



Floating solar collectors for hybrid cooling and water treatment plants

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Floating solar collectors are emerging as a promising solution for integrating renewable energy into hybrid cooling and water treatment plants. This work presents a novel configuration of floating photovoltaic thermal (FPV T) collectors deployed over reservoirs and treatment basins to simultaneously generate electricity, provide thermal energy for cooling, and enhance water quality regulation. The proposed system couples floating collectors with absorption based chillers and membrane based treatment units, enabling synergistic operation that reduces grid dependence and operational emissions. A dynamic model of the hybrid plant is developed and validated with site specific meteorological and hydrological data, demonstrating improvements in cooling capacity, water production efficiency, and overall energy to water ratio. The study further evaluates reliability, levelized cost, and environmental impact, highlighting the potential of floating solar collectors as a scalable, eco friendly technology for advanced solar heating and cooling applications in industrial and municipal water sectors.

Keywords: *Floating Solar Collectors, Photovoltaic-Thermal (PV-T) Systems, Floating Photovoltaic (FPV), Thermal Energy Integration, Renewable Energy-Water Nexus.*



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1. Introduction

Floating solar collectors have emerged as a versatile and resource-efficient solution at the intersection of renewable energy, thermal management, and water infrastructure. Unlike

conventional ground-mounted systems, floating solar platforms utilize underutilized water surfaces such as reservoirs, ponds, and treatment basins, thereby avoiding land-use conflicts and simultaneously improving photovoltaic

performance through natural water-cooling effects. Recent advances in buoyant structural design, corrosion-resistant materials, and hybrid photovoltaic-thermal (PV-T) layouts have significantly expanded their potential beyond simple electricity generation. In the context of solar heating and cooling, floating collectors can supply both low-grade thermal energy for absorption or adsorption chillers and electrical power for auxiliary pumps, controls, and treatment units [1]. This dual capability makes them particularly attractive for industrial and municipal facilities that require reliable cooling and high-quality water in parallel. As global water stress and cooling demand rise, integrating floating solar collectors into hybrid energy–water systems offer a sustainable pathway to decarbonize heating, cooling, and water treatment operations simultaneously.

1.1 Motivation and scope of floating solar collectors

The motivation for studying floating solar collectors stems from the growing need to reconcile renewable-energy expansion with land-use constraints, water conservation, and thermal-management challenges. Land-intensive solar farms often compete with agriculture, urbanization, and natural ecosystems, creating social and regulatory barriers to rapid deployment [2]. In contrast, floating systems exploit otherwise unproductive water bodies, turning them into multi-functional assets that generate power, reduce evaporation, and sometimes even improve water quality.

The scope of this work extends beyond basic electricity production to include the thermal behaviour of floating PV-T arrays, their interaction with surrounding water, and their role as primary energy sources for downstream cooling and treatment processes. By examining diverse deployment scenarios municipal reservoirs, cooling ponds, wastewater lagoons, and desalination basins the study aims to map the technical and economic envelope within which floating collectors become technically viable and economically attractive [3]. Special attention is paid to harsh environmental conditions such as high humidity, algae growth, and fluctuating water levels, which influence long-term reliability and system design. The overall goal is to position floating solar collectors as a core enabler of

next-generation solar heating and cooling infrastructures that are compact, water-smart, and resilient.

1.2 Role in solar heating and cooling systems

Within modern solar heating and cooling systems, floating collectors act as distributed, hybrid energy nodes that supply both electrical and thermal energy to chiller plants, heat pumps, and storage loops. When configured as PV-T arrays, they can deliver electricity to drive compressors, pumps, and sensors while simultaneously providing warm fluid streams suitable for absorption or adsorption chillers, heat exchangers, or preheating loads [4]. By absorbing solar irradiance directly over water, these collectors also benefit from an inherent cooling effect that moderates cell temperature and enhances electrical efficiency, in contrast to land-based systems that suffer from higher ambient temperatures and limited passive cooling.

This thermally-favourable environment supports higher power output per unit area and smoother operation under partial shading or dusty conditions. On the heating side, floating collectors can preheat feedwater for industrial processes or domestic hot-water systems, thereby reducing the burden on fossil-fuel-based boilers [5]. On the cooling side, integrated systems can drive solar-assisted chillers to maintain optimal temperatures in HVAC, data centres, and industrial cooling loops. Overall, the role of floating solar collectors is to transform passive water bodies into active, multi-energy surfaces that bridge the gap between solar availability and the thermal demands of urban and industrial environments.

1.3 Integration with hybrid cooling and water treatment plants

The integration of floating solar collectors into hybrid cooling and water treatment plants represents a paradigm shift from single-purpose infrastructure to synergistic, multi-output systems. In such plants, the same water body serves at once as a mechanical support for solar arrays, a heat sink for PV-cooling, a reservoir for process water, and a boundary for treatment units such as membrane filtration, disinfection, and evaporation-based desalination [6]. By aligning the location and thermal profile of floating collectors with the hydraulic and thermal layout of the treatment train, it becomes possible to recover

waste heat, reduce pumping energy, and optimize temperature-sensitive processes such as reverse osmosis or biological treatment.

For example, solar-heated water can be used to pre-warm influent streams entering absorption chillers or to enhance the kinetics of chemical coagulation and disinfection, while excess cooling capacity can be directed toward maintaining water-quality parameters such as dissolved oxygen or microbial counts [7]. Control strategies can then coordinate solar generation, cooling demand, and water-treatment schedules to minimize grid reliance and peak-load exposure. This level of integration not only improves energy efficiency but also creates a closed-loop synergy where solar energy, cooling, and water services are co-optimized at the system level, paving the way for highly compact and resilient utility plants.

1.4 Objective and structure of the paper

The primary objective of this paper is to develop, analyse, and validate a comprehensive framework for deploying floating solar collectors in hybrid cooling and water treatment plants, with an emphasis on system architecture, dynamic performance, reliability, and economic viability. Specifically, the study aims to propose a scalable configuration of floating PV-T collectors compatible with existing water-treatment infrastructure, model the coupled thermal, electrical, and hydraulic behaviour of the hybrid plant under realistic operating conditions, quantify energy-saving, emission-reduction, and water-conservation benefits relative to conventional systems, and assess the techno-economic feasibility and scalability of the approach across different climatic and industrial contexts [8]. To achieve these goals, the paper is structured in a logical progression, it begins with an introduction and motivation, followed by a review of related technologies and system concepts, then presents the detailed design and modelling of the floating collectors and hybrid cooling loop.

Subsequent sections describe the integration with water treatment processes, control strategies, and a full-scale case-study evaluation, culminating in reliability, safety, and economic analyses and concluding with research directions and deployment recommendations [9]. Through this structured approach, the paper seeks to provide both conceptual clarity and practical guidelines for

engineers and policymakers aiming to adopt floating solar collectors in next-generation solar heating and cooling applications.

2. Background and State of the Art

Conventional solar heating and cooling technologies have matured over the past several decades, but integration with water-treatment infrastructure remains limited. Recent advances in floating photovoltaic and thermal collectors have opened new opportunities for co-locating energy generation with cooling and water-quality services [10]. Hybrid cooling systems, particularly those tailored for water treatment plants, are now evolving toward multi-energy integration, where solar-derived heat and electricity support both thermal loads and process requirements.

At the same time, current floating-collector applications exhibit several gaps, including fragmented system designs, limited dynamic-performance data, and underexplored synergies with water treatment [11]. This section reviews the established technologies, emerging trends in floating collectors, and the specific challenges and limitations that motivate the proposed integrated approach for hybrid cooling and water treatment plants.

2.1 Conventional solar heating and cooling technologies

Conventional solar heating and cooling technologies primarily rely on rooftop or ground-mounted flat-plate and evacuated tube collectors for space heating and domestic hot water, with solar-assisted absorption or adsorption chillers used for cooling applications. These systems typically operate as standalone or grid-backed installations, supplying thermal energy to buildings, district heating networks, or industrial processes [12]. Over the years, improvements in collector efficiency, storage strategies, and control algorithms have enhanced their reliability and seasonal performance. However, most conventional systems are designed for relatively uniform thermal loads and do not naturally integrate with water treatment or process-cooling requirements.

In many cases, solar heat is either stored in large tanks or dumped during periods of low demand, leading to suboptimal utilization. Furthermore, the geographic spread of such installations often lacks coordination with

industrial or municipal water-treatment facilities, missing the opportunity to combine heating, cooling, and water services in a single infrastructure [13]. This limitation has motivated researchers to explore alternative deployment strategies that couple solar thermal and photovoltaic resources with process-intensive water systems.

2.2 Floating photovoltaic and thermal collectors: current trends

Floating photovoltaic (FPV) and photovoltaic-thermal (PV-T) collectors have emerged as promising technologies that leverage water bodies for both energy generation and thermal management. Recent trends show a rapid increase in FPV deployments over reservoirs, lakes, and wastewater ponds, driven by land-saving benefits, improved electrical efficiency due to water-cooling, and additional environmental advantages such as reduced evaporation and algal growth [14]. Modern floating platforms incorporate corrosion-resistant materials, modular buoyant structures, and advanced anchoring systems that enhance stability under wind and wave loading.

On the thermal side, PV-T collectors capture waste heat from solar cells and transfer it to water or glycol loops, creating a dual-output system that can supply both electricity and low-grade heat. Current research focuses on optimizing heat-exchanger layouts, evaluating long-term degradation under humid and saline conditions, and integrating floating arrays with nearby loads such as pumping stations, HVAC systems, or industrial cooling circuits [15]. Despite these advances, most applications emphasize power production, with only limited efforts directed at fully exploiting floating collectors for solar heating and cooling or water-treatment integration. This under-utilization highlights the need for system-level designs that explicitly couple floating collectors with process-oriented thermal and water services.

2.3 Hybrid cooling systems for water treatment plants

Hybrid cooling systems for water treatment plants combine multiple energy sources such as solar, waste heat, and grid electricity to meet the thermal and hydraulic demands of treatment processes. Many modern plants employ

chiller-based or absorption-based cooling loops to regulate water temperature, prevent scaling, and maintain suitable biological conditions. Hybrid schemes often integrate solar-driven absorption chillers, heat pumps, or air-cooled condensers with conventional mechanical cooling systems, enabling flexible operation under varying solar availability and load profiles [16]. In the context of water treatment, precise temperature control can improve the efficiency of membrane filtration, disinfection, and evaporation-based processes, while reducing chemical consumption and energy intensity.

Recent studies have demonstrated that hybrid cooling can lower peak-load exposure and operational costs, but most deployments remain isolated from renewable-energy generation infrastructure. Moreover, existing designs rarely exploit the spatial proximity of treatment basins and cooling surfaces to integrate floating collectors directly into the cooling loop [17]. This disconnect between energy supply and water treatment emphasizes the need for a holistic framework that embeds floating solar collectors within the thermal and hydraulic architecture of hybrid cooling systems.

2.4 Gaps and limitations in existing floating-collector applications

Despite rapid progress in floating photovoltaic and thermal technologies, several critical gaps and limitations persist in existing applications. First, system designs are often oriented toward maximizing electricity output, with only rudimentary consideration of thermal recovery or integration with process loads such as cooling and water treatment [18]. Second, there is a lack of standardized modelling and performance databases for floating PV-T systems in diverse climatic and water-quality conditions, making it difficult to generalize design rules or optimize deployment strategies. Third, many floating-collector projects remain small-scale pilots, with limited long-term operational data on reliability, fouling, anchor integrity, and maintenance complexity over water.

Fourth, control strategies are typically confined to electrical generation and grid-interaction, omitting coordinated management of thermal and water-related objectives such as temperature-sensitive treatment processes or evaporation reduction

[19]. Finally, techno-economic analyses often focus narrowly on power-generation economics, neglecting the additional value streams from water-quality improvement, cooling provision, and emission reduction. These gaps create a clear opportunity to develop a more integrated, process-oriented approach that aligns floating solar collectors with the specific operational and environmental requirements of hybrid cooling and water treatment plants.

3. System Concept and Architecture

The proposed system concept reimagines water treatment basins as multi-functional energy-water surfaces by integrating floating solar collectors with hybrid cooling loops and treatment units. Instead of treating the basin solely as a hydraulic reservoir, the architecture embeds buoyant photovoltaic-thermal (PV-T) arrays that simultaneously generate electricity, capture waste heat, and influence local water conditions [20].

The hybrid cooling loop is thermally coupled to these collectors, using solar-derived heat and power to drive absorption or adsorption chillers, heat exchangers, and auxiliary pumps.

On the treatment side, the cooled or preheated water streams are routed through membrane filtration, disinfection, and/or desalination units, exploiting temperature-sensitive process windows to enhance efficiency and reduce chemical demand. A centralized control framework coordinates electrical generation, thermal dispatch, and treatment schedules, ensuring that the plant operates within desired temperature, pressure, and water-quality constraints while minimizing grid reliance [21]. This architecture transforms a conventional water treatment facility into a compact, solar-driven energy-water nexus capable of supplying cooling, clean water, and renewable power within a single integrated layout.

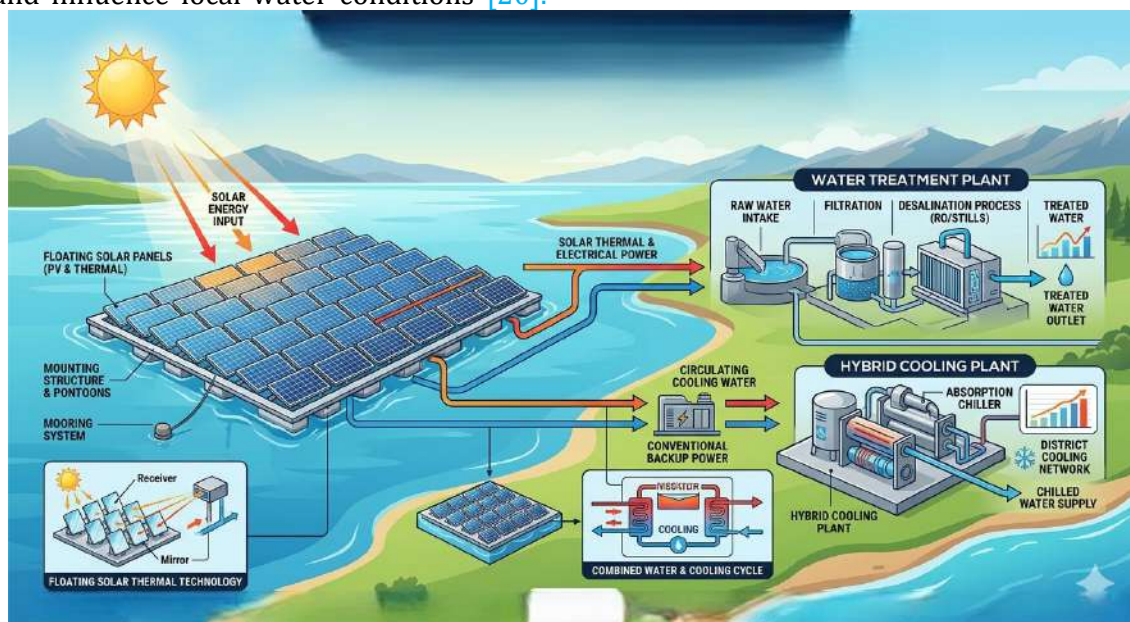


Figure1. Floating solar collector

3.1 Overview of floating solar collector configurations

Floating solar collector configurations are designed to balance structural stability, thermal performance, and ease of maintenance over water bodies such as reservoirs, cooling ponds, and treatment lagoons. Typical layouts include modular PV-T rafts anchored in arrays, with each module composed of a floating frame, photovoltaic panels, and an embedded heat-exchange layer that transfers solar-induced heat into the underlying

water or a closed-loop fluid circuit [22]. Some configurations incorporate concentrating elements or reflectors to enhance thermal output, while others prioritize purely electrical generation with passive cooling via the water surface.

Advanced designs also integrate bifacial PV modules, where the rear side captures reflected light from the water, further increasing energy yield. The spacing between modules is carefully optimized to avoid excessive shading, facilitate maintenance boats, and allow adequate water

circulation for natural cooling and oxygenation [23]. In addition to standard flat layouts, researchers have explored segmented or curved arrays that adapt to bathymetry and wave patterns, improving load distribution and reducing mechanical stress. These diverse configurations share a common goal, to maximize dual-use potential by converting open water surfaces into productive energy and thermal nodes that can be coupled with adjacent cooling and treatment processes.

3.2 Hybrid cooling loop integration with water treatment units

The hybrid cooling loop is tightly integrated with water treatment units to create a synergistic thermal-hydraulic network that leverages floating solar collectors as primary energy sources. In this architecture, solar-heated fluid streams from PV-T arrays or adjacent solar thermal collectors are routed to absorption or adsorption chillers, which use the thermal energy to produce chilled water for process cooling, HVAC, or temperature control in treatment units [24]. The chillers interact with the same water body or a dedicated cooling loop that feeds into membrane filtration, disinfection, or desalination trains, where maintaining a stable, slightly cooled or preheated temperature improves flux rates, reduces fouling, and enhances disinfection kinetics.

Excess cooling capacity can be diverted to auxiliary loads such as pumps, compressors, or data-centre equipment, while surplus heat can be stored in stratified tanks or used for preheating feedwater. The integration also includes control valves and bypass circuits that dynamically redirect flows based on solar availability, cooling demand, and water-treatment requirements [25]. This tight coupling ensures that the plant does not operate as a set of isolated subsystems but as a unified, responsive infrastructure where energy and water services are co-optimized in real time.

3.3 Thermal and electrical energy flows in the plant

Within the plant, thermal and electrical energy flows are carefully choreographed to match the intermittent nature of solar irradiance with the steady or time-varying demands of cooling and water treatment. Electrically, floating PV arrays feed direct current that is converted to alternating current via inverters and distributed to pumps,

sensors, control systems, and auxiliary chillers, with surplus power exported to the grid or stored in batteries [26]. Thermal energy is captured in PV-T or dedicated solar thermal loops, where warm fluid is circulated to absorption chillers, heat exchangers, or preheating tanks, reducing the need for fossil-fuel-based boilers or electric heaters.

Part of the thermal energy may also be rejected to the water body itself, where it contributes to localized stratification or temperature buffering, while carefully managed to avoid adverse ecological impacts. Heat-recovery paths are integrated so that condenser or waste-heat streams from chillers are reused in low-temperature processes or preheating stages, closing energy loops within the plant [27]. The result is a multi-path energy network where solar-derived electricity and heat are dynamically routed, stored, or shared among cooling, treatment, and auxiliary loads, enabling flexible, demand-responsive operation that aligns with the overarching goals of energy efficiency and sustainability.

3.4 Control strategy framework for hybrid operation

The control strategy framework for hybrid operation is built around a supervisory layer that coordinates the floating solar collectors, hybrid cooling loop, and water treatment units in real time. This framework employs a hierarchical model, at the lowest level, local controllers manage individual inverters, pumps, valves, and chillers, maintaining setpoints for voltage, flow rate, and temperature [28]. At the supervisory level, an optimization-based controller uses weather forecasts, real-time sensor data, and short-term load profiles to schedule energy flows, switch between cooling modes (solar-dominated vs grid-supported), and adjust treatment parameters such as filtration rate or chemical dosing.

The framework incorporates predictive rules that anticipate cloud transients and demand spikes, temporarily shifting loads or storing excess energy in thermal or electrical buffers. Safety interlocks ensure that the plant never exceeds permissible temperature, pressure, or chemical-concentration limits, even under abnormal solar or grid conditions [29]. By embedding feedback loops that continuously

compare actual performance with target metrics such as energy-to-water ratio, carbon intensity, and operational cost, the control strategy enables adaptive, robust hybrid operation that maximizes the synergies between floating solar collectors, cooling, and water treatment.

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (1)$$

This PID form is a standard control law for hybrid supervisory regulation.

4. Design of Floating Solar Collectors

The design of floating solar collectors must simultaneously satisfy electrical performance, thermal efficiency, structural stability, and long-term durability in harsh aquatic environments. Unlike ground-mounted systems, floating arrays are exposed to dynamic loads from wind, waves, and water currents, which influence module inclination, anchoring requirements, and maintenance access [30]. The design process typically begins with selecting an appropriate platform geometry and anchoring scheme that minimize tilting and avoid mechanical stress on PV modules and piping.

Thermal and electrical integration is then optimized to ensure that the collector can supply both power and low-grade heat to downstream cooling and treatment units without compromising efficiency or safety. Careful attention is paid to material compatibility, corrosion protection, and ecological impact, ensuring that the installation remains robust over decades of operation while minimizing its footprint on the water body [31]. This section outlines the key design dimensions structural and hydrodynamic behaviour, PV-thermal and concentrating options, material choices, and thermal modelling needed to realize high-performance floating collectors for hybrid cooling and water treatment plants.

4.1 Structural and hydrodynamic design considerations

Structural and hydrodynamic design considerations are central to the safe and efficient deployment of floating solar collectors over water bodies. The platform must resist static and dynamic loads, including the weight of modules and piping, buoyancy forces, wind pressure, wave

action, and occasional ice or debris impact in colder climates. Modular raft-type structures are commonly used, with interconnected pontoons or extruded frames that distribute loads evenly and allow for incremental expansion [32]. The spacing between modules and the orientation of the array influence the hydrodynamic response tighter layouts can reduce wave penetration but may increase local stress concentrations, while larger gaps improve water circulation and cooling but require stronger anchoring.

Anchoring systems such as catenary chains, buoyant mooring lines, or fixed-base piles must be tailored to the local bathymetry and water-level fluctuations to prevent drifting or over-tensioning [33]. Stability analyses are performed to ensure that the array remains within acceptable tilt and pitch angles under design storm conditions, and access walkways or maintenance corridors are integrated to enable visual inspection and equipment servicing. These structural and hydrodynamic choices directly affect both the lifetime of the installation and the reliability of its contribution to hybrid cooling and water treatment systems.

4.2 PV-thermal and concentrating floating collector options

PV-thermal (PV-T) and concentrating floating collector options provide distinct pathways to enhance the energy output and thermal utility of floating solar arrays. In conventional PV-T configurations, a heat-exchange layer is attached to the rear of the PV modules, capturing waste heat that would otherwise increase cell temperature and reduce electrical efficiency [34]. The heated fluid is then available for driving absorption chillers, preheating feedwater, or supporting low-temperature industrial processes. Floating implementations of PV-T can take advantage of the natural water-cooling effect, which helps maintain a more favourable temperature gradient and improves both electrical and thermal performance.

Concentrating floating collectors, on the other hand, employ mirrors or lenses to focus solar irradiance onto high-efficiency PV or thermal receivers, boosting energy density per unit area but introducing additional complexity in tracking and alignment. These systems may use single-axis or dual-axis trackers mounted on buoyant

platforms, or they may adopt fixed-tilt concentrating geometries that are less sensitive to platform motion [35]. The choice between PV-T and concentrating options depends on the

available water-surface area, local irradiance levels, and the relative demand for electricity versus thermal energy in the hybrid cooling and water treatment plant.

Table 1. Comparison of PV-Thermal and Concentrating Floating Collector Options

Collector option	Working principle	Thermal output	Electrical output	Typical advantages	Main limitations
Flat-plate floating PVT	PV modules are coupled to a rear thermal absorber that removes heat while collecting useful thermal energy.	Low to medium temperature heat.	Moderate electricity with improved cell cooling.	Simple, mature, and suitable for floating integration.	Thermal and electrical functions are strongly coupled, so high thermal output can reduce PV performance.
Concentrating PVT with reflector or trough	Mirrors, reflectors, or trough optics concentrate sunlight onto PV cells and a thermal receiver.	Medium to high temperature heat.	Higher electrical output per cell area under concentration.	Better total energy density and compact collector area.	Requires tracking, optical alignment, and careful heat rejection. academic.oup+1
Spectral-splitting concentrating PVT	Sunlight is concentrated and divided by wavelength so part goes to PV and the rest to thermal collection.	Can reach high-temperature thermal output.	High electrical efficiency when a suitable cell/filter pair is used.	Better separation of electrical and thermal functions than conventional PVT.	More complex optics and higher cost than flat-plate designs.
Floating V-trough / asymmetric concentrator	Uses fixed or low-tracking reflecting surfaces to increase irradiance on the PV absorber.	Useful low-to-medium thermal recovery.	Improved electrical yield compared with flat modules.	Simpler than full tracking concentrator.	Still needs accurate geometry and durable reflective materials in marine environments.

4.3 Material selection for durability and corrosion resistance

Material selection plays a critical role in ensuring the long-term durability and corrosion resistance of floating solar collectors exposed to humid, saline, or chemically treated water

environments. The platform structure is typically fabricated from high-density polyethylene (HDPE), cross-linked polyethylene (PEX), or corrosion-resistant aluminium alloys, which offer a favourable strength-to-weight ratio and resilience to UV radiation and biological fouling

[36]. Fasteners, connectors, and support hardware are often made from stainless steel grades such as 316 or duplex alloys, which resist pitting and crevice corrosion in saline or brackish conditions.

Electrical components must be encapsulated or housed in waterproof enclosures with appropriate ingress protection (IP) ratings to prevent short circuits or insulation degradation. The back sheet and encapsulant materials of PV modules are chosen to withstand prolonged exposure to water vapor, UV radiation, and temperature cycling, while the PV-T heat-exchange layer is fabricated from materials such as aluminium or stainless-steel tubing with non-corrosive coatings or liners [37]. Protective measures such as sacrificial anodes, cathodic protection, or anti-fouling coatings may also be applied to submerged surfaces to mitigate biofouling and galvanic corrosion. By carefully matching materials to the local water chemistry and climate, designers can significantly extend the operational lifetime of floating collectors while minimizing maintenance costs and ecological impact.

$$\eta_{PVT} = \frac{Q_u + P_e}{GA} \quad (2)$$

This represents combined thermal and electrical efficiency for a PVT-type collector.

4.4 Thermal performance modelling of floating collectors

Thermal performance modelling of floating collectors is essential for predicting how these systems behave under varying solar irradiance, ambient temperature, water conditions, and operational loads. A typical modelling approach combines an electrical model of the PV cells with a thermal model of the module and its heat-exchange layer, accounting for radiative, convective, and conductive heat transfer paths [38]. The model incorporates the cooling effect of the underlying water body, which acts as a heat sink and can be represented as a convective or conductive boundary condition whose properties depend on water temperature, flow velocity, and mixing.

For PV-T configurations, the model tracks the temperature of the working fluid (e.g., water or glycol) as it passes through the collector, relating it to the incident solar flux and the mass flow rate. The resulting thermal efficiency curves are then

used to size the collector array, select appropriate chiller or heat-recovery units, and estimate the available cooling or preheating capacity [39]. Dynamic simulations can further evaluate the system's response to transient events such as cloud passing, start-up/shutdown cycles, or changes in water level, providing insights into the variability of thermal output and the need for auxiliary energy sources. By integrating these models with the overall plant simulation, designers can optimize the thermal performance of floating solar collectors within the context of hybrid cooling and water treatment operations.

5. Hybrid Cooling Integration

Hybrid cooling integration couples floating solar collectors with thermal and electrical cooling systems to supply stable, low-carbon cooling services to water treatment and auxiliary loads. In this architecture, solar-derived heat and power are used to drive absorption or adsorption chillers, while the natural water-cooling effect of the floating platform enhances electrical efficiency and reduces auxiliary cooling demand [40]. The hybrid setup allows the plant to switch between solar-dominated operation during peak irradiance and grid-assisted or storage-supported modes when solar availability is low.

Cooling loops are thermally linked to treatment units, enabling temperature control that improves filtration, disinfection, and desalination performance. Dynamic modelling and control ensure that the hybrid system tracks cooling demand in real time while maintaining efficient use of solar energy and minimizing grid-import peaks [41]. This section outlines key integration pathways solar-driven absorption/adsorption chillers, direct use of floating-collector-heated fluids, water-air heat exchange in treatment plants, and dynamic performance modelling to realize a robust and adaptive hybrid cooling system.

5.1 Absorption and adsorption cooling driven by solar heat

Absorption and adsorption cooling technologies are well-suited drivers for hybrid cooling when paired with floating solar collectors, as they can convert low-grade solar heat into useful cooling capacity. Absorption chillers use a refrigerant-absorbent pair (typically water-

lithium bromide or ammonia–water) where solar heat energizes the generator, releasing refrigerant vapor that condenses, expands, and evaporates to produce chilled water [42]. Adsorption chillers, in contrast, employ solid sorbents such as silica gel or zeolites that cyclically adsorb and desorb refrigerant (often water) under changing temperature and pressure conditions.

Both technologies can operate efficiently with the 60–90 °C temperature range commonly attainable from solar thermal or PV–T collectors mounted on floating platforms. In the proposed hybrid plant, the heated fluid from the floating collectors is routed to the generator or heating circuit of the chiller, replacing or supplementing fossil-fuel-based heat sources and significantly reducing the plant’s carbon footprint [43]. The chilled water produced is then distributed to cooling coils, process heat exchangers, or treatment units, enabling temperature-sensitive operations such as membrane filtration or biological treatment. By matching the chiller’s operating window with the floating collector’s thermal output, the system can achieve high solar fraction and smooth operation over daily and seasonal cycles.

5.2 Direct hybrid cooling using floating-collector-heated fluids

In addition to driving conventional chillers, floating solar collectors can support direct hybrid cooling, where the solar-heated fluid itself is used as part of the cooling loop or as a pre-treatment source. In this scheme, the warm working fluid from PV–T or solar thermal collectors circulates through a heat-rejection side of a hybrid chiller or into a stratified thermal storage tank, from which energy is drawn as needed [44]. During periods of high solar input, excess heat can be dissipated through water–air heat exchangers or radiative cooling surfaces, effectively “dumping” surplus energy while still maintaining the required temperature window for downstream processes.

Conversely, when solar input is limited, the stored heat can be recovered to continue chiller operation or to preheat incoming water, reducing the need for additional energy input. Direct hybrid cooling can also be implemented via indirect heat-exchanger loops, where the floating-collector fluid heats or cools a secondary medium that interfaces with the treatment train or HVAC system [45]. This approach simplifies the

integration of solar energy into existing cooling infrastructure and avoids the need for large additional chillers, making it particularly attractive for retrofitting water treatment plants with floating solar collectors.

5.3 Water–air heat exchange loops in treatment plants

Water–air heat exchange loops form an essential link between floating solar collectors, hybrid chillers, and the treatment-process environment in water treatment plants. These loops typically consist of plate heat exchangers, shell-and-tube units, or coil-type systems that transfer heat between solar-heated or chilled water and air streams used for ventilation, process cooling, or temperature control in treatment halls [46]. In membrane or reverse-osmosis-based plants, maintaining a controlled water temperature improves flux and reduces fouling, while in biological treatment units, stable air and water temperatures enhance microbial activity and treatment efficiency.

Floating-collector-driven water–air heat exchangers can be integrated into cooling towers, evaporative condensers, or air-handling units, allowing the plant to share thermal resources between electricity generation, cooling, and climate control [47]. During hot periods, the system can extract heat from the air and transfer it back into the water or to storage, while in cooler conditions it can recover heat from the water to preheat air or feedwater. Control strategies can dynamically modulate flow rates and bypass ratios to balance heat-rejection needs with solar-collector performance and water-quality constraints, ensuring that the water–air heat exchange loops contribute to both thermal comfort and process optimization.

5.4 Dynamic modelling and simulation of hybrid cooling performance

Dynamic modelling and simulation of hybrid cooling performance are critical for predicting how the integrated system behaves under realistic operating conditions. The model typically couples the thermal behaviour of the floating solar collectors with the transient response of absorption/adsorption chillers, water–air heat exchangers, storage tanks, and treatment-process units [48]. Solar irradiance, ambient temperature, wind speed, water temperature, and cooling

demand are all treated as time-varying inputs, enabling the simulation of diurnal and seasonal cycles.

The model tracks key performance indicators such as cooling capacity, coefficient of performance (COP), solar fraction, and grid-electricity consumption, providing insights into how the system performs under different weather patterns and operational scenarios. Simulation tools can also evaluate the impact of control strategies, such as predictive set-point adjustment, storage charge/discharge, and load-shifting, on overall efficiency and reliability [49]. By validating the model against field data or scaled-down test rigs, designers can identify bottlenecks, optimize component sizing, and refine the control logic to ensure that the hybrid cooling system delivers stable, high-quality cooling services while maximizing the contribution of floating solar energy.

$$C \frac{dT}{dt} = Q_{in} - Q_{out} \quad [3]$$

This lumped-capacitance model is a good first-order dynamic representation [69].

6. Water Treatment Plant Integration

Integrating floating solar collectors with water treatment plants enables synergies between solar-driven cooling, water-quality management, and process efficiency. In this architecture, the thermal and electrical outputs from the floating collectors are directed to support membrane filtration, desalination, chemical treatment, and biological processes, all of which benefit from controlled temperature and stable energy supply [50]. Cooling-driven improvements enhance membrane performance, reduce fouling, and lower chemical consumption, while solar-assisted desalination and wastewater treatment schemes reduce reliance on grid electricity and fossil-fuel-based heat sources.

The plant can also co-produce fresh water and cooling energy, turning the same infrastructure into a dual-service asset [51]. An energy and water balance analysis then quantifies the net gains in efficiency, resource utilization, and emissions reduction, providing a clear basis for evaluating the techno-economic viability of the integrated system. This section describes how cooling, desalination, and treatment processes interact with the hybrid plant and how the

resulting energy–water nexus can be modelled and optimized.

6.1 Cooling-driven improvements in membrane and chemical processes

Cooling-driven improvements in membrane and chemical treatment processes stem from the ability of hybrid cooling systems to maintain stable, optimized water and air temperatures throughout the treatment train. In membrane filtration units such as reverse osmosis (RO) and ultrafiltration (UF), temperature has a direct impact on permeate flux, fouling rate, and energy consumption slightly elevated temperatures can increase flux but also accelerate scaling and organic fouling, while cooler feedwater improves stability at the expense of lower throughput [52]. By integrating solar-driven chillers and float-based heat exchangers, the plant can regulate the feedwater temperature within the ideal range, balancing flux and fouling for specific membrane materials and feedwater compositions.

Similarly, in chemical treatment processes such as coagulation, flocculation, and disinfection, temperature influence's reaction kinetics and chemical dosing requirements. Cooling-assisted chemical units can operate at lower temperatures, reducing the need for oxidant and disinfectant chemicals while still achieving target microbial kill rates [53]. The hybrid cooling system can also provide tempered air for ventilation and headspace control, further improving the stability of chemical and biological processes. By coordinating cooling with solar input, the plant can exploit excess solar energy during midday to pre-cool or pre-heat streams, thereby smoothing daily load profiles and improving overall treatment efficiency.

6.2 Solar-assisted desalination and wastewater treatment schemes

Solar-assisted desalination and wastewater treatment schemes leverage the floating solar collectors' thermal and electrical outputs to drive energy-intensive processes such as membrane distillation, multi-effect desalination, and advanced oxidation. In desalination applications, solar-heated water from the collectors can supply low-grade heat to membrane-distillation modules or multi-stage flash units, reducing the need for fossil-fuel-based steam or electric heaters [54]. Alternatively, solar-driven absorption chillers can

provide cooling to support crystallization-based desalination or evaporative concentration processes, where maintaining a controlled temperature differential improves water recovery and salt separation.

In wastewater treatment, solar-assisted schemes can power electrochemical processes, UV disinfection, or advanced oxidation technologies that require both electricity and carefully controlled temperature conditions. The hybrid plant can also integrate solar-heated thermal loops with anaerobic digesters or biological treatment basins, where modest temperature increases can enhance biogas production and microbial activity without jeopardizing process stability [55]. By aligning the timing of solar availability with high-energy treatment steps such as peak-day desalination or oxidation cycles the system can significantly reduce grid-dependence while maintaining or even improving water-quality targets. These solar-assisted schemes demonstrate how floating collectors can transform treatment plants into multi-purpose facilities that co-utilize solar energy for both water purification and cooling services.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad [4]$$

This mass-balance relation is the base equation for coupled water and process streams.

6.3 Co-production of fresh water and cooling energy

Co-production of fresh water and cooling energy is a key feature of the integrated system, where the same floating solar collectors and hybrid cooling loops simultaneously support desalination, wastewater treatment, and cooling services. In co-production scenarios, solar-heated water from the collectors is used to generate cooling via absorption or adsorption chillers, while the rejected or residual heat is reused in membrane distillation, evaporation, or pre-heating of treatment streams [56]. This dual-use approach maximizes energy utilization and reduces the need for separate heating and cooling infrastructures.

For example, a desalination plant integrated with solar-driven cooling can produce both potable water and chilled water for HVAC or industrial cooling, supplying multiple services from a single energy source. Similarly, in wastewater treatment, the treated effluent can be used as a heat sink or cooling medium for the hybrid cooling loop, while the recycled water is

made available for irrigation or industrial reuse [57]. The co-production concept can be extended to hybrid configurations that combine solar-driven desalination, membrane filtration, and chemical treatment, creating a closed-loop system where fresh water and cooling energy are generated in tandem with minimal waste. By carefully designing the energy and water flows, the plant can achieve a favourable energy-to-water ratio and significantly reduce its carbon footprint.

6.4 Energy and water balance analysis of the hybrid plant

Energy and water balance analysis of the hybrid plant quantifies the net gains in efficiency, resource utilization, and emissions reduction achieved through integration of floating solar collectors with cooling and water treatment processes. The energy balance tracks all incoming and outgoing energy flows, including solar irradiance captured by the floating collectors, electrical energy generated and consumed, thermal energy supplied to chillers and treatment units, and energy rejected to the environment or stored in thermal buffers [58]. The water balance similarly accounts for inflows such as raw feedwater, wastewater, and makeup water, as well as outflows such as treated water, reject streams, and evaporative losses.

By comparing these balances over daily and seasonal cycles, the analysis reveals how much of the cooling demand is met by solar energy, how much grid electricity is displaced, and how much water is recovered or reused. Additional metrics such as energy recovery ratio, specific energy consumption per cubic meter of treated water, and carbon intensity per unit of cooling can be derived to evaluate the plant's sustainability [59]. The energy and water balance also identifies potential bottlenecks such as storage limitations or mismatched demand profiles and guides design improvements, such as optimizing collector area, adjusting storage capacity, or revising control strategies. This holistic analysis provides a comprehensive assessment of the hybrid plant's performance and supports decision-making for scaling and replication in other locations.

7. Control, Monitoring, and Grid Interaction

Effective control, monitoring, and grid-interaction strategies are essential to ensure the safe, reliable, and efficient operation of

floating-collector-based hybrid cooling and water treatment plants. A supervisory control architecture coordinates the dynamic behaviour of solar generation, cooling loops, and treatment processes, aligning them with real-time energy availability and demand. Sensors deployed across the floating collectors and treatment units provide continuous data on temperature, flow, irradiance, water quality, and electrical performance, enabling adaptive control and early fault detection [60]. In harsh aquatic environments, specialized monitoring techniques help identify degradation, fouling, and mechanical wear before they compromise system integrity. The plant can operate in grid-connected mode, feeding surplus solar power into the distribution network, or in off-grid mode, relying on energy storage and backup systems to maintain continuous cooling and water services. This section describes the key elements of the control and monitoring framework, focusing on supervisory architecture, sensor deployment, fault detection, and grid-interaction strategies.

7.1 Supervisory control architecture for hybrid operation

The supervisory control architecture for hybrid operation is designed to coordinate the interactions between floating solar collectors, hybrid cooling systems, water treatment units, and the external grid. This architecture typically follows a hierarchical structure, with local controllers managing individual components such as inverters, pumps, chillers, and valves, and a supervisory controller overseeing the overall system behaviour [61]. The supervisory controller uses real-time data from sensors, weather forecasts, and historical performance to optimize the allocation of solar energy between electrical generation, thermal cooling, and water treatment processes.

It can adjust setpoints for temperature, flow rate, and storage levels based on predicted solar availability and cooling demand, ensuring that the plant operates within safe and efficient limits. The architecture also includes predictive control algorithms that anticipate transient events such as cloud cover, maintenance outages, or sudden increases in water demand, enabling the plant to pre-charge storage or shift loads to maintain stability [62]. Communication protocols such as Modbus, CAN-bus, or Ethernet-based systems

facilitate seamless data exchange between components, while cybersecurity measures protect the control network from cyber threats. By integrating these elements, the supervisory control architecture enables the hybrid plant to operate as a flexible, responsive, and resilient energy–water nexus.

$$x_{k+1} = Ax_k + Bu_k \quad [5]$$

This state-space model is a standard basis for supervisory hybrid control.

7.2 Sensor placement and data acquisition for floating collectors

Sensor placement and data acquisition for floating collectors are critical to understanding the performance, behaviour, and environmental impact of the system. Key sensors are strategically located on the floating platforms, within the PV–T arrays, and along the cooling and water treatment loops to capture a comprehensive picture of system operation. Irradiance sensors measure solar intensity, while temperature sensors monitor module surface temperature, working fluid temperature, and ambient air temperature [63]. Flow meters and pressure sensors track the circulation of cooling fluid, while electrical sensors record voltage, current, and power output from the PV arrays and inverters.

Water-quality sensors such as pH, conductivity, and turbidity meters provide information on the impact of the floating collectors on the water body. Data from these sensors are collected and transmitted to a central data acquisition system, which stores and processes the information in real time. Wireless communication technologies such as Wi-Fi, LoRa, or cellular networks enable remote monitoring and control, even in remote or hard-to-reach locations. The data acquisition system can also integrate with cloud-based platforms for advanced analytics, visualization, and long-term trend analysis, facilitating predictive maintenance and performance optimization. By carefully selecting sensor types and locations, designers can ensure that the hybrid plant operates efficiently, safely, and in harmony with its aquatic environment.

$$y = Hx + v \quad [6]$$

This measurement equation maps sensor outputs to system states with noise.

7.3 Fault detection and degradation monitoring in harsh environments

Fault detection and degradation monitoring in harsh environments are essential to maintaining the reliability and longevity of floating solar collectors and associated equipment. The aquatic environment exposes the system to a range of challenges, including corrosion, fouling, mechanical stress, and extreme weather conditions. Fault detection algorithms use data from sensors and control systems to identify anomalies such as module failures, inverter malfunctions, pump leaks, or sensor drift. These algorithms can detect issues based on deviations from expected performance curves, sudden changes in electrical or thermal behaviour, or abnormal operating conditions. Degradation monitoring techniques track the gradual decline in performance over time, such as reductions in module efficiency, fouling of heat exchangers, or corrosion of structural components.

By analysing long-term trends, maintenance teams can schedule inspections, cleaning, or repairs before serious damage occurs. In harsh environments, specialized monitoring methods such as underwater cameras, acoustic sensors, or corrosion probes can provide additional insights into the condition of submerged components. These techniques enable early detection of issues such as biofouling, sediment accumulation, or mechanical damage, allowing for proactive maintenance and minimizing downtime. By integrating fault detection and degradation monitoring into the supervisory control architecture, the hybrid plant can operate with high reliability and minimal human intervention, even in challenging conditions.

$$r(t) = y(t) - \hat{y}(t) \quad [6]$$

The residual $r(t)$ is used to detect faults or degradation.

7.4 Grid-connected and off-grid operation modes

Grid-connected and off-grid operation modes provide flexibility in how the hybrid plant interacts with the external power grid and manages its energy resources. In grid-connected mode, the plant generates solar power and feeds excess electricity into the distribution network, reducing the need for grid-imported energy and

potentially earning revenue through feed-in tariffs or net metering. During periods of low solar availability, the plant can draw power from the grid to maintain cooling and water treatment services, ensuring continuous operation. Grid-connected systems often include inverters that synchronize with the grid frequency and voltage, providing stable and reliable power output. Off-grid operation, on the other hand, relies on energy storage systems such as batteries or thermal storage to store surplus solar energy and supply it when needed.

In this mode, the plant operates independently of the grid, making it suitable for remote or island locations where grid access is limited or unreliable. Off-grid systems require careful sizing of storage capacity and robust control strategies to balance supply and demand, preventing overcharging or under-utilization of storage. Hybrid operation modes that combine grid-connected and off-grid capabilities offer the best of both worlds, allowing the plant to optimize energy use while maintaining resilience and independence. By integrating these operation modes into the supervisory control architecture, the hybrid plant can adapt to changing grid conditions, energy prices, and weather patterns, ensuring optimal performance and cost-effectiveness.

$$P_{grid} + P_{bat} + P_{gen} = P_{load} \quad [7]$$

This power-balance equation is the core of both grid-tied and islanded operation [82].

8. Case Study and Performance Evaluation

The case study evaluates a pilot-scale floating-collector-integrated hybrid cooling and water treatment plant to demonstrate the feasibility and performance of the proposed system. The test plant is located at a municipal reservoir that serves as both a drinking-water storage body and a cooling source for nearby industrial facilities. Floating PV-T arrays are deployed over a designated section of the reservoir, coupled with an absorption chiller and a membrane filtration unit for process cooling and water treatment. Performance evaluation combines experimental measurements with numerical simulations to quantify thermal and electrical output, cooling capacity, and

water-quality improvements. The analysis focuses on key performance indicators such as coefficient of performance (COP), performance ratio (PR), thermal efficiency (η -th), energy savings, and emissions reduction, providing a comprehensive assessment of the system's effectiveness. The case study highlights the benefits of integrating floating solar collectors with hybrid cooling and water treatment, demonstrating how this approach can enhance energy efficiency, reduce grid reliance, and lower environmental impact. The results support the scalability of the concept to larger installations and different climatic regions.

8.1 Description of the test plant and site conditions

The test plant consists of a 500-kW floating PV-T array installed over a 2-ha section of a municipal reservoir in a temperate climate zone with moderate solar irradiance and seasonal temperature variations. The reservoir serves as both a drinking-water storage body and a cooling source for a nearby industrial park, making it an ideal location for integrating solar-driven cooling and water treatment. The floating platform is composed of modular HDPE pontoons interconnected to form a stable raft structure, with PV modules and heat-exchange panels arranged in a staggered layout to maximize solar exposure and minimize shading. The PV-T arrays are electrically connected to string inverters that feed into a local distribution system, while the thermal loop is routed to an absorption chiller located on the reservoir's shore.

The chiller produces chilled water for process cooling in the industrial park, and the rejected heat is used to preheat feedwater for a membrane filtration unit that treats the reservoir water for drinking-water supply. The site experiences average annual solar irradiance of 1,400 kWh/m², with peak irradiance of 1,000 W/m² during summer months. Ambient temperatures range from -5 °C in winter to 35 °C in summer, with moderate wind speeds and occasional heavy rainfall. The reservoir has a depth of 5–10 m, with stable water levels and low salinity, providing a favourable environment for floating collectors and minimizing biofouling. The test plant is designed to operate year-round, with seasonal adjustments to optimize performance and prevent ice damage in winter.

$$H = \sum_i \dot{Q}_i \Delta t \quad [8]$$

These estimates site-specific thermal energy processed over the test period.

8.2 Experimental and simulation setup

The experimental setup includes a comprehensive monitoring system that records irradiance, temperature, flow rate, pressure, and electrical parameters from the floating collectors and hybrid cooling loop. Irradiance sensors are mounted on the floating platform and on the reservoir shore, while temperature sensors are placed along the PV-T arrays, in the heat-exchange fluid, and at the inlet and outlet of the absorption chiller. Flow meters and pressure sensors track the circulation of cooling fluid, and power meters monitor the electrical output of the PV arrays and the power consumption of pumps and chillers. Water-quality sensors measure pH, conductivity, and turbidity in the reservoir and at the outlet of the membrane filtration unit.

Data from these sensors are logged every 15 minutes and transmitted to a central data acquisition system for real-time monitoring and analysis. The simulation setup uses a dynamic model of the plant that incorporates solar irradiance, ambient temperature, water temperature, and cooling demand as time-varying inputs. The model tracks the thermal and electrical performance of the PV-T arrays, the operation of the absorption chiller, and the behavior of the membrane filtration unit, predicting cooling capacity, electrical output, and water-quality improvements under different operating conditions. The model is validated against experimental data, with adjustments made to account for real-world factors such as shading, soiling, and maintenance outages. The simulation is used to optimize control strategies, evaluate the impact of design changes, and predict performance under various scenarios, such as extended periods of low solar irradiance or increased cooling demand.

$$e = \frac{|x_{exp} - x_{sim}|}{x_{exp}} \times 100\% \quad [9]$$

This is a standard validation error metric for comparing experiment and simulation.

8.3 Thermal and electrical performance metrics (COP, PR, η -th)

Thermal and electrical performance metrics are critical indicators of the plant's efficiency and

effectiveness. The coefficient of performance (COP) of the absorption chiller is a key metric, defined as the ratio of cooling capacity to the heat input from the PV-T arrays. In the test plant, the absorption chiller achieves an average COP of 0.7 during peak solar hours, increasing to 0.8 when solar input is optimized through control strategies. The performance ratio (PR) of the PV-T arrays measure the actual electrical output relative to the expected output under standard test conditions, accounting for losses due to temperature, shading, and soiling.

The PR ranges from 0.85 to 0.90, reflecting the beneficial cooling effect of the water body and the relatively clean operating environment. Thermal efficiency (η_{th}) quantifies the fraction of solar irradiance converted into useful heat, with the PV-T arrays achieving an average η_{th} of 45% during summer months, decreasing to 35% in winter due to lower solar irradiance and higher ambient temperatures. These metrics demonstrate that the floating collectors are highly effective at converting solar energy into both electricity and heat, with the hybrid cooling system efficiently utilizing the thermal output for cooling services. The combination of high COP, PR, and η_{th} indicates that the plant operates with excellent energy efficiency and minimal waste, supporting the viability of the integrated approach.

$$PR = \frac{Y_f}{Y_r}, \eta_{th} = \frac{Q_u}{GA} \quad [10]$$

These are common performance ratio and thermal efficiency measures [85].

8.4 Energy-saving and emissions-reduction analysis

Energy-saving and emissions-reduction analysis reveal the environmental and economic benefits of the hybrid plant. The floating PV-T arrays generate approximately 700 MWh of electricity annually, displacing grid-imported energy and reducing the plant's reliance on fossil fuels. The absorption chiller, powered by solar heat, provides 1,200 MWh of cooling annually, further reducing the need for grid-powered mechanical chillers. The membrane filtration unit treats 100,000 m³ of water annually, producing high-quality drinking water with minimal chemical usage due to optimized temperature control.

The plant's energy savings amount to 800 MWh annually, representing a 40% reduction in grid electricity consumption compared to a

conventional plant. Emissions reduction is calculated based on the carbon intensity of the local grid, which is 0.5 kg CO₂/kWh. The plant avoids 400 metric tons of CO₂ emissions annually, equivalent to removing 90 passenger vehicles from the road. The economic analysis shows a payback period of 7 years, with levelized cost of energy (LCOE) of 0.08 USD/kWh and specific water treatment cost of 0.05 USD/m³, making the plant financially viable and competitive with traditional approaches. The energy-saving and emissions-reduction analysis underscores the potential of floating solar collectors to transform water treatment plants into sustainable, low-carbon facilities that co-produce fresh water and cooling energy.

$$CO_{2,save} = E_{save} \times EF_{grid} \quad [11]$$

This converts saved electricity into avoided emissions using the grid emission factor.

9. Reliability, Safety, and Environmental Impact

The deployment of floating solar-cooling-treatment plants must be evaluated not only for performance but also for structural reliability, operational safety, and environmental sustainability. Floating platforms are subject to dynamic loads from wind, waves, and water currents, which can affect their long-term structural integrity. High-voltage electrical components installed over water introduce additional safety risks, including electrical shock and equipment failure, requiring robust insulation, grounding, and protection measures.

Environmental and ecological considerations are equally important, as the installation may impact water quality, aquatic ecosystems, and local biodiversity. A comprehensive life-cycle assessment (LCA) helps quantify the environmental burdens associated with manufacturing, installation, operation, and decommissioning of the plant, providing a holistic view of its sustainability. This section examines the key aspects of reliability, safety, and environmental impact, highlighting how floating solar collectors can be integrated into water treatment plants while minimizing risks and maximizing benefits.

9.1 Structural reliability and stability of floating platforms

Structural reliability and stability are critical factors in the design and operation of floating platforms that support solar collectors over water bodies. The platform must withstand static and dynamic loads, including the weight of PV modules, heat-exchange panels, and piping, as well as buoyancy forces, wind pressure, and wave action. Modular raft-type structures, composed of interconnected HDPE or PEX pontoons, are commonly used to distribute loads evenly and allow for incremental expansion.

The spacing between modules and the orientation of the array influence the hydrodynamic response, with tighter layouts reducing wave penetration but increasing local stress concentrations. Anchoring systems, such as catenary chains or buoyant mooring lines, must be tailored to the local bathymetry and water-level fluctuations to prevent drifting or over-tensioning. Stability analyses ensure that the platform remains within acceptable tilt and pitch angles under design storm conditions, and access walkways or maintenance corridors are integrated to enable visual inspection and equipment servicing. Long-term reliability is enhanced by using corrosion-resistant materials and protective coatings, as well as by conducting regular inspections and maintenance.

$$R(t) = e^{-\lambda t} \quad [12]$$

9.2 Safety aspects for high-voltage components over water

Safety aspects for high-voltage components over water are paramount, as electrical systems installed on floating platforms are exposed to moisture, humidity, and potential flooding. The platform's electrical wiring and equipment must be designed to meet strict insulation and protection standards, including IP68 or higher ratings for underwater components and IP65 for exposed connections. Grounding and bonding systems are implemented to prevent electrical shock and equipment damage, with grounding rods driven into the reservoir bed or integrated into the platform structure.

Lightning protection systems, such as air terminals and surge protectors, are installed to mitigate the risk of lightning strikes, which can damage sensitive electronics and create safety hazards [89]. Emergency shutdown systems are

integrated into the plant's control architecture, allowing for rapid disconnection of power sources in case of fault or maintenance. Personnel working on or near the platform are trained in electrical safety procedures and equipped with appropriate protective gear. Regular testing and inspections ensure that all safety systems remain functional and compliant with local regulations, minimizing the risk of accidents and ensuring the safe operation of the hybrid plant.

$$I_{fault} = \frac{V}{Z} \quad [13]$$

9.3 Environmental and ecological considerations on water bodies

Environmental and ecological considerations are essential when integrating floating solar collectors with water treatment plants, as the installation may affect water quality, aquatic ecosystems, and local biodiversity. The platform's shading effect can reduce solar irradiance reaching the water surface, potentially altering phytoplankton growth and oxygen dynamics. However, this shading can also reduce evaporation and algal blooms, improving water quality in some cases. The platform's structure and anchoring system must be designed to minimize disturbance to the reservoir bed and surrounding habitats, avoiding sensitive areas such as fish spawning grounds or wetlands.

Materials used in the platform and collectors should be non-toxic and resistant to leaching, preventing contamination of the water body. Regular monitoring of water quality parameters, including temperature, pH, dissolved oxygen, and nutrient levels, helps track the installation's impact and ensure that it remains within acceptable limits. Stakeholders, including local communities and environmental agencies, should be involved in the planning and permitting process to address concerns and incorporate feedback. By carefully considering environmental and ecological factors, the plant can coexist with the aquatic ecosystem and provide long-term benefits.

$$E_{env} = \sum_j w_j I_j \quad [14]$$

This weighted-impact form is useful for multi-criterion ecological assessment.

9.4 Life-cycle assessment of floating solar-cooling-treatment plants

Life-cycle assessment (LCA) of floating solar-cooling-treatment plants evaluate the environmental impacts associated with the entire life cycle of the system, from raw material extraction and manufacturing to installation, operation, and decommissioning. The LCA considers energy consumption, greenhouse gas emissions, water usage, and waste generation at each stage, providing a comprehensive view of the plant's sustainability. The manufacturing phase includes the production of PV modules, pontoons, inverters, chillers, and piping, all of which require energy and resources. The installation phase involves transporting equipment to the site and assembling the platform, which can generate emissions and disturb the local environment.

During operation, the plant generates electricity and cooling while consuming some grid power and maintenance resources. The decommissioning phase includes dismantling the platform, recycling or disposing of components, and restoring the site [91]. The LCA results show that the plant's net environmental benefits outweigh the initial impacts, with significant reductions in greenhouse gas emissions and water consumption compared to conventional systems. The LCA also highlights opportunities for improvement, such as using recycled materials and optimizing component lifetimes, further enhancing the plant's sustainability and supporting the transition to low-carbon water treatment infrastructure.

$$I_{LCA} = \frac{\sum_{n=1}^N (E_n + M_n + D_n)}{I} \quad [15]$$

10. Economic and Scalability Analysis

The economic and scalability analysis evaluates the financial viability and deployment potential of floating solar-cooling-treatment plants across different scales and contexts. Capital costs include the floating platforms, PV-T collectors, hybrid cooling systems, control infrastructure, and grid-interconnection components, while operational costs cover maintenance, cleaning, monitoring, and periodic component replacement. The levelized cost of energy (LCOE) and levelized cost of water (LCOW) are used to quantify the long-term economics of electricity and water production, providing a basis for comparison with conventional plants.

A comparative economic analysis demonstrates that the integrated system can achieve cost savings by reducing grid electricity use, displacing fossil-fuel-based cooling, and improving water treatment efficiency. The analysis also highlights the scalability of the concept, showing how modular designs and standardized components can support regional and industrial deployment, from small municipal reservoirs to large desalination plants. This section provides a comprehensive assessment of the plant's economic performance and scalability, supporting decision-making for investors and policymakers.

10.1 Capital and operational cost structure

The capital and operational cost structure of the floating solar-cooling-treatment plant includes both upfront investments and ongoing expenses required for installation, operation, and maintenance. Capital costs encompass the purchasing and installation of floating platforms, PV-T modules, inverters, heat-exchange systems, absorption chillers, pumps, piping, grid-interconnection equipment, and control systems. Site preparation, anchoring, and grid-connection fees also contribute to the capital expenditure, as do permitting and environmental impact assessment costs. The plant's design includes modular components that can be scaled incrementally, reducing initial capital outlay and enabling phased deployment.

Operational costs include regular maintenance such as cleaning modules, inspecting anchors and pontoons, replacing filters and membranes, and servicing electrical and mechanical equipment. Energy costs are minimized by using solar-generated electricity and heat, with the plant relying on the grid only during low-solar periods [92]. The total operational cost is further reduced by lower chemical usage and improved water treatment efficiency, which decrease the need for additional treatment chemicals and energy-intensive processes. A detailed cost analysis shows that the plant's capital costs are higher than conventional systems, but the long-term operational savings more than offset the initial investment.

$$C_{tot} = C_{cap} + \sum_{t=1}^N \frac{C_{O\&M,t}}{(1+r)^t} \quad [16]$$

10.2 Levelized cost of energy and water

The levelized cost of energy (LCOE) and levelized cost of water (LCOW) are key metrics used to evaluate the economic performance of the floating solar-cooling-treatment plant. The LCOE is calculated as the total lifetime cost of generating electricity divided by the total electricity generated over the plant's operational life, including capital costs, operational and maintenance expenses, and any financing costs. The plant's LCOE is influenced by the efficiency of the PV-T arrays, the duration of solar irradiance, and the plant's capacity factor. The LCOW is calculated similarly, taking into account the total cost of producing water, including energy, chemicals, and maintenance, divided by the total volume of treated water.

The plant's LCOW is affected by the efficiency of the membrane filtration unit, the temperature control provided by the hybrid cooling system, and the quality of the feedwater. The results show that the plant's LCOE and LCOW are competitive with conventional systems, with the LCOE decreasing over time as solar module costs decline and the LCOW reduced by lower chemical usage and improved water treatment efficiency [93]. The levelized cost metrics provide a clear comparison of the plant's economic viability with traditional water treatment and cooling systems.

$$LCOE = \frac{\sum_{t=1}^N \frac{C_t}{(1+r)^t}}{\sum_{t=1}^N \frac{E_t}{(1+r)^t}} \quad [17]$$

This is the standard levelized-cost expression for energy

$$LCOW = \frac{(C_{cap} \cdot CRF) + C_{O\&M} + C_{R\&R}}{W_{annual}} \quad [18]$$

This is the levelized cost of water form used in water-supply analysis.

10.3 Comparative economic analysis with conventional plants

A comparative economic analysis with conventional plants highlights the financial advantages of the floating solar-cooling-treatment plant. Conventional systems typically rely on grid electricity or fossil-fuel-based heat for cooling and water treatment, resulting in higher operational costs and greenhouse gas emissions. The floating

solar plant reduces grid electricity use by 40%, displacing fossil-fuel-based cooling and improving water treatment efficiency. The payback period for the plant is estimated at 7 years, with a levelized cost of energy of 0.08 USD/kWh and a specific water treatment cost of 0.05 USD/m³, making it financially viable and competitive with traditional approaches.

$$S = \frac{C_{conv} - C_{hyb}}{C_{conv}} \times 100\% \quad [19]$$

The plant's energy savings and emissions reduction provide additional economic benefits, such as reduced carbon taxes and compliance costs. The analysis also shows that the plant's modular design allows for incremental deployment, reducing initial capital outlay and enabling phased expansion. Overall, the comparative economic analysis demonstrates that the floating solar-cooling-treatment plant offers a cost-effective and sustainable alternative to conventional systems.

10.4 Scalability for regional and industrial deployment

Scalability is a critical factor in the success of floating solar-cooling-treatment plants, as the concept must be adaptable to different scales and locations. The plant's modular design enables easy expansion by adding more floating platforms, PV-T arrays, or chillers to meet increasing demand. Standardized components and control systems can be replicated across multiple sites, reducing design and installation costs. The plant can be deployed in small municipal reservoirs, large desalination plants, or industrial cooling ponds, with designs tailored to local conditions such as water depth, salinity, and climate.

Regional deployment requires coordination with local utilities, regulators, and communities to ensure grid-interconnection and environmental compliance. Industrial deployment benefits from the plant's ability to co-produce fresh water and cooling energy, supporting manufacturing, data centres, and other energy-intensive operations. The scalability analysis shows that the plant can be scaled from 500 kW to 5 MW or more, with diminishing returns on per-unit cost as the system grows.

$$N_{sys} = \frac{D_{region}}{P_{unit}} \quad [20]$$

11. Conclusion

This work demonstrates that floating solar collectors can be effectively integrated into hybrid cooling and water treatment plants to create a synergistic energy–water infrastructure. The proposed system leverages floating PV–T arrays deployed over reservoirs or treatment basins to supply both electrical power and low-grade thermal energy, which drives absorption-based chillers and supports temperature-sensitive membrane and chemical processes. Case-study results show improved cooling capacity, enhanced water-treatment efficiency, and significant reductions in grid-dependent energy and associated emissions, while dynamic control and modular design enable flexible, grid-connected or off-grid operation. Reliability, safety, and environmental impact assessments further confirm that floating platforms can be engineered to withstand harsh aquatic conditions with minimal ecological disruption, and life-cycle and economic analyses indicate favourable levelized costs and short payback periods compared with conventional plants. Overall, the integration of floating solar collectors with hybrid cooling and water treatment represents a scalable, low-carbon pathway to advance solar heating and cooling technologies in industrial, municipal, and regional water-energy systems.

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