski, & Matzarakis, 2019), (Li, Hua, Tu, & Wang, 2019). The literature indicates no inherent conflict between comfort, efficiency, and cost when designs are co-optimized indeed, several variables improve all three suggesting a path to thermal technologies that are not only cleaner, but also simpler, smaller, and more human-centered (Mani et al., 2023), (Zhang et al., 2022), (Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021), (Jung et al., 2022).

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