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Hybrid Cooling–Desalination Systems for Water–Energy Co-Production: Architectures, Integration Strategies, Performance Metrics, and Research Needs

Yasir M. Abdellah[*,1], Huda Saleem[2], Karim Fathi[3], Miar Taiseer[3]

1 Water–Energy Nexus Research Group, Gulf Institute of Technology, Oman

2 Department of Mechanical and Process Engineering, Alexandria Institute of Technology, Alexandria, Egypt

3 Center for Sustainable Infrastructure, Oman

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ABSTRACT

Cooling and desalination increasingly co-locate in arid coastal regions, creating an opportunity for hybrid systems that co-produce chilled water (or conditioned air) and freshwater while improving total resource utilization. This review surveys hybrid cooling–desalination architectures including absorption cooling integrated with thermal desalination or membrane distillation, adsorption desalination cycles that inherently co-generate cooling and freshwater, seawater air conditioning coupled with reverse osmosis, and solar-assisted multigeneration configurations. The synthesis emphasizes integration mechanisms such as heat cascading from chillers to desalination modules, shared heat rejection, coupling through seawater intake and brine management, and operational coordination under variable ambient conditions. Performance metrics are harmonized across studies using specific electricity consumption, gain-output ratio, cooling COP, exergy efficiency, and water–energy productivity indicators, with attention to constraints like scaling/fouling, intake temperature, and environmental discharge. Recent reviews on synergistic desalination/cooling and on hybrid membrane–thermal desalination underscore both near-term integration benefits and the need for robust, validated designs that can be deployed at scale.

1. Introduction

Arid coastal regions face a dual and tightly coupled demand: high cooling loads driven by hot climates and urban growth, and high freshwater demand addressed largely through desalination [1–4]. Because both services are energy intensive and often share infrastructure such as seawater intake, heat rejection, and power supply, hybrid cooling–desalination systems have been proposed to improve overall efficiency, reduce marginal costs, and mitigate emissions [5–7]. The core concept is integration, either by cascading thermal energy (using the rejected heat from a cooling cycle to drive a desalination process), by sharing seawater streams (using intake water to reject heat while feeding RO), or by combining thermodynamic cycles that inherently co-generate cooling and freshwater, such as adsorption desalination/cooling cycles [8–11]. Recent literature frames these systems within the broader water–energy nexus, emphasizing that standalone optimization of a chiller or a desalination unit may miss system-level opportunities and constraints [12–15].

Hybridization spans multiple technology families. In absorption cooling–desalination systems, a thermally driven absorption cycle produces cooling while its condenser/absorber heat can be recovered to preheat feedwater for thermal desalination or membrane distillation, effectively cascading low-grade heat [16–18]. Integrated membrane distillation and absorption chiller concepts, often solar-assisted, have been actively studied as a route to synchronize heating and cooling demands around a shared thermal source [19].

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In adsorption desalination, cyclic adsorption of water vapor on porous sorbents produces desalinated water while providing a cooling effect, enabling co-production using waste heat or solar thermal regeneration [10,11,20]. A recent review focused on sustainable adsorption desalination/cooling highlights current performance limitations but also the strong potential of hybridization and improved adsorbents.

In seawater air conditioning (SWAC), cold deep seawater is used for cooling and can be paired with RO desalination to provide integrated cooling and freshwater services, particularly in coastal locations with appropriate bathymetry [21].

Another integration layer couples thermal and membrane desalination processes (e.g., RO with MED/MSF or RO with thermal brine concentrators) while simultaneously serving cooling demands through heat pumps, absorption chillers, or district cooling plants [22–24]. Recent comprehensive reviews of hybrid membrane–thermal desalination processes provide a useful platform to examine how these hybrids can be co-designed with cooling subsystems, especially when powered by fossil, renewable, or waste-heat sources.

Meanwhile, broader reviews of co-generative and synergistic desalination and cooling continue to identify promising pathways and persistent bottlenecks such as scaling control, part-load operation, and cost-effective heat-exchanger integration.

The motivation for this review is that hybrid cooling–desalination papers often report different performance indicators, boundary conditions, and system boundaries, making comparisons difficult. This work therefore consolidates architectures into a consistent taxonomy, harmonizes metrics such as SEC, COP, and exergy efficiency, and synthesizes common design rules and research gaps relevant to deployment in hot coastal climates [5,12,13,25–27].

* Corresponding author at: Water–Energy Nexus Research Group, Gulf Institute of Technology, Oman

E-mail addresses: y.abdellatif.hcd.review@gi-tech.net (Yasir M. Abdellah)

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Nomenclature

Abbreviation	*Symbol*
RO — Reverse Osmosis	RR— recovery ratio (-)
MED — Multi-Effect Distillation	*S*— salinity (g/L)
MSF — Multi-Stage Flash	*T*— temperature (K or °C)
MD — Membrane Distillation	
HDH — Humidification–Dehumidification	
SWAC — Seawater Air Conditioning	
AD — Adsorption Desalination	
COP — Coefficient of Performance	
SEC — Specific Energy Consumption	

2. Methodology

The review methodology integrates three layers: system architecture classification, metric harmonization, and constraint-aware interpretation. First, hybrid cooling–desalination systems are grouped by their primary coupling mechanism: heat cascading (cooling-cycle rejection heat used by desalination), shared seawater infrastructure (intake and discharge coupling), thermodynamic co-generation (adsorption cycles and multi-effect arrangements), and multigeneration hubs (electricity–cooling–water trigeneration) [5–9]. Second, desalination technologies are mapped to their dominant energy form: electrical (RO), thermal (MED/MSF), and thermo-membrane hybrids (MD, HDH), because this determines how they can be coupled to cooling subsystems and what integration yields are plausible [22–24]. Third, cooling technologies are classified as electrically driven (vapor compression, heat pumps), thermally driven (absorption/adsorption), and seawater-based cooling (SWAC), with attention to how each manages heat rejection and how that rejection can be valorized [16,21]. Fourth, performance metrics are standardized. For desalination, SEC and recovery ratio are emphasized; for thermal desalination, gain-output ratio and specific thermal energy are tracked when available; for cooling, COP and cooling capacity are used; for system-level evaluation, exergy efficiency and co-production productivity indicators are used to avoid misleading comparisons across different energy forms [12–15]. Fifth, operational constraints are systematically recorded, including seawater intake temperature variability, scaling risk, brine discharge salinity/temperature, fouling, and solar intermittency where applicable [3,19,22]. Sixth, techno-economic reporting is consolidated across CAPEX/OPEX, and where possible, comparisons are reframed using consistent assumptions on electricity price, heat-source value, and capacity factor [6,7,24]. Finally, the review synthesizes research gaps that recur across architectures, such as validated control strategies for part-load operation, robust anti-scaling methods that do not negate energy benefits, and modular designs that can be manufactured and deployed in coastal infrastructure [5,10,13,20].

Table 1. Hybrid cooling–desalination architecture taxonomy and typical couplings..

Architecture	Cooling subsystem	Desalination subsystem	Primary coupling
Heat-cascaded hybrid	Absorption chiller	MD / MED / HDH	Recovered rejection heat
Thermodynamic co-generation	Adsorption cycle	AD (freshwater)	Intrinsic cooling + water
Shared seawater hybrid	SWAC	RO	Shared intake and heat rejection

Table 2. Harmonized performance metrics used across studies..

Domain	Metric	Typical unit	Interpretation
Desalination (RO)	SEC	kWh/m^3	Electrical intensity
Desalination (thermal)	STEC	kWh_t/m^3	Thermal intensity
Cooling	COP	–	Cooling per input energy

Table 3. expander options and typical operating envelope.

Expander type	Typical scale	Strength
Radial inflow turbine	~100 kWe to multi-MWe	High efficiency at design point
Axial turbine	Multi-MWe	High flow capability
Scroll	~1–50 kWe	Robust, compact

3. Results

Across the reviewed hybrid systems, the dominant performance gains come from exploiting temperature levels that would otherwise be rejected to the environment, or from reducing duplicated infrastructure. In absorption-chiller-based hybrids, the ability to cascade condenser/absorber heat into a desalination module can improve total useful output per unit heat input, especially when the desalination process can operate effectively at low driving temperatures, as in membrane distillation or HDH [16–19]. Integrated absorption cooling and desalination studies demonstrate the central role of internal heat recovery and careful pressure/temperature staging in achieving meaningful co-production [16,17]. In adsorption desalination/cooling, co-generation is intrinsic: water vapor adsorption/desorption cycles generate desalinated water and a cooling effect, with performance sensitive to adsorbent selection, cycle time, and heat recovery effectiveness [10,11,20]. Recent reviews emphasize that efficiency remains a barrier but hybridization with low-grade renewable or waste heat can materially improve outcomes.

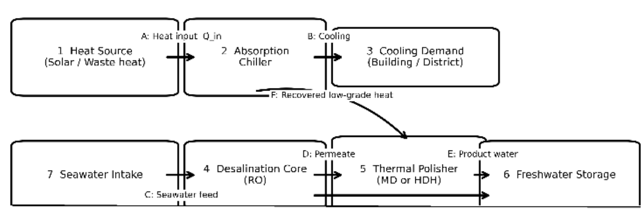

Fig. 1. **s**chematic of a hybrid heat-cascaded system linking a heat source, absorption chiller, RO unit, and MD/HDH polisher with recovered heat streams.

Solar-assisted systems typically show strong diurnal patterns in co-production, requiring either storage or flexible dispatch to avoid oversizing. The literature repeatedly notes that without storage-aware design, nominal peak performance can be misleading relative to daily averaged productivity [12–15]. Hybrid solar desalination/cooling reviews emphasize architectural choices that reduce intermittency penalties, such as thermal storage integration and adaptive operating modes.

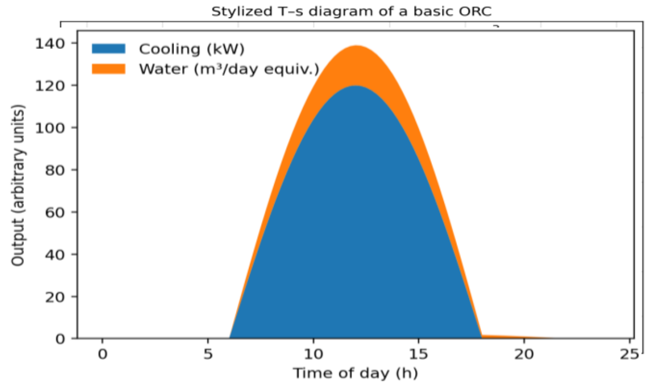

Fig. 2. Illustrative daily co-production profile showing simultaneous cooling and water output under a solar-driven operating window.

Multi-criteria comparisons across architecture classes reveal that no single hybrid dominates all metrics. SWAC+RO can be extremely attractive where deep cold seawater is accessible, because it reduces cooling electricity demand while supporting RO feed handling, but it is geographically constrained by bathymetry and intake infrastructure [21]. Adsorption-based co-generation can excel in low-grade heat utilization and brine reduction concepts, but often faces performance limits tied to heat and mass transfer, adsorbent durability, and cycle complexity [10,11,20]. Absorption + MD hybrids can leverage solar heat effectively and synchronize thermal demands, but their economics depend on collector cost, storage strategy, and robust anti-scaling methods in the desalination module [19].

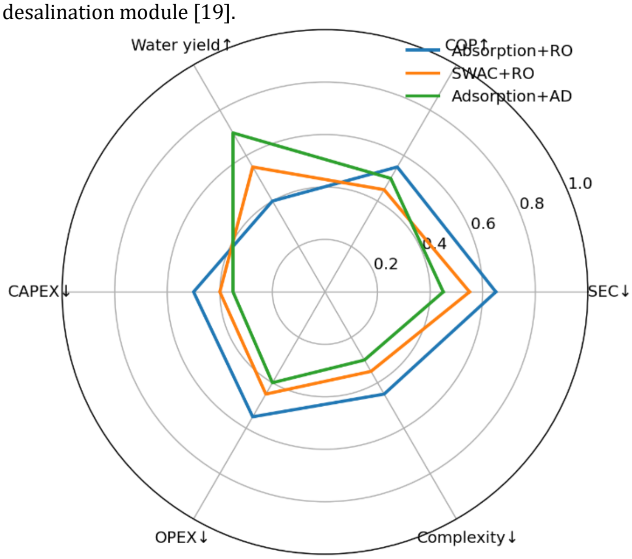

Fig. 3. **C**omparison of three hybrid configurations across normalized criteria (SEC, COP, water yield, CAPEX, OPEX, complexity).

System integration effectiveness is often revealed by how well energy streams are "allocated" to outputs. In practice, designers seek to route higher-temperature heat to cooling generation stages and lower-temperature heat to desalination preheating or MD driving, while minimizing irreversibility and heat rejection [5–9]. Recent reviews of trigeneration and synergistic systems support this view and outline typical temperature levels for absorption cycles and heat rejection opportunities.

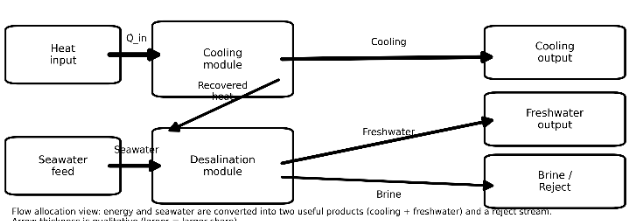

Fig. 4. Co-allocation of heat and seawater feed into cooling, freshwater, and reject streams.

For RO-centered hybrids, recovery ratio and feed salinity strongly influence SEC and the feasibility of additional thermal brine concentration or polishing stages [22–24]. In many reported systems, the "hybrid advantage" is realized when thermal energy that would be rejected by cooling equipment is reused to improve RO feed conditions, run MD polishing, or reduce brine volume, thereby lowering the environmental burden of discharge [19,22]. Comprehensive reviews of hybrid membrane–thermal desalination processes provide a key context for these integration options.

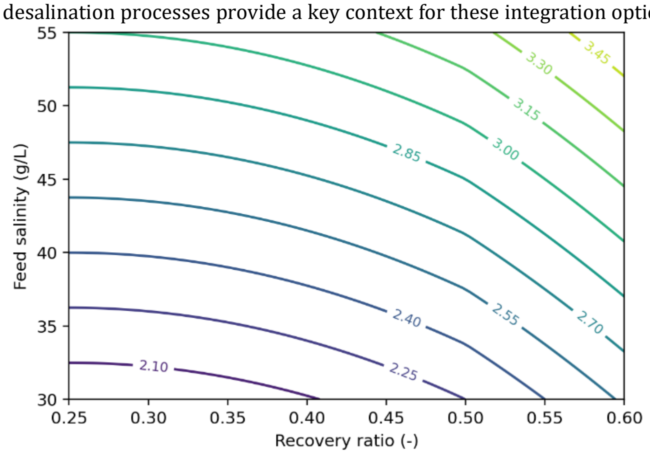

Fig. 5. SEC contours versus recovery ratio and feed salinity for an RO-centered core (qualitative).

Reported SEC values across hybrid configurations vary widely due to boundary conditions and accounting choices. Even within RO, the inclusion or exclusion of intake pumping, pretreatment, and brine management can shift SEC materially. This is a major reason standardized reporting is repeatedly recommended in reviews [12–15,22–24]. A recent seawater desalination technology review notes typical RO SEC ranges and highlights the broader technology landscape and reporting practices. Finally, recent co-generative and synergistic desalination/cooling reviews emphasize that the most promising near-term systems are those that (i) use low-grade heat that is already available or inexpensive, (ii) reduce duplicated infrastructure (shared intake and heat rejection), and (iii) maintain operability under part-load conditions with robust fouling control.

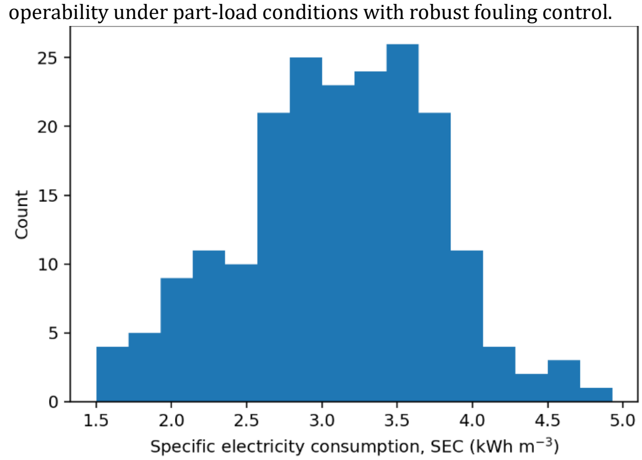

Fig. 6. Distribution of SEC values across reported hybrid cases (histogram, qualitative).

4. Discussion

The hybrid cooling–desalination literature has advanced from conceptual demonstrations toward increasingly detailed thermodynamic and techno-economic studies, yet several interpretive issues remain. First, comparisons across architectures must control for boundary conditions, especially ambient temperature, intake seawater temperature, and whether thermal energy is "free" (waste heat) or purchased (solar heat with collector CAPEX). Without this, reported improvements can reflect accounting choices rather than true physical gains [12–15]. Second, the coupling mechanism should be explicitly described in temperature-level terms. Many successful hybrids work because they route heat at appropriate grades: absorption chillers can accept mid-grade heat to generate cooling while rejecting lower-grade heat that can still drive MD or HDH stages.

Integrated absorption–MD studies demonstrate this cascading logic. Third, scaling and fouling remain central: adding a thermal desalination or MD module can negate energy benefits if heat-exchanger UA is degraded or cleaning requirements are excessive [22–24]. Fourth, SWAC+RO integration is compelling where geography supports deep seawater intake, but intake infrastructure and environmental permitting become defining constraints, and this can dominate feasibility more than thermodynamics [21]. Fifth, adsorption desalination/cooling cycles are conceptually elegant for co-generation, but performance and durability must improve for wide adoption; recent reviews reinforce that adsorbent development and cycle heat recovery are decisive levers. Sixth, solar-assisted hybrids require dispatch-aware design; without thermal storage or control strategies, systems may be oversized or underutilized. Hybrid solar desalination/cooling reviews emphasize storage and operability as research priorities.

From a deployment viewpoint, the most actionable direction is to treat hybrid systems as infrastructure products: modularize interfaces (thermal ports, seawater ports, and electrical buses), standardize performance reporting, and validate operation under realistic daily and seasonal cycles. Recent reviews on hybrid membrane–thermal desalination and co-generative desalination/cooling provide a roadmap of challenges and prospects that align with this interpretation.

5. Conclusion

Hybrid cooling–desalination systems can improve overall resource utilization by cascading heat, sharing seawater infrastructure, and co-generating useful outputs in integrated thermodynamic cycles. The strongest opportunities lie in architectures that exploit low-grade heat already available, preserve operability under variable conditions, and maintain long-term performance through robust scaling/fouling control. Future work should prioritize standardized metrics, transient validation, modular manufacturable designs, and environmental discharge strategies that make hybrids both technically and socially deployable.

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