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Water Resource Challenges in the Renewable Energy Transition: A Life Cycle and Climate Nexus Perspective

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Abstract:
Water resources management faces unprecedented challenges in the renewable energy transition process. This paper systematically analyzes the impacts of green energy technologies, including solar, wind, hydropower and bioenergy, on water resources from an energy life-cycle perspective, covering the dimensions of water extraction, water consumption, water pollution and ecosystem disturbance. The study found that, despite the significant advantages of renewable energy in terms of carbon reduction, some technologies (e.g., hydropower and biomass) have a high-water footprint during the operation or feedstock production phase, and may lead to deterioration of water quality, ecosystem fragmentation, and regional conflicts, especially in water-stressed areas. In addition, climate change is altering both water availability and renewable energy generation efficiency, exacerbating the risks of water-energy-climate coupling and creating negative feedback loops. The article emphasizes that to achieve a truly sustainable green transition, it is necessary to advance interdisciplinary integration of policymaking, low water-dependency technological innovations, and prioritize the deployment of energy systems with a low water footprint in water-stressed regions. Future research should focus on integrated governance and technological synergies under the water-energy-climate linkage mechanism to crack the structural contradiction between resource and environmental pressures and energy development.

Keywords: Renewable energy; Water-energy nexus; Hydropower.

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1. Introduction

With the intensification of global climate change, energy transformation has become a key strategy to deal with environmental problems. The use of fossil fuels has caused serious greenhouse gas emissions. According to statistics, from 2016 to 2020, the national electricity demand grew at a rate of 4.2-5.0%, of which more than 57% of the electricity supply is still dependent on fossil fuels [1], resulting in climate warming, and the ecosystem has been destroyed. Therefore, the development and application of green low-carbon energy has become a trend in global development. Green energy usually refers to low-carbon energy sources derived from nature, such as wind energy, solar energy, water energy, hydrogen energy, etc. These energy technologies can not only reduce carbon emissions, but Olabi [2] said that relying on renewable energy (RE) is the most promising way to get rid of fossil fuels as soon as possible. And the use of renewable energy can also promote the optimization of energy structure and sustainable development. For example, Stillwell et al. studied the relationship between energy and water in the United States and found that improving energy efficiency will promote the sustainable use of energy and water [3].

Among them, water resources play an important role in green energy production. In 2035, the water consumption of energy production will increase by 85%, which is due to the shift to more efficient power plants, greater water consumption, the increase in biofuel production, and the energy sector accounts for 10-15% of China's water consumption, ranking among all economic sectors. Second (First of all, the agricultural sector, which accounts for about 60-70% of the water volume) [4, 5]. For example, hydropower and thermoelectric power generation require a large amount of water resources to cool down, while some new energy technologies, such as the core of the PHS, pumped energy storage system, are a large-scale, reversible energy storage technology that uses the potential energy of water to store and release electricity [6].

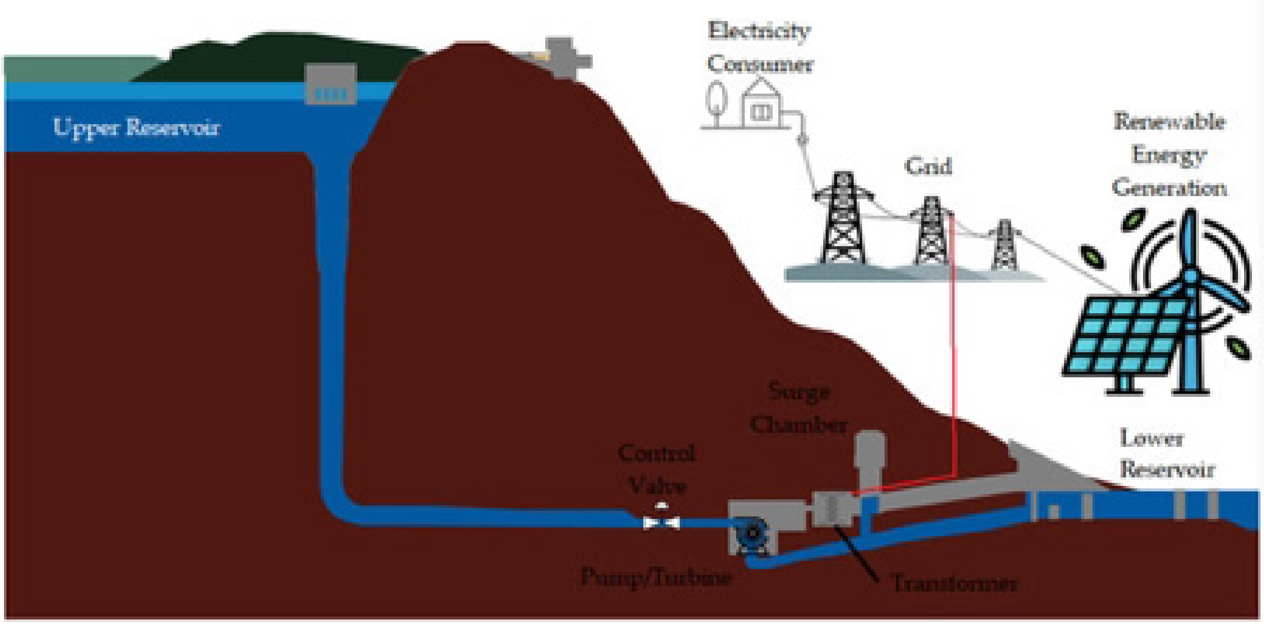

Fig. 1 A possible layout of a PHS system [6].

By using the simple principle of converting electrical energy into potential energy (and vice versa), the PHS system has proven to be an important part of the modern power grid, which can balance supply and demand and promote the integration of renewable energy.) A large amount of water resources may also be consumed in the process of energy production. How to balance the relationship between green energy development and water resources management has become a key issue in the transformation of green energy.

Green energy technology is developing rapidly, but it often consumes many water resources in the production process. How to realize the sustainable management of water resources while promoting the transformation of green energy is a key issue facing the world. By analyzing the water-energy coupling relationship, this research aims to provide a scientific basis for the formulation of a coordinated development strategy that considers energy security and water resources protection, which is of great practical significance for the realization of the United Nations Sustainable Development Goals (SDG 6 clean drinking water and SDG 7 affordable energy).

This study aims to systematically evaluate the impact mechanism of green energy technologies such as solar energy, wind energy and hydrogen energy on the balance of water resources supply and demand, deeply analyze the applicability of sustainable management models of water resources in different climate zones and put forward an optimization path based on the water-energy coupling model to provide regionally differentiated energy policies. Decision-making support to realize the synergy and win-win situation between green development and water resources safety (Fig. 1).

2. The relationship between green energy and water resources

The relationship between green energy and water resources is close and complex, with significant differences in the water requirements of different green energy technologies. Hydroelectric power generation is directly dependent on water resources, while solar photovoltaic power generation uses less water, but photovoltaic power generation requires cooling water; wind power does not consume water, but hydrogen energy production requires many water resources. Such differences make it necessary to comprehensively consider regional water resource endowments in the energy transition process and formulate differentiated green energy development strategies to achieve synergistic development of water resources and energy security. The following is an analysis of the water use of different types of renewable energy.

Hydropower, as the name suggests, uses a large amount of water resources to convert energy into electricity, so the demand and loss of water resources are very large. According to Bakken's reference [7], the data obtained in many references are not calculated according to consistent methods, which leads to research difficulties. And it is impossible to derive accurate values. In addition, due to the different calculation standards, there is a big difference between the data. For example, Herath said that the net water consumption is in the range of 45%-60% of the total water consumption [8], and whether to use the net evaporation rate and the total evaporation rate to calculate the water consumption is also to determine the dilemma on the data. Therefore, considering the standard and scope of measurement methods (all studies assume that the water consumption from the operation phase by far dominates the water consumption from the construction and decommissioning, and therefore neglects the water consumption from these phases [9]. The data adopted in this article is: that the average net water consumption of two hydropower plants in Norway is 37.8m2MHh-1[7], which is a very low total net consumption. The reason for the low is that the data was measured in relatively cold areas.

While often considered less water-intensive than conventional thermal power plants, solar and wind energy generation technologies still exhibit distinct water footprints that warrant careful consideration. The role of water in these renewable energy systems varies significantly based on the specific technology.

For solar energy, the primary distinction lies between photovoltaic (PV) and concentrated solar power (CSP) systems. PV panels, which directly convert sunlight into electricity, typically have minimal operational water requirements. Their main water demand comes from module cleaning, particularly in dusty or arid environments, to maintain efficiency [10]. The water usage for PV can range from virtually zero in self-cleaning or rain-washed areas to about 0.2 to 100 liters per megawatt-hour (L/MWh) for regular washing [11]. In contrast, CSP plants, which use mirrors to concentrate sunlight and heat a fluid to produce steam for a turbine, resemble traditional thermal power plants in their water needs. CSP facilities employing wet-cooling systems can be water-intensive, consuming substantial amounts for cooling towers to condense steam, often ranging from 2,000 to 3,500 L/MWh. However, using dry-cooling or hybrid-cooling technologies can significantly reduce this water footprint, though at a higher cost and potentially lower efficiency [12]. Water is also used for cleaning the mirrors or heliostats to optimize light reflection.

Wind energy, conversely, is widely recognized as one of the least water-intensive electricity generation technologies. Wind turbines do not directly use water in their electricity generation process, as there is no steam cycle or direct heat transfer involved. The marginal water consumed in wind power generation is predominantly associated with manufacturing components, minor cleaning, and occasional maintenance activities [13]. Lifecycle water consumption for wind power is remarkably low, often cited as less than 20 L/MWh, making it a highly water-efficient energy source [14].

Water plays a foundational role in the burgeoning field of hydrogen energy generation, particularly for producing "green hydrogen" and its subsequent use in fuel cell systems. The most critical function of water is serving as the primary feedstock for electrolysis, an electrochemical process where renewable electricity is used to split water molecules (H_2O) into high-purity hydrogen (H_2) and oxygen (O_2) [15]. This method is pivotal for achieving zero-carbon hydrogen production. For efficient electrolysis, high-purity water is typically required, necessitating pre-treatment such as deionization, which itself can entail minor water losses. While theoretically, 9 kilograms of

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water are needed to produce 1 kilogram of hydrogen, practical operations, accounting for water purification, cooling demands within the electrolyser system, and evaporative losses, typically consume between 18 to 24 kilograms of water per kilogram of hydrogen produced [16].

Conversely, water emerges as the sole and clean byproduct during electricity generation in fuel cells, where hydrogen reacts with oxygen [17]. This process essentially reverses electrolysis, demonstrating a closed-loop potential for water management in a future hydrogen economy. Despite the water input required for hydrogen production, its overall water footprint can be competitive, or even more favorable, than that of some conventional energy generation methods. For example, studies indicate that the operational water consumption for hydrogen-derived electricity can be significantly lower than that from fossil fuel or nuclear power when assessed across the entire lifecycle [11]. Effective water resource management, including the potential for recycling water from fuel cell output, is therefore paramount for the sustainable scaling of hydrogen energy, especially in regions facing increasing water scarcity.Page Numbers

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3. Water Resource Implications across the Energy Life Cycle

3.1 Life cycle impact of water resources

The pursuit of sustainable energy necessitates a comprehensive understanding of water resource impacts throughout the entire energy life cycle, from resource extraction and manufacturing to operation, and waste management. While many renewable energy sources are often perceived as less water-intensive than fossil fuels, their overall life cycle water footprint can still be significant and varies widely by technology, resource type, and geographical context [18]. This includes both water withdrawals (water removed from a source) and water consumption (water not returned to the source).

For instance, in solar photovoltaics (PV) and wind power, the predominant portion of water consumption often occurs during the upstream manufacturing phases, encompassing processes like material refining, component fabrication, and transportation. Operational water use for PV is primarily for module cleaning, particularly in arid regions, while wind turbines typically exhibit negligible operational water demands [19]. Conversely, concentrated solar power (CSP), especially when employing wet-cooling systems, can be highly water-intensive during its operational phase, closely resembling the substantial water consumption of traditional thermal power plants. Furthermore, water resources can be impacted during the decommissioning and waste treatment of energy infrastructure, for example, in processing materials for recycling or disposing of hazardous waste. Addressing these multi-faceted water demands and ensuring sustainable water management across the full energy value chain is therefore crucial for genuinely sustainable energy transitions [18, 19].

The transition to renewable energy is vital for mitigating climate change, but it presents substantial challenges for water resource management. These challenges arise from the uneven distribution of water, the potential for pollution and overconsumption by certain green energy technologies, and the complex, reciprocal impacts of climate change on both water availability and renewable energy output. Addressing these interconnected issues is crucial for achieving a truly sustainable energy transition.

3.2 Challenges in Water Resource Management

Geographical Imbalance of Water Resources and Regional Conflicts

The global distribution of freshwater resources is uneven, a disparity intensified by increasing demand and the widespread effects of climate change. This poses a significant barrier to sustainable development and energy transition. Projections indicate that by 2025, up to 4.8 billion people could reside in water-stressed nations, highlighting the urgency of the water crisis [20]. Climate change acts as a “threat multiplier” rather than a direct cause of conflict, intensifying existing socio-political challenges and exacerbating competition over vital resources like water [21, 22]. Water conflicts are defined as disagreements leading to non-violent or violent actions between parties concerning freshwater management and distribution [21].

Regional differences in conflict factors are evident. For instance, farmer-herder conflicts are common in Africa, while water-related conflicts in Asia are more closely tied to governance and water management issues [21]. The Syrian conflict, for example, has been partly attributed to climate change-induced water scarcity and poor water management, leading to large-scale rural-to-urban migration [23].

The development of hydropower projects, while contributing to low-carbon energy goals, can lead to significant socio-environmental impacts, including population relocation, changes in water quality, and alterations to land and aquatic communities [24, 25]. These projects often involve altering natural water flows, causing irreversible impacts on natural habitats and local populations, including forced displacement [26]. Transboundary river basins are particularly susceptible to conflicts arising from hydropower development [27]. The construction of upstream dams, such as those in the Mekong River basin or the Grand Ethiopian Renaissance Dam in the Nile basin, can profoundly alter downstream water availability, escalating geopolitical tensions and affecting multilateral relations [28]. Conversely, some renewable energy solutions, like solar photovoltaic (PV) systems, have demonstrated the capacity to ensure reliable water supply in conflict-affected regions, as seen in Syria, suggesting their potential to mitigate conflict when appropriately deployed [23]. The widespread water stress predicted for 2025 necessitates immediate and integrated water-energy planning, as any water-intensive energy development in these regions will inevitably intensify existing tensions [20].

Water Pollution and Resource Overconsumption from Renewable Energy Technologies

While renewable energy technologies are crucial for decarbonization, certain applications, particularly hydropower and bioenergy, can lead to substantial water pollution and resource overconsumption, impacting ecosystems and human health.

3.3 Hydropower's Environmental Footprint

Hydropower dams and reservoirs can severely degrade water quality. This includes the release of nutrients from submerged biomass, leading to reduced oxygen levels and harmful algal blooms in downstream water bodies. Some algal blooms are toxic, posing risks to human health and aquatic life, and affecting water taste and odor [26]. The long-term presence of reservoirs can also facilitate mercury biomagnification within the food chain, presenting significant health risks to local communities reliant on aquatic food sources [26]. Furthermore, thermal pollution can occur from construction activities and the discharge of water from deeper, colder reservoir layers [26].

Hydropower profoundly modifies environmental conditions and alters river connectivity, which is crucial for riverine species [26]. Dams act as physical barriers, impeding the upstream-downstream movement of migratory fish and other aquatic organisms, leading to reduced gene flow and potential local extinctions [26]. Reservoirs transform flowing river environments into still-water habitats, affecting sediment retention, nutrient concentrations, and favoring generalist species over those adapted to flowing water [26]. The operation of hydropower, particularly flexible hydropower production (hydropeaking), significantly alters downstream flow conditions. These rapid, sub-daily flow changes can cause acute impacts like fish stranding during down-ramping events and chronic effects on community composition [29]. Additionally, reservoir evaporation losses contribute to water consumption, directly affecting reservoir water supply [30].

Despite hydropower's low-carbon advantages, its extensive and severe environmental impacts, including mercury biomagnification, algal blooms, and profound ecosystem fragmentation, reveal that its "green" label does not equate to comprehensive environmental sustainability [26]. These impacts represent long-term ecological degradation and public health risks often overlooked in the broader context of renewable energy transition. This necessitates comprehensive environmental impact assessments beyond carbon emissions to encompass water quality, biodiversity, and human health, ensuring that energy transition does not inadvertently create new environmental crises. The operational flexibility of hydropower, valuable for integrating intermittent renewables like wind and solar into the grid, creates a fundamental dilemma: how to achieve grid stability without compromising riverine biodiversity [31, 32]. This implies a need for grid stabilization technologies that are less water-dependent or ecologically damaging, or strict regulation of hydropower operations to prioritize ecological flows, even if it means some reduction in flexibility or energy output.

3.4 Bioenergy's Water Footprint and Competition

Biofuel production has a substantial water footprint, with nearly all water consumption occurring during the agricultural activities required to produce feedstocks [33]. Producing one liter of biofuel can require between 500 and 2000 liters of water, with demand varying based on feedstock type, soil, and climate [34]. Agrochemicals used to boost biofuel crop yields can leach into surface water bodies, causing pollution [34].

Large-scale biomass production inherently competes with

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agricultural systems for critical natural resources like land and water [34]. "First-generation biofuels," derived from starch, sugar, and oil crops, are particularly problematic as they directly compete with food production for land and "blue water" (irrigation water) [33]. This raises serious food security concerns, especially in water-stressed regions, where the inclusion of water-intensive crops like rapeseed in energy strategies is not recommended. "Second-generation biofuels," derived from residues, generally have lower water and carbon footprints and reduce the need for additional farmland [34]. The distinction between "green water" (precipitation) and "blue water" (irrigation) is crucial in bioenergy production. While woody crops primarily utilize green water, oil crops and first-generation biofuels heavily rely on blue water, which directly competes with other essential freshwater uses like drinking water and food agriculture. This means that not all water footprints have the same environmental impact, and policies must prioritize bioenergy feedstocks and cultivation practices that minimize blue water consumption, especially in water-stressed areas, to mitigate competition with food production and human needs.

3.5 Dual Impact of Climate Change on Renewable Energy Output and Water Availability

Climate change exerts profound dual impacts, directly altering water resource availability and distribution while simultaneously affecting the output and reliability of climate-dependent renewable energy sources, thereby creating complex feedback loops within the water-energy nexus.

Climate change significantly influences water resources in terms of both quantity and quality, primarily through shifts in precipitation patterns, temperature, snowmelt, evapotranspiration, and river discharge [35]. Future projections indicate a reduction in terrestrial water storage (TWS) in many regions, particularly in the Southern Hemisphere, leading to increased drought severity [36]. By the end of the 21st century, the global land area and population experiencing extreme-to-exceptional TWS drought could more than double [37]. This altered water availability will result in a more water-constrained future, impacting the energy sector and potentially driving up energy costs [37, 38].

Regarding renewable energy production, run-of-river (RoR) hydropower projects are highly susceptible to climate change impacts, with significant reductions in pre-monsoon energy generation (up to -53%) projected due to decreased streamflow [39]. In contrast, reservoir-based hydropower projects demonstrate greater resilience and adaptive potential through optimized operations, with annual energy generation potentially increasing (up to +7.3%) even under changing conditions [35]. Climate change is likely to alter river flows, rendering historically developed reservoir operation strategies inapplicable [39]. The stark difference between RoR and reservoir-based hydropower projects under climate change highlights a critical finding: RoR projects, lacking storage capacity, are highly vulnerable to climate-induced hydrological variability, risking substantial generation declines. Conversely, reservoir projects, with their storage and optimization potential, show greater resilience and can even increase output. This implies that future hydropower development and management strategies must prioritize flexible, storage-based systems and advanced operational optimization over RoR projects, which may become increasingly unreliable and unsustainable in a changing climate.

For solar and wind energy, while the overall climate impact is considered minor globally, regional variations are significant [37]. For example, India may experience a decrease in solar energy use, while parts of Brazil could see an increase. The impacts on wind energy remain uncertain, with projections showing declines in some regions and increases in others. Concentrated solar power (CSP) plants, often located in arid areas, require substantial cooling water, exacerbating pressure on already scarce resources. Climate change may lead to increased bioenergy availability, contingent on the strength of the CO2 fertilization effect. However, as previously noted, bioenergy production itself has significant water demands and involves land-use considerations.

The water-energy nexus underscores a fundamental interdependence: water is consumed in all stages of energy production, while energy is essential for water management (extraction, treatment, distribution) [33, 40]. Climate change-induced water scarcity increases the demand for energy-intensive water solutions, such as desalination and wastewater treatment [33] These processes currently account for 2-3% of global energy consumption and are often powered by fossil fuels, thereby contributing to greenhouse gas emissions and further exacerbating climate change. This creates a detrimental feedback loop were addressing water scarcity through energy-intensive means, if not decarbonized, inadvertently worsens climate change. The increased demand for energy-intensive water solutions (e.g., desalination) due to climate change-induced water scarcity creates a critical "trap" in sustainable transitions: if this increased energy demand is met by fossil fuels, it will exacerbate climate change, which in turn will worsen water scarcity, forming a vicious cycle. This highlights the urgent need to decarbonize the "energy-for-water" sector itself, for instance, by powering desalination plants with dedicated renewable energy sources, to break this feedback loop and ensure a truly sustainable water-energy future.

4. Conclusion

Water resources play a pivotal role in the renewable energy transition, with their management challenges profoundly influencing global sustainable development. This study has elucidated the intricate impacts and challenges posed by the green energy transition on water resource management, emphasizing the complexities arising from geographical water imbalances, water pollution and overconsumption, and the dual effects of climate change.

The findings underscore that water scarcity is an escalating global crisis, with a significant portion of the world's population projected to face water stress by 2025, necessitating immediate and integrated water-energy planning. While renewable energy is indispensable for climate mitigation, large-scale hydropower projects can exacerbate water conflicts and environmental degradation, including mercury biomagnification and ecosystem fragmentation, indicating that their "green" label is not universally comprehensive. Furthermore, an inherent tension exists between hydropower's operational flexibility and ecological integrity, while bioenergy's reliance on "blue water" intensifies competition with food production. Climate change not only directly impacts water availability but also differentially affects the output of various renewable energy sources, particularly highlighting the vulnerability of run-of-river hydropower. Finally, a detrimental feedback loop exists within the water-energy nexus, where increased energy consumption to address water scarcity, if reliant on fossil fuels, can paradoxically worsen climate change.

The significance of this research lies in its emphasis on the imperative for a deep, interdisciplinary consideration of the complex challenges facing water resource management amidst climate change and energy transition. Future research should intensify its focus on the interrelationship between green energy and water resources, especially in the context of global energy transformation, escalating climate change, and increasing water scarcity, to explore innovative technological solutions, integrated policy frameworks, and effective governance mechanisms that can pave the way for truly sustainable development.

References

[1] Dai Jiangyu, Wu Shiqiang, Han Guoyi, Weinberg Josh, Xie Xinghua, Wu Xiufeng, Song Xingqiang, Jia Benyou, Xue Wanyun, Yang Qianqian. Water-energy nexus: A review of methods and tools for macro-assessment. Applied Energy, 2018, 210: 393-408.

[2] Olabi A.G., Abdelkareem Mohammad Ali. Renewable energy and climate change. Renewable and Sustainable Energy Reviews, 2022, 158: 112111.

[3] Duan Cuncun, Chen Bin. Energy–water nexus of international energy trade of China. Applied Energy, 2017, 194: 725-734.

[4] Duan Cuncun, Chen Bin. Driving factors of water-energy nexus in China. Applied Energy, 2020, 257: 113984. https://doi.org/10.1016/j.apenergy.2019.113984.

[5] Al-Saidi Mohammad, Elagib Nadir Ahmed. Towards understanding the integrative approach of the water, energy and food nexus. Science of The Total Environment, 2017, 574: 1131-1139.

[6] Nikolaos P. C., Marios F., Dimitris K. A Review of Pumped Hydro Storage Systems. Energies, 2023, 16(11): 4516.

[7] Bakken Tor Haakon, Killingtveit Ånund, Alfredsen Knut. The Water Footprint of Hydropower Production—State of the Art and Methodological Challenges. Global Challenges, 2017, 1(5): 1600018.

[8] Herath Indika, Deurer Markus, Horne David, Singh Ranvir, Clothier Brent. The water footprint of hydroelectricity: a methodological comparison from a case study in New Zealand. Journal of Cleaner Production, 2011, 19(14): 1582-1589.

[9] Bakken Tor Haakon, Modahl Ingunn Saur, Engeland Kolbjørn, Raadal Hanne Lerche, Arnøy Silje. The life-cycle water footprint of two hydropower projects in Norway. Journal of Cleaner Production, 2016, 113: 241-250.

[10] PV Magazine. (2023). Optimizing PV Cleaning Strategies for Arid Regions. https://www.pv-magazine.com

[11] Macknick, J., Newmark, R., Heath, G., & Hallett, K.C. (2012). Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies: A Review of Existing Literature. National Renewable Energy Laboratory (NREL). NREL/TP-6A20-56900. https://www.nrel.gov/docs/fy12osti/56900.pdf

[12] International Renewable Energy Agency (IRENA). (2021). Water Use in Concentrated Solar Power: A Global Outlook. Publication. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Water_use_CSP_2021.pdf

[13] American Wind Energy Association (AWEA). (2020). The Environmental Benefits of Wind Power. Fact Sheet. https://cleanpower.org/resources/the-environmental-benefits-of-wind-power/

[14] U.S. Department of Energy (DOE). (2019). Water Use in U.S. Electricity Generation: An Update. Report. https://www.energy.gov/

[15] International Energy Agency (IEA). (2019). The Future of Hydrogen: Seizing today's opportunities. Report. IEA. https://www.iea.org/reports/the-future-of-hydrogen

[16] Dawood, F., & Višković, A. (2020). Water Consumption in Hydrogen Production via Electrolysis: A Review. Journal

ISSN 2959-6157

of Cleaner Production, 275, 123847. https://doi.org/10.1016/j.jclepro.2020.123847

[17] Wang, Y., Chen, K. S., & Chou, S. K. (2011). Fuel cell: Current technology status and future prospects. Progress in Natural Science, 21(6), 614-621. https://doi.org/10.1016/j.pnsc.2011.11.002

[18] Stillwell, A. S., Hoang, H. M., & VanBriesen, J. M. (2018). Water-energy nexus: A review of the literature for water resources and energy researchers. WIREs Water, 5(3), e1296. https://doi.org/10.1002/wat2.1296

[19] Stokes, E. C., & Horvath, A. (2014). Life-cycle water consumption of solar photovoltaics and wind power in the Southwestern United States. Environmental Science & Technology, 48(16), 9924-9931. https://doi.org/10.1021/es502409f

[20] Ayt Ougougdal, H., & El-Khori, M. (2023). More than 2.4 billion people have lived in water-scarce countries since 2000, and by 2025, that figure is predicted to increase to 4.8 billion. UNICEF.

[21] Kåresdotter, E., Destouni, G., Lammers, R. B., & Keskinen, M. (2024). Water conflicts under climate change: Research gaps and. PLoS Water, 3(1), e0000128.

[22] United Nations Climate Change. (2020). Climate change is now seen as a pressing global issue with severe implications for vulnerable regions. United Nations Climate Change.

[23] Alfandi, M., & Seçkiner, S. U. (2025). Renewable energy and greenhouse gas reduction for water supply in conflict-affected Syria. Renewable and Sustainable Energy Reviews, 211, 115353.

[24] Al-Ghussain, L., Al-Abed, M., & Al-Abed, S. (2023). The major negative impacts are changing in water quality, relocation of people, changes in the structure of the land and aquatic communities, loss in agriculture production, landslides and slopes destabilization and changing in climate. Sustainability, 15(21), 15467.

[25] Karacan, A. (2015). THE TRIPLE CONFLICTS IN HYDRO PROJECTS: ENERGY, ECONOMY AND ENVIRONMENT. Journal of Environmental Protection, 6(05), 441.

[26] He, J., Li, Y., & Zhang, Y. (2024). Hydropower impacts on riverine biodiversity. Nature Reviews Earth & Environment.

[27] Munia, H., Rigi, M., & Warner, J. (2023). Transboundary river basin conflict risk under climate change and hydropower development. International Journal of Water Resources Development, 39(2), 263-285.

[28] Dartmouth. (2025). Using conflicts over hydropower development in the Mekong River basin, this project brings together research and education activities to explore how environmental knowledge production and circulation influences the governance of, and conflicts over, hydropower development. Dartmouth.

[29] Antonetti, J., Hayes, M., & Hayes, M. (2025). Environmental impact of hydropower: A systematic review of ecological effects of sub-daily flow. Pacific Northwest National Laboratory.

[30] Sibale, D., Kranjac-Berisavljevic, G., & Abdul-Ganiyu, S. (2021). Impact of Reservoir Evaporation Losses on Water Demand: A Case Study of Bontanga Reservoir, Northern Region of Ghana. Journal of Water Resources Management, 1(1), 7-17.

[31] Al-Shetwi A Q. Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges[J]. Science of The Total Environment, 2022, 822: 153645..

[32] PNNL. (2025). Hydropower operation in future power grid with various renewable power integration. PNNL.

[33] Popescu, F., & Popescu, L. (2023). Water Energy Nexus and Energy Transition—A Review. Energies, 16(4), 1879.

[34] Warner, E., Daioglou, V., & van Vuuren, D. P. (2020). Projected water usage and land-use-change emissions from biomass production (2015–2050). Renewable and Sustainable Energy Reviews, 120, 109657.

[35] Piao, S., Grafton, R. Q., Li, W., & Habib-ur-Rahman, M. (2024). Climate change impact on hydropower generation and. Journal of Water and Climate Change, 15(9), 4631-4648.

[36] Shrestha, S., & Baniya, S. (2021). Climate change impact on hydropower generation and. Journal of Water and Climate Change, 15(9), 4631-4648.

[37] Al-Ghussain, L., Al-Abed, M., & Al-Abed, S. (2025). Integrating renewable energy for power security under water stress scenarios due to climate change: Strategies and opportunities. ResearchGate.

[38] ResearchGate. (2025). Integrating renewable energy for power security under water stress scenarios due to climate change: Strategies and opportunities. ResearchGate.

[39] Alotaibi, A., & Al-Abed, S. (2023). Climate change leading to global warming and other associated concerns is expected to result in rising temperatures and precipitation deficit making water scarcity worse in the near future. Cambridge Prisms: Water, 1(1), e1.

[40] U.S. Department of Energy. (2014). The Water-Energy Nexus: Challenges and Opportunities. DOE/EE-1042.