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Optimizing Water Resource Management For Sustainable Power Plant Operations: Balancing Efficiency And Environmental Impact

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Abstract: The intricate interdependence between power generation and water resources is increasingly acknowledged as a critical sustainability challenge. Thermal power plants, which play a pivotal role in meeting rising global energy demands, consume substantial volumes of water, primarily for cooling, steam production, and emissions control. This reliance on water is being strained by growing scarcity, intensified by climate change and population growth, and is further complicated by the environmental impacts of water withdrawals and discharges. Consequently, the need for improved water management within the power sector has become urgent. This article offers a comprehensive analysis of the energy-water nexus, focusing on operational practices in power plants. The diverse applications of water in power generation are detailed, and the water intensity of various technologies is quantified. Environmental impacts such as thermal pollution, hydrological disruptions, aquatic ecosystem damage, chemical contamination, and consumptive losses are critically examined. A wide range of strategies aimed at enhancing water-use efficiency is explored, including advanced cooling technologies (air-cooled, hybrid, and advanced wet systems), water-efficient steam cycles, and cutting-edge wastewater treatment and reuse technologies. Operational best practices such as water audits, leakage detection, and real-time monitoring are also addressed. The influence of policy instruments, regulatory frameworks, and economic incentives on promoting water conservation is analyzed to highlight their role in driving sectoral change. Through illustrative case studies drawn from various geographical and technological contexts, successful implementations are showcased, offering replicable best practices. The article concludes by identifying emerging trends, existing research gaps, and future directions, emphasizing the necessity for integrated, sustainable approaches to water and energy resource management.

Index Terms - Water Resource Management, Power Plant Operations, Sustainable Energy, Water-Energy Nexus, Cooling Technologies, Water Efficiency, Environmental Impact, Thermal Pollution, Water Reuse, Water Policy.

1.Introduction

1.1. The water-energy nexus: Challenges in thermal power generation.

The generation of electricity, considered a cornerstone of modern civilization, has been inherently dependent on the availability and careful management of water resources. In particular, thermal power generation—including fossil fuel-based (coal, natural gas, oil), nuclear, and geothermal plants—has been characterized by a significant reliance on water as a critical medium for the conversion of heat into electrical energy. Water has been utilized extensively as the working fluid in steam cycles that drive turbines, as the coolant in systems designed to dissipate excess thermal energy, and as an essential component in emissions control technologies such as flue gas desulfurization (FGD) systems (IEA, 2021; Gleick, 1994).

However, this dependence has been increasingly challenged by escalating global water stress. Freshwater, which accounts for only a small fraction of the Earth's total water resources, has been subjected to intensifying demand due to population growth, agricultural expansion, industrialization, and the adverse effects of climate change. These effects include altered precipitation patterns, increased evaporation rates, and a heightened frequency of droughts and floods (IPCC, 2021). The power sector has been identified as one of the largest water-withdrawing sectors in numerous countries, placing it at the centre of water-energy tensions (WWAP, 2014).

Large volumes of water have been withdrawn by power plants from rivers, lakes, estuaries, and aquifers. Although a majority of this water has been returned to its source—particularly in once-through cooling systems—it is often thermally altered and may carry residual chemical pollutants (Macknick et al., 2012). Furthermore, considerable quantities of water have been consumed through evaporation, especially in recirculating cooling towers, thereby contributing to freshwater depletion in water-scarce regions. This consumption has been observed to compete directly with other critical water uses, such as municipal supply, irrigation, and environmental flow maintenance (Stillwell et al., 2011). Environmental consequences associated with these practices have included thermal pollution, the impingement and entrainment of aquatic organisms at intake structures, hydrological disruptions affecting downstream ecosystems, and contamination from blowdown water and wastewater discharges (USDOE, 2006; EPRI, 2008).

1.2. The Interdependence of power generation and water resources.

The symbiotic, yet frequently strained, relationship between power generation and water resources is driven by the fundamental thermodynamic principles governing thermal power plants, along with the ancillary processes required for their operation and environmental compliance. An understanding of the specific modes of water utilization, the volumes involved, and the influencing factors on water availability is considered essential for effective management of this interdependency (Stillwell et al., 2011; Mack nick et al., 2012).

1.2.1. Water utilization in power plants.

Within a typical thermal power plant, water is utilized to perform several critical functions:

1. **Cooling systems:** Cooling has been identified as the largest category of water use in most thermal power plants (US DOE, 2006). In the Rankine cycle, which serves as the basis for most steam-electric power generation, low-pressure steam exiting the turbine must be condensed back into liquid form before being returned to the boiler. This condensation process involves the release of significant quantities of waste heat, which must be rejected to the environment through cooling systems (EPRI, 2008).

- **Once-through cooling:** In this method, water is withdrawn from natural sources such as rivers, lakes, or oceans, passed through condensers to absorb waste heat, and subsequently discharged back into the original source at an elevated temperature. Although this approach involves substantial water withdrawals, the actual consumption is relatively low, with losses mainly occurring through minor evaporation within the thermal discharge plume. However, its use has been increasingly restricted due to concerns regarding thermal pollution and adverse impacts on aquatic ecosystems (Gleick, 1994; Macknick et al., 2012).
- **Recirculating cooling (Wet cooling towers):** In recirculating systems, water is cycled continuously between the condenser and a cooling tower. Within the tower, heat is transferred to the atmosphere primarily through the evaporation of a portion of the circulating water. While this method reduces water withdrawal by more than 95% compared to once-through systems, it significantly increases water consumption due to evaporative losses (Torcellini et al., 2003). Additional water—referred to as makeup

water—is required to offset losses from evaporation, drift (droplets carried with exhaust air), and blowdown (periodic discharge of water to control dissolved solids).

2. **Steam generation (Boiler feedwater):**
   Water of high purity is required for the generation of steam in boilers. The presence of impurities must be avoided, as scaling, corrosion, and deposition on boiler tubes and turbine blades can occur, leading to reduced efficiency or even catastrophic equipment failure (U.S. EPA, 2011). Therefore, extensive water treatment processes—including demineralization and deaeration—are employed to prepare boiler feedwater. Ongoing losses within the steam cycle, such as steam leaks and boiler blowdown, must be compensated by the continuous addition of makeup water.
3. **Emissions control:**
   The control of air pollutants such as sulphur dioxide (SO_2) and particulate matter has been mandated by environmental regulations to mitigate atmospheric pollution and protect public health (U.S. EPA, 2015; Srivastava et al., 2001).

- **Wet flue gas desulfurization (Wet scrubbers):** In these systems, flue gases are passed through a slurry composed of water and an alkaline reagent, typically limestone ($CaCO_3$), allowing sulphur dioxide (SO_2) to be absorbed and chemically neutralized. This reaction forms calcium sulphite or calcium sulphate (commonly known as synthetic gypsum), into which a portion of the water becomes incorporated. Additional water losses occur through evaporation during the gas-liquid contact process. Wastewater—referred to as scrubber blowdown—is also produced and must be treated to remove contaminants before discharge or reuse (Srivastava & Jozewicz, 2001; EPRI, 2008). The water demands of wet FGD systems are considered substantial, especially in coal-fired power plants operating at high sulphur loads.
- **Particulate control:** Water is occasionally used in particulate control systems. In wet electrostatic precipitators, water sprays are employed for conditioning the flue gas or for cleaning the electrodes. Similarly, in certain fabric filter applications, water may be used to suppress dust or to aid in filter maintenance. Although water use in particulate control systems is generally lower than in SO_2 scrubbing, it remains an important consideration in the overall water footprint of emissions control technologies (Zhou et al., 2016).

1.2.2. Water intensity of different power generation technologies.

The amount of water that is withdrawn and consumed per unit of electricity generated—typically expressed in litters or gallons per megawatt-hour (L/MWh or gal/MWh)—has been found to vary significantly depending on the generation technology, the type of cooling system used, and site-specific environmental conditions (Macknick et al., 2012; Meldrum et al., 2013).

- **Conventional Thermal (Coal, Natural Gas, and Nuclear):** Water intensity in these plants is largely determined by the cooling technology employed. Plants utilizing once-through cooling systems have been observed to exhibit extremely high withdrawal rates, ranging between 75,000 and 225,000 L/MWh, while their water consumption remains relatively low (<1,900 L/MWh), as most of the withdrawn water is returned to the source (Macknick et al., 2012). In contrast, wet recalculating cooling systems drastically reduce withdrawal rates (1,900–3,800 L/MWh) but substantially increase consumption (1,500–2,600 L/MWh) due to evaporation in cooling towers (Torcellini et al., 2003). Nuclear power plants tend to require more cooling water than fossil fuel plants, owing to their lower thermal efficiencies and the absence of heat loss through flue gases (DOE, 2006). Combined-cycle natural gas (NGCC) plants generally achieve lower water intensities because of their higher overall thermal efficiency (Meldrum et al., 2013).
- **Geothermal:** Water consumption rates in geothermal plants vary depending on the technology. Flash and dry steam plants may consume condensed geothermal fluids or require supplemental cooling water, often via wet cooling towers, leading to consumption levels ranging from 2,500 to 6,800 L/MWh (Clark et al., 2011). Binary cycle plants, which use closed-loop secondary working fluids, are more amenable to dry cooling, significantly reducing water usage.
- **Concentrating Solar Power (CSP):** Thermal CSP systems—such as parabolic trough and power tower designs—exhibit water demands similar to those of conventional thermal plants when wet cooling is applied. Water consumption under these configurations has been estimated to be high, often exceeding 3,000 L/MWh (Macknick et al., 2012). Dry cooling is technically feasible and can dramatically reduce water use, though it may result in a performance trade-off in high-temperature climates (Turchi et al., 2010). Dish-Stirling systems, which are modular and use mechanical engines, require minimal water.
- **Biomass:** Water requirements in biomass power plants resemble those of coal-fired facilities due to similar thermal and cooling needs. However, the overall water footprint may be significantly expanded

when water used for crop irrigation is considered. Irrigation-related water use can exceed operational requirements, particularly in regions relying on agricultural biomass feedstock.

- **Hydropower:** Although water is not directly consumed during electricity generation by hydro turbines, substantial evaporative losses can be associated with reservoir-based systems. These losses have been attributed to the large surface areas of reservoirs and can range from 0.2 to more than 245,000 L/MWh, depending on regional climate, reservoir design, and operational patterns (Mekonnen & Hoekstra, 2012). Run-of-river hydropower systems, by contrast, exhibit negligible water consumption.
- **Wind and Solar Photovoltaic (PV):** These renewable technologies are characterized by minimal operational water use, typically limited to the occasional cleaning of photovoltaic panels or wind turbine blades. Consumption has been reported between 0–100 L/MWh (Macknick et al., 2012). However, the embedded water footprint associated with the manufacturing, material extraction, and processing stages occurs upfront and is amortized over the project's lifecycle.

Water withdrawal and consumption volumes for various power generation technologies, based on data from sources such as Gleick (1994), Goldstein and Smith (2002a), Woods et al. (2007), and the National Renewable Energy Laboratory (2008), have been documented across different fuel and cooling technology combinations. As shown in Table 1, water withdrawal intensities were reported to vary significantly depending on both the type of fuel used and the cooling system employed. Similarly, Table 2 presents the corresponding water consumption volumes, which also exhibited notable variation. Technologies such as once-through cooling and wet recirculating systems were found to require substantial water inputs, whereas air-cooling was identified as requiring negligible water and was shown to be compatible with all examined technologies. The water intensity of different power generation technologies was characterized to highlight the trade-offs involved in energy production and water resource use, underscoring the potential for reduced water use through the implementation of air-cooling systems. As an example, Fig. 1 illustrates water consumption and withdrawal for power plant construction across different fuel types, aggregated for the entire African continent.

Table 1. Water withdrawal reported volumes for different fuels and cooling technologies.

	Cooling Technologies-Water Withdrawal (L [MWh]$^{-1}$) †				
	Open-Loop	Closed-Loop Reservoir	Closed-Loop Cooling Tower	Hybrid Cooling	Air-Cooling
Coal	132,00(±57,000)	1700(±500)	2100 (±200)	between	<400
Nuclear	161,00(±66,000)	3000(±1,100)	3600(±600)	between	<400
Natural Gas Combustion Turbine	negligible	negligible	negligible	negligible	negligible
Natural Gas Combined-Cycle	52,000(±24,000)	600‡ (±100)	900	between	<400‡
Integrated Gasification Combined-Cycle	not used	not used	1500‡ (±400)	between	<400‡
Concentrated Solar Power	not used	not used	3200‡ (±300)	between	<400‡
Wind	none	none	none	none	none
Photovoltaic Solar	none	none	none	none	none

Table 2. Water consumption reported volumes for different fuels and cooling technologies.

Cooling Technologies-Water Consumption (L [MWh]$^{-1}$) †					
	Open-Loop	Closed-Loop Reservoir	Closed-Loop Cooling Tower	Hybrid Cooling	Air-Cooling
Coal	1100	1500(±400)	1800	between	200(±40)
Nuclear	1500	2400(±850)	2700	between	200(±40)
Natural Gas Combustion Turbine	negligible	negligible	negligible	negligible	negligible
Natural Gas Combined-Cycle	400	500‡ (±80)	700	between	200‡(±40)
Integrated Gasification Combined-Cycle	not used	not used	1300‡ (±100)	between	200‡ (±40)
Concentrated Solar Power	not used	not used	3200‡ (±100)	between	300‡ (±40)
Wind	none	none	none	none	none
Photovoltaic Solar	none	none	none	none	none

- †L [MWh]$^{-1}$: liters per megawatt-hour
- ‡Estimated based on withdrawal and consumption ratios

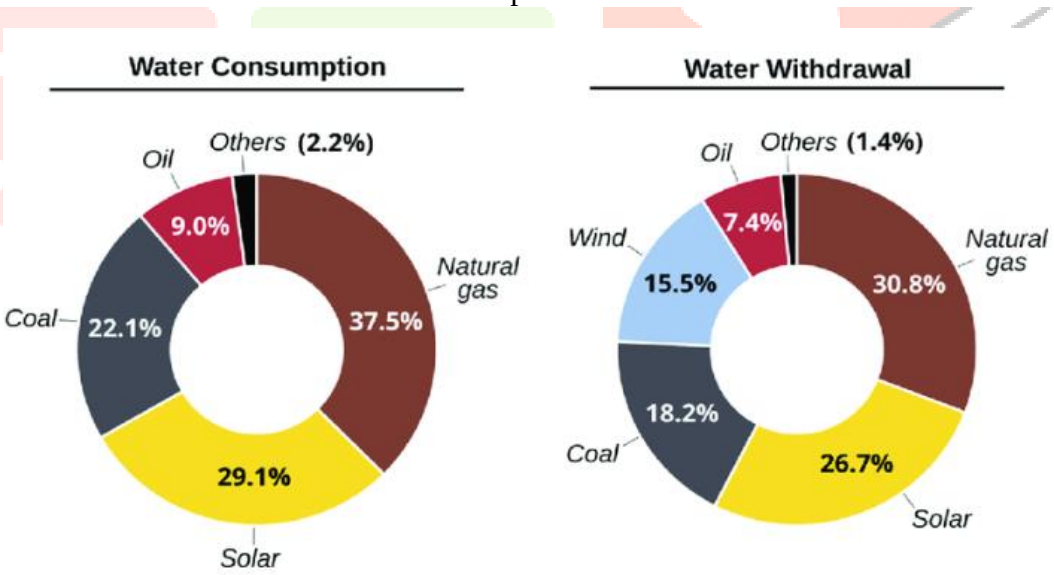

Fig.1.Water consumption and withdrawal for power plant construction for different fuel types aggregated for the whole African continent. [Source:https://www.researchgate.net/figure/Water-consumption-and-withdrawal-for-power-plant-construction-for-different-fuel-types

1.2.3. Geographical and temporal variability of water availability.

Water availability has been observed to vary across geographical regions and seasonal cycles. In arid and semi-arid areas, power generation has been consistently challenged by limited water supplies. Seasonal rainfall fluctuations, prolonged droughts—exacerbated by climate change—and competition from agriculture and municipal users have further strained the availability of water resources (U.S. DOE, 2006; IPCC, 2021).

- **Siting decisions:** New thermal power plants are increasingly being sited based on proximity to reliable water sources. Access to seawater near coastlines has been used for cooling, although additional infrastructure, such as desalination units or corrosion-resistant materials, may be required. Inland facilities, by contrast, are dependent on limited freshwater sources (Stillwell et al., 2011).
- **Operational reliability:** Reductions in water availability have forced several power plants to curtail or suspend operations, especially during heatwaves when electricity demand peaks and river flows decline due to high evaporation. This has compromised grid reliability and led to economic losses (Scanlon et al., 2013).
- **Technology choice:** Water scarcity has driven the implementation of dry or hybrid cooling technologies, despite their higher capital costs and lower thermodynamic efficiency (Macknick et al., 2012).

2. Environmental impacts of water use in power plants.

2.1. Thermal pollution.

Thermal pollution has been predominantly linked with once-through cooling systems. In such systems, large volumes of heated water are discharged back into water bodies, often at elevated temperatures. This discharge has been found to disrupt aquatic ecosystems (USEPA, 2001).

- **Physiological stress and mortality:** Aquatic organisms have been shown to suffer from heat shock, reduced dissolved oxygen levels, and increased disease susceptibility under thermal stress conditions (Caissie, 2006).
- **Altered species composition and habitat degradation:** Temperature changes have encouraged the proliferation of heat-tolerant and invasive species, often at the expense of native species, such as cold-water fish like salmon (Rahel & Olden, 2008).
- **Synergistic effects:** Thermal discharges have also been observed to enhance the toxicity of chemical pollutants already present in the aquatic environment (USEPA, 2001). Regulations have been enforced to limit the discharge temperature and the maximum allowable increase above ambient water temperatures. However, cumulative thermal impacts within entire watersheds remain a concern.

2.2. Hydrological Alterations.

Hydrological regimes have been altered through the large-scale water withdrawals required for power plant operations.

- **River flow reduction and lake level drawdown:** Significant reductions in streamflow and lake levels have been attributed to once-through cooling withdrawals, with implications for water quality, aquatic habitat, and downstream users (Averyt et al., 2011).
- **Groundwater depletion and altered flow regimes:** Over-extraction from aquifers has resulted in lower water tables, land subsidence, and saltwater intrusion in coastal zones. Altered timing of water return flows has also disrupted ecological cues such as fish spawning migrations (Konikow & Kendy, 2005). These impacts have been noted to be particularly severe in drought-prone or already stressed regions (U.S. DOE, 2006).

2.3. Entrainment and impingement.

The intake of cooling water has posed significant threats to aquatic life.

- **Impingement:** Large organisms such as fish and turtles have frequently been trapped against intake screens, suffering injury or death due to mechanical damage or stress (USEPA, 2014).
- **Entrainment:** Smaller organisms—plankton, larvae, eggs—have been drawn into cooling systems and exposed to lethal temperatures, pressure changes, and chemical agents. These impacts have led to declines in local fish populations, particularly in estuarine and coastal regions (Barnthouse, 2013).

Section 316(b) of the U.S. Clean Water Act mandates the use of Best Technology Available (BTA) to reduce these impacts, including fine-mesh screens, velocity caps, fish diversion systems, or closed-cycle cooling retrofits (USEPA, 2014).

2.4. Chemical pollution.

Power plants generate multiple wastewater streams that, if untreated, have been known to introduce harmful substances into water bodies.

- **Cooling tower blowdown:** This stream contains concentrated dissolved solids and chemical additives—such as biocides (e.g., chlorine) and scale inhibitors—that are toxic to aquatic organisms and can cause eutrophication (Snyder et al., 2017).
- **Flue Gas Desulfurization (FGD) wastewater** systems produce effluents rich in heavy metals (e.g., selenium, arsenic), sulphates, chlorides, and TDS. Despite the use of advanced treatment systems, discharges have continued to pose water quality risks (Zhang et al., 2017).
- **Boiler cleaning and miscellaneous wastes:** Chemical cleaning of boilers and demineralization units results in acidic or metal laden discharges. Additionally, stormwater runoff from coal piles and maintenance areas can carry oil, sediment, and other pollutants into nearby waters (USEPA, 2014). To mitigate these risks, effluent guidelines and permits under the National Pollutant Discharge Elimination System (NPDES) have been applied, requiring monitoring and treatment prior to discharge.

2.5. Water consumption.

Although once-through cooling systems have been associated with higher water withdrawals, recirculating systems such as cooling towers and cooling ponds have been found to consume considerably more water through evaporation. This consumptive use is characterized by the permanent removal of water from the local watershed, contributing to a net depletion of water resources (Macknick et al., 2012). In water-stressed regions, this loss has been shown to intensify competition among various sectors—ecosystems, agriculture, and domestic supply—resulting in heightened water scarcity (Averyt et al., 2011).

Long-term declines in river flows or lake levels have been attributed to sustained evaporative losses, which may lead to increased concentrations of pollutants and subsequent degradation of aquatic habitats (Stillwell et al., 2011). These impacts are expected to become more severe as climate change elevates temperatures and reduces hydrological availability in many areas (IPCC, 2021). Therefore, the consumptive use of water by thermal power plants has emerged as a critical issue requiring focused mitigation efforts.

2.6. Impacts on wetlands and riparian zones.

Indirect effects on wetlands and riparian habitats have been observed as a consequence of water withdrawals and altered flow regimes by power plants. Dewatering of these ecologically sensitive areas has been linked to shifts in vegetation composition, loss of habitat function, and diminished biodiversity (Dudgeon et al., 2006). Groundwater-dependent ecosystems, particularly those containing phreatophytic vegetation, have been impacted by reductions in the water table caused by groundwater extraction for power generation (Konikow & Kendy, 2005).

In addition to hydrological impacts, the physical siting of energy infrastructure—including pipelines, access roads, and transmission corridors—has been associated with habitat fragmentation, increased erosion, and loss of sensitive ecological zones. These developments, if not carefully planned, can permanently degrade the ecological integrity of wetland and riparian environments (USEPA, 2013).

2.7. Cumulative impacts.

Although the environmental effects of individual power plants have been well-documented, cumulative impacts have often been underestimated. When multiple power generation facilities operate within the same watershed or coastal system, compounded pressures on water bodies have been reported.

- **Thermal loading:** Cumulative thermal discharges have been shown to elevate baseline water temperatures beyond ecologically safe thresholds, impairing aquatic ecosystems over broader spatial scales (Caissie, 2006).
- **Combined withdrawals:** Aggregate water withdrawals have the potential to deplete aquifers and surface water bodies to levels that are unsustainable, particularly under drought conditions (Scanlon et al., 2013).
- **Entrainment pressure:** When intake zones overlap, cumulative entrainment and impingement pressures on fish populations have been magnified, increasing mortality rates and reducing recruitment (Barnthouse, 2013).

These challenges underscore the necessity for watershed-scale planning and integrated management approaches. Collaborative governance involving utilities, water managers, and regulatory agencies has been recommended to address cumulative effects effectively (OECD, 2012).

3. Strategies for optimizing water resource management in power plants.

To address the growing challenges of water scarcity and environmental degradation, various strategies have been proposed and implemented to optimize water use in power plants. These measures have been developed to reduce both water withdrawal and consumption, enhance water reuse, and minimize ecological harm. Smart water resource management, as illustrated in Fig. 2, is being adopted to support these goals.

- **Implementation of advanced cooling technologies:** Technologies such as dry cooling and hybrid cooling systems have been deployed to significantly reduce water consumption. Although associated with higher capital and operational costs, these systems have been favoured in water-constrained regions (Macknick et al., 2012; EPRI, 2011).
- **Water recycling and reuse:** Internal recycling of process water and reuse of municipal or treated industrial wastewater have been promoted to reduce freshwater intake. Closed-loop systems have been adopted to limit the discharge of contaminants and improve water efficiency.
- **Use of non-traditional water sources:** Alternative sources such as saline water, mine drainage, or reclaimed wastewater have been evaluated and, in some cases, utilized to offset demands on freshwater supplies. This approach has been especially relevant for coastal or industrial areas with limited freshwater availability (Veil et al., 2003).
- **Operational optimization:** Water-intensive processes have been scheduled during cooler periods or low-demand intervals to minimize evaporation losses and thermal impacts. Leak detection and maintenance programs have been institutionalized to prevent unnecessary water loss.
- **Regulatory compliance and best practices:** Compliance with regulatory frameworks, such as the Clean Water Act (Section 316(a) and 316(b)), has required the use of Best Technology Available (BTA) to reduce ecological harm from cooling water intake and discharge. Voluntary industry guidelines and benchmarking have also been adopted to drive continuous improvement (USEPA, 2014).
- **Integrated Water Resource Management (IWRM):** A holistic approach that considers hydrological, ecological, and socioeconomic factors has been advocated to ensure long-term water sustainability in power generation. Regional water-energy planning efforts have been initiated in several jurisdictions to align energy development with sustainable water use (World Bank, 2014).

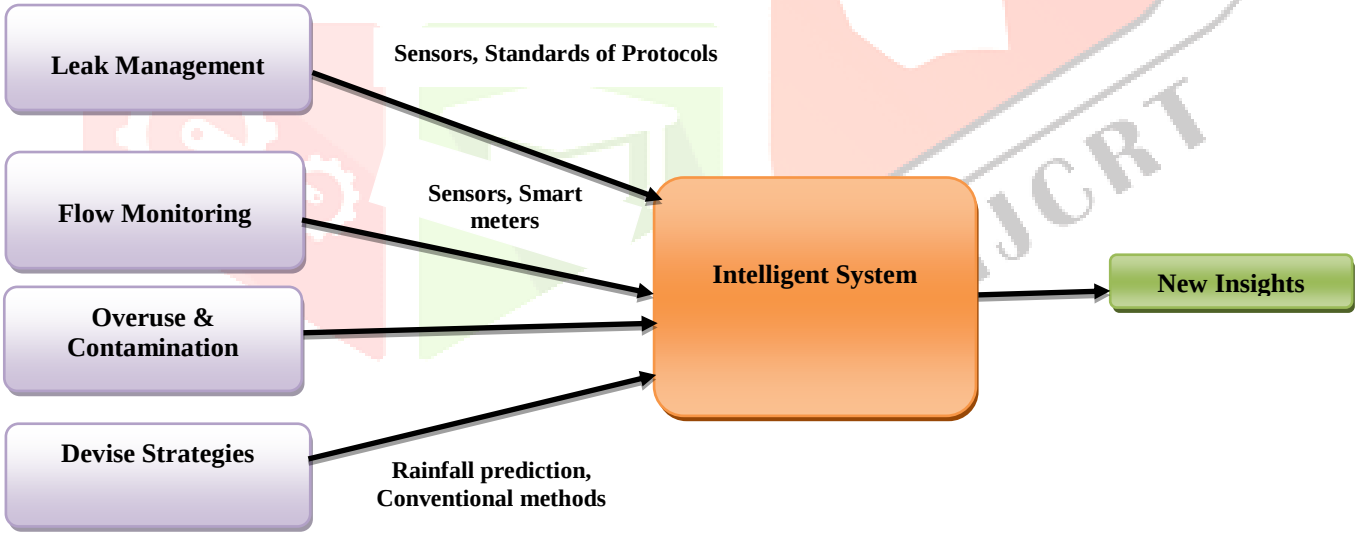

Fig.2. Smart Water Resource Management.

3.1. Cooling system optimization for water-scarce regions.

3.1.1. Advanced cooling technologies.

Cooling system optimization has been recognized as essential, given that cooling accounts for the majority of water use in thermal power plants.

1. Air-Cooled Condensers (ACCs) / Dry cooling:

- **Principle:** Heat is rejected directly to ambient air via finned tube arrays and fan systems, thereby eliminating water withdrawal and consumption (Macknick et al., 2012).
- **Efficiency considerations:** Higher turbine backpressure has been observed, especially under high ambient temperatures, resulting in thermal efficiency penalties. Reductions in output of 3–10% during hot periods have been reported (ACC Performance Data).

- **Cost implications:** Capital costs are typically higher due to the large heat exchange surface and fans. Increased auxiliary power consumption contributes to higher operating expenses (EPRI, 2011).
- **Suitability:** Best suited for arid or water-stressed regions and increasingly applied in NGCC and geothermal plants. Use in large coal/nuclear facilities is limited due to performance penalties. Supplemental cooling has been explored to mitigate peak efficiency losses [Citation Needed: ARPA-E ACT Project].

2. Hybrid cooling systems:

- **Principle:** Wet and dry cooling technologies are combined to balance performance and water use (DOE, 2006).
- **Operation:** Systems can be operated in dry, wet, or mixed modes depending on temperature, water availability, and electricity demand. Water consumption reductions of 50–80% compared to wet cooling have been achieved [Citation Needed: Hybrid Cooling Performance Studies].
- **Applications:** Deployed where variable water constraints or strict environmental regulations are present. Suitable for various thermal power technologies. Capital costs are typically intermediate between dry and wet systems (Macknick et al., 2012).

3. Advanced wet cooling technologies:

- **Drift eliminators:** High-efficiency eliminators have been used to reduce drift loss, thereby minimizing water and chemical discharge (Cooling Tower Institute, 2012).
- **Optimized fill media:** Advanced materials have enhanced thermal performance, enabling lower water use for the same heat rejection duty (USEPA, 2014).
- **Higher Cycles of Concentration (COC):** Operating at higher COC has been shown to reduce blowdown volume. Use of chemical treatment, side-stream filtration, and precise monitoring is required to control scaling and fouling. While typical COC ranges from 3–7, operation at 10+ is feasible with advanced management (CTI Guidelines).

3.2. Water-efficient steam cycle technologies.

Enhancements in thermal cycle efficiency have been recognized as a primary strategy for reducing cooling water needs in power generation.

1. **Supercritical (SC) and Ultra-Supercritical (USC) boilers:**
   - Steam conditions above the critical point (22.1 MPa, 374°C) are employed to improve Rankine cycle efficiency.
   - Water requirements have been reduced by 15–25% compared to subcritical units due to less waste heat being rejected (DOE/NETL, 2010; Macknick et al., 2012).
   - These technologies have been applied in modern coal-fired plants and proposed for use in advanced nuclear designs.
   - Advanced alloys and tighter control systems are required to withstand the extreme operating conditions.
2. **Combined Cycle Gas Turbine (CCGT/NGCC) plants:**
   - Waste heat from a gas turbine has been recovered in a heat recovery steam generator (HRSG) to drive a steam turbine, increasing overall efficiency.
   - Thermal efficiencies exceeding 60% have been achieved, leading to a significantly lower water footprint per MWh generated (IEA, 2021; EPRI, 2013).
   - Air-cooled condensers (ACCs) and hybrid systems are often integrated to further reduce water use, especially in water-scarce areas.
3. **Optimized steam turbine cycles and condensate management:**
   - Efficiency has been improved by the use of advanced turbine blades and sealing technologies.
   - Condensate polishing systems have been implemented to maintain high water purity, thereby allowing higher boiler cycles of concentration and reducing blowdown volumes (Cooling Technology Institute, 2012).
   - Steam and water losses have been minimized through continuous leak detection and repair programs, reducing makeup water needs.

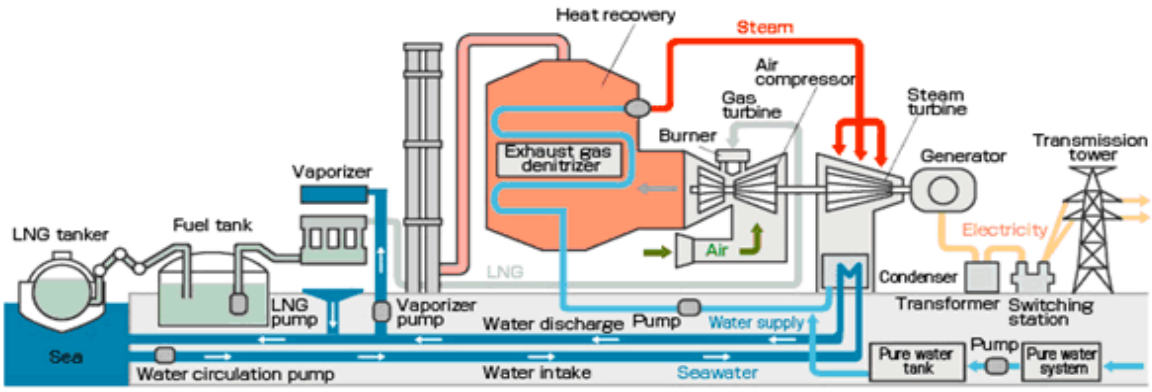

Fig.2. Combined Cycle System. [Source.https://www.araner.com/blog/combined-cycle-power-plants.]

4. Emerging technologies and innovative approaches for water optimization in power generation.

Innovative approaches and emerging technologies are increasingly being explored to address the growing need for water efficiency in power generation. In response to tightening environmental regulations and increasing water scarcity, research and development efforts have been directed toward the advancement of materials, cooling technologies, and water treatment methods. These technologies are being designed to reduce water withdrawal and consumption, improve heat transfer efficiency, and enable greater reuse and recovery of water resources. Their integration into power plant systems is being viewed as a critical step toward achieving sustainable and resilient energy-water systems in a changing climate.

1. Advanced Cooling Materials and Designs:

Significant advancements have been made in the development of materials with superior thermal conductivity and surface characteristics that enhance heat transfer efficiency. These materials are being investigated for application in air-cooled heat exchangers, with the goal of reducing both the physical footprint and capital costs of dry cooling systems. In particular, metamaterials engineered for passive radiative cooling have been explored for their ability to emit heat directly to outer space without relying on ambient air temperature, thus offering potential for supplemental cooling and thermal energy storage applications. Research under initiatives such as the ARPA-E STATIC program has highlighted the feasibility of these technologies for future integration into power plant systems (ARPA-E STATIC Project, 2020).

2. Membrane technology advancements:

Ongoing improvements in membrane technologies—such as reverse osmosis (RO), ultrafiltration (UF), and membrane distillation (MD)—have been aimed at increasing water flux, enhancing fouling resistance, and improving contaminant selectivity. These developments are expected to reduce the energy intensity and operational cost of water treatment and desalination processes. Membrane distillation, in particular, has been identified as a promising method for niche applications where low-grade or waste heat from the power plant can be utilized to drive water purification. These advancements support greater water reuse and improve the viability of zero-liquid discharge (ZLD) systems.

3. Biomimicry for water conservation:

Biologically inspired strategies have been investigated for their potential to reduce water loss and enhance collection efficiency. Mechanisms observed in nature—such as the moisture-harvesting capabilities of desert beetles and the surface microstructures of certain plant leaves—have informed experimental designs for cooling tower drift eliminators and fog-harvesting systems. While practical implementation at scale remains in early stages, such biomimetic approaches offer a promising avenue for reducing evaporative losses in water-intensive systems.

5. Integrating sustainable water management in power generation: Global practices and lessons.

As water scarcity has intensified across many regions, the importance of sustainable water management in the power sector has increasingly been recognized. Greater attention has been placed on optimizing water use to reduce environmental impacts and ensure long-term operational reliability. In response to regulatory pressures, climate variability, and rising competition for freshwater, innovative strategies have been adopted by power plants worldwide. These strategies have been tailored to local hydrological, climatic, and technological contexts.

Through the analysis of case studies, valuable insights have been gained into how water efficiency can be improved, alternative sources can be utilized, and environmental risks can be mitigated. Best practices have been shaped by real-world experience, where practical challenges have been addressed through engineering solutions, policy instruments, and stakeholder collaboration. By examining these examples, transferable lessons can be identified, and guidance can be offered for the design and operation of water-resilient power systems globally.

5.1. Innovative wastewater reuse in arid-region nuclear power: The Palo Verde experience.

Case Study 1: Palo Verde Generating Station – Reclaimed water use in nuclear power (Arizona, USA)

- **Context:**

Located in the Sonoran Desert of Arizona, the Palo Verde Generating Station—one of the largest nuclear power plants in the United States (≈3.9 GW)—was sited in an environment characterized by extreme aridity and a lack of perennial surface water. A sustainable cooling water solution was required due to the absence of nearby freshwater sources and the environmental and political constraints associated with groundwater and Colorado River water allocations.

- **Water challenge:**

A long-term, non-traditional water source had to be secured to support the facility's substantial cooling requirements. Freshwater withdrawals were deemed unsustainable due to scarcity and regulatory pressures.

- **Implemented solution:**

Treated municipal wastewater (reclaimed water) has been utilized for all cooling needs. Effluent from several municipalities in the Phoenix area has been transported via a 90-mile dedicated pipeline. Advanced onsite treatment—such as clarification, filtration, and chemical conditioning—has been applied to ensure water quality suitable for recirculating cooling tower use. The system has been operated at high cycles of concentration to reduce blowdown volumes and maximize water reuse.

- **Results:**

Freshwater consumption has been virtually eliminated for cooling operations, and over 20 billion gallons of reclaimed water have been reused annually [EPRI, 2012; DOE Water-Energy Nexus Report, 2014]. This has provided both economic and environmental benefits, avoiding impacts on critical regional water bodies and showcasing one of the largest wastewater reuse systems for power generation globally.

5.2. Lessons learned / best practices.

- Reclaimed municipal wastewater can be effectively used as a sustainable cooling source for large-scale thermal power generation.
- Long-term utility–municipal partnerships are essential for consistent supply and coordinated water quality management.
- Onsite water treatment systems must be designed for variable influent quality, supporting high-efficiency operations through increased cycles of concentration.
- This approach has been demonstrated as a replicable model for other arid or water-stressed regions seeking to balance energy and water demands.

6.1. Important research needs for improving water use in power generation.

- **Lifecycle water footprints:**

Although operational water use in power generation has been relatively well documented, significant research gaps have been identified in the comprehensive assessment of lifecycle water impacts. Standardized and robust lifecycle assessments (LCAs) are still lacking, particularly for emerging energy technologies such as advanced battery systems, hydrogen production methods, and next-generation nuclear reactors. These assessments must include water used in the extraction of raw materials, component manufacturing, system operation, and decommissioning phases. Greater methodological consistency is required to facilitate cross-comparison and policy-relevant decision-making (Gleick et al., 2011; DOE Water-Energy Nexus, 2014).

- **Cost-benefit analysis of water technologies under uncertainty:**

Current economic evaluations of advanced water technologies often fail to incorporate critical uncertainties related to future water availability, regulatory shifts, and the impacts of climate change. Improved cost-benefit analysis frameworks should be developed, wherein the risks of water scarcity, environmental penalties, and system resilience are monetized and integrated into long-term financial models. This would

allow more informed investment decisions in water-efficient technologies and better reflect their value under future climate and policy scenarios.

- **Optimization of Hybrid Systems:**

Hybrid wet/dry cooling systems, although increasingly adopted, still require further investigation to optimize their design and operation across varied climate zones and load conditions. The integration of real-time data, predictive control algorithms, and adaptive management principles into system operation has been recommended to balance water savings with performance efficiency and operational cost. Expanded field trials and modelling studies are necessary to inform best practices and to support wider deployment in regions with variable water availability (DOE NETL, 2013).

6.2. Climate change adaptation and adaptive management.

Projected climate scenarios indicate that power plant water management will be increasingly challenged by higher ambient temperatures and shifting hydrological patterns. These changes are expected to exert compound stresses on power generation infrastructure and water resources.

- **Increased cooling demand:**

Under elevated temperature conditions, the thermal efficiency of power plants is expected to decline, and the cooling demand is projected to increase. This is particularly critical for air-cooled and hybrid cooling systems, which exhibit reduced performance during heatwaves.

- **Reduced water availability:**

Diminished river flows, prolonged droughts, and variable precipitation patterns are anticipated to reduce the availability of water for cooling and other plant processes. These constraints will likely be exacerbated in already water-stressed basins (Macknick et al., 2012).

- **Need for adaptive strategies:**

To address these emerging risks, adaptive strategies must be implemented. These include investing in resilient cooling technologies (e.g., dry and hybrid systems), expanding the use of non-traditional water sources (e.g., municipal wastewater, brackish water), and adopting flexible operational protocols. The integration of adaptive management frameworks—which rely on iterative monitoring, evaluation, and policy adjustments—is strongly recommended. Power plant operators are also encouraged to participate in collaborative watershed-level planning initiatives to ensure sustainable regional water use and conflict mitigation (USGCRP, 2018; IPCC AR6, 2022).

Interdisciplinary collaboration will be essential in developing innovative and sustainable water solutions for the power sector. Joint efforts among engineers, environmental scientists, economists, policymakers, and social scientists are necessary to ensure energy reliability while minimizing water use and adapting to future climatic uncertainties.

7.Conclusion.

The intricate and often stressed relationship between power generation and water resources has been recognized as a defining challenge for sustainable development in the 21st century. As outlined throughout this article, a fundamental dependence on water for critical processes—primarily cooling and steam generation—has been exhibited by thermal power plants, placing considerable demands on freshwater resources that are becoming increasingly scarce and vulnerable due to climate change and competing demands.

The environmental consequences resulting from this water use—ranging from thermal pollution and hydrological changes to impacts on aquatic life and consumptive losses—have been underscored, reinforcing the urgency for optimization of water management practices within the sector. The multifaceted nature of this challenge has been highlighted, demonstrating that sustainable water use in power generation cannot be achieved through incremental improvements alone. Rather, a holistic approach has been deemed necessary—one that integrates technological innovation, operational excellence, and supportive, forward-looking policy frameworks.

A wide range of strategies have been examined in this context, including the deployment of advanced cooling technologies such as air-cooled and hybrid systems, the integration of water-efficient supercritical and combined cycle plants, and the implementation of advanced wastewater treatment and reuse systems that could potentially lead to Zero Liquid Discharge. Additionally, emphasis has been placed on meticulous water loss control and the application of operational best practices cantered around regular auditing, continuous monitoring, and data-informed decision-making.

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