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The Convergence of Renewable Energy and Aquacultural Engineering for a Sustainable Food System

Priyanka Roy[1], Asaruddin Sheikh[2], Diwakar Kumar[3], Pranjal Saikia[4]
Department of Agricultural Engineering, Triguna Sen School of Technology, Assam University, Silchar-788011, India

Abstract: Renewable energy and aquacultural engineering combine to provide a disruptive approach to developing a sustainable and resilient food supply. This area of aquacultural engineering would automate feeding systems, oxygenation, recirculating aquaculture systems, and water quality monitoring by integrating renewable energy sources such as sun, wind, hydropower, and bioenergy. In order to improve the efficiency of freshwater and marine aquaculture systems, energy from renewable sources will reduce waste and maximize the usage of IoT and AI toward resource efficiency. For the agricultural sector, implementing renewable energy will diminish greenhouse gas emissions, reduce operations cost, and create energy independence for farms especially off-grid and remote ones. Diversification promotes eco-friendly practices such as IMTA and biofloc systems, increasing the organization's resilience to energy volatility and climate change. Although there are obstacles in the form of high upfront costs and integration complexity, renewable technology and hybrid systems do offer a viable solution. Through the preservation of ecological balance and the provision of a sustainable food supply for future generations, this combination of renewable energy and aquacultural innovation has the potential to completely transform aquaculture.
Keywords: Renewable energy, Aquaculture, SolarPV, Offshore wind, GHG emissions, Technology adoption

I. INTRODUCTION

The increasing growth of the world's population has brought up concerns on food security and sustaining current agricultural use. Currently, it is projected that the world population will be 9.7 billion in 2050 [1]. Given that the major supplier of seafood comes from aquaculture, which provides more than 52% of all seafood consumed worldwide [2], it has been one of the answers and a significant part of global food systems. Aquaculture allows for the scaling and controlling of the increasing demand for aquatic protein as wild fish stocks decline due to overfishing and habitat degradation. Yet, estimates currently indicate that traditional aquaculture systems emit significant levels of GHG, amounting to nearly 5% of global emissions [3], are energy intensive, and highly reliant on fossil fuels. It leads to significant environmental problems, such as habitat deterioration, water pollution, and high operating expenses, due to this unsustainable energy dependence. Technology for renewable energy with aquacultural engineering is a pioneering solution to these problems. Renewable sources of energy, such as solar photovoltaics (PV), offshore wind, and biofuel, can be used to improve the efficiency of aquaculture systems, minimize their carbon footprint, and reduce their operational costs. AI-optimized energy management and hybrid systems of renewable energy add to these promising possibilities regarding the resilience and feasibility of energy and cost. Thanks to these technologies, aquaculture is now a more sustainable and scalable way to provide food on a global scale while also resolving environmental and economic problems.

Renewable energy adoption in aquaculture is not merely a choice but a necessity. Current aquaculture operations face several challenges

Aspect	Challenges in Traditional Aquaculture	Benefits of Renewable Energy Integration
Energy dependence	Overreliance on fossil powers for water pumping, air circulation and warm-up. Vitality costs account for 30–50% of add up to operational costs [4].	Sun-oriented PV frameworks can decrease vitality costs by up to 35%. Reliable vitality supply through wind and half-breed frameworks
Environmental impact	High GHG emanations (5% of worldwide outflows) from fossil fuel utilize [5]. Supplement over-burdening and living space lowering in.	Decreased outflows: Seaward wind reduces CO_2 by 60%. Cleaner operations with bioenergy transforming waste into usable energy in [4].

Energy solutions	Existing vitality frameworks bound versatility.	Half breed frameworks improve power dependability by up to 50–70%.Dependence on non-renewable vitality [2].
Global trends	Dependence on non-renewable energy sources.	China, Norway, and India set examples with sun powered PV and seaward wind [6].

This review discusses the integration of renewable energy technologies with aquacultural engineering towards building sustainable food systems. It provides a detailed analysis of renewable energy applications, such as solar PV, offshore wind, bioenergy, and hybrid systems, into the impact of energy efficiency, cost reduction, and GHG emissions. Based on real-world cases this paper discusses the opportunity for transforming aquaculture into a sustainable and scalable food production system through renewable energy. Other policy issues, economic factors, and future advancements into the realms of AI-optimized energy systems and co-location of renewable and aquaculture infrastructure are discussed. We present, by way of this review, a comprehensive roadmap for researchers, policymakers, and industry stakeholders to harness renewable energy as a key enabler to sustainable aquaculture and global food security.

II. RENEWABLE ENERGY TECHNOLOGIES IN AQUACULTURE

Aquaculture is experiencing an innovative integration of renewable energy technologies that offer energy-efficient solutions to high energy demands in the sector [7]. In addition to reducing greenhouse gas emissions, their adoption reduces operating costs significantly, making aquaculture more viable and environmentally friendly. Below is a overview of the main renewable energy technologies used in aquaculture together with their respective quantitative data and specific use cases.

A. *Solar Photovoltaic Systems*

Solar photovoltaic systems are an innovative solution for powering aquaculture operations by converting sunlight into electricity [8]. These systems offer significant advantages, including energy cost savings of up to 30–50%, and their scalability makes them suitable for both small and large operations [9], [10]. Applications of solar PV systems in aquaculture include powering aeration devices to supply oxygen to fish ponds, turning over water in holding tanks, and supporting automation and lighting systems such as automated feeders and LED lights in indoor aquaculture facilities. Solar photovoltaic systems are increasingly being integrated into aquacultural operations to power automated feeding and water monitoring systems. Similar to crop health monitoring with Python-based Raspberry Pi systems can facilitate real-time monitoring of aquaculture ponds [11]. Real-world examples highlight their impact; for instance, shrimp farmers in India using solar-powered aerators reported a 25% increase in profitability. Despite the high initial capital costs, the payback period is typically achieved within 3–5 years [12]. Case studies further illustrate the potential of solar PV systems. For example, solar-powered water pumps in Indian aquaculture ponds reduced energy costs by 30%, with annual savings estimated at $500 per hectare [13]. New innovations, such as floating solar PV systems installed on aquaculture ponds, not only generate renewable energy but also reduce water evaporation by 10–20% [14]. Globally, the capacity of solar PV systems reached 1,140 GW in 2023, demonstrating their role in addressing energy demands in aquaculture (Annamalai & Prabha, 2023). These systems contribute significantly to operational efficiency, providing a sustainable and cost-effective energy solution for the aquaculture sector **(Figure 1).**

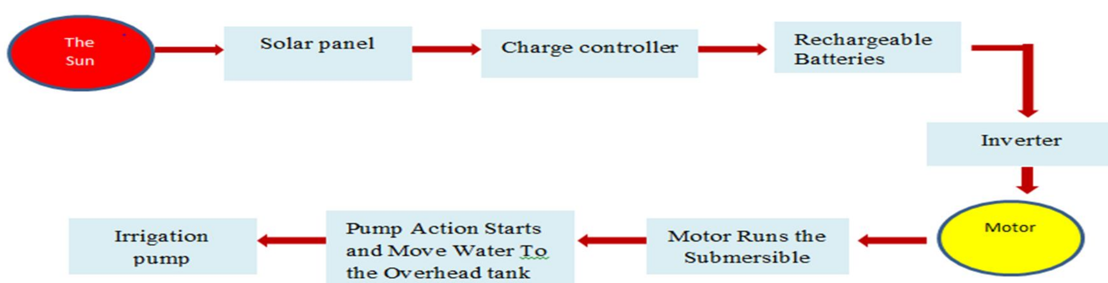

Figure 1. Diagram a solar PV system powering and pumping systems in aquaculture facilities.

B. Offshore Wind Energy

Since offshore wind energy is created consistently and efficiently, it stands as one possible solution for the coastal aquaculture facilities [16]. Offshore wind farms also produce twice to thrice the electricity compared to that of the onshore systems that reduce fossil fuel dependency with a consistent power supply [16], [17]; this also decreases the emission of up to 60% of CO_2, thus decreasing the impact caused by climate change [16]. Long-term cost-effectiveness in energy is achieved by offshore wind adoption since it stabilizes coastal operation energy prices. Examples of practical applications in aquaculture for integration with offshore wind energy include electricity powering automated monitoring systems, water pumps, fish farming cages, and ancillary structures like processing and cold storage facilities. The two are Offshore wind turbines erected alongside the South China Sea Aquaculture Cages, Norway Hywind Tampen Floating Wind Farm [18]. With despite challenges, expansion in offshore wind energy is positive, with an expected annual growth of 15% up to 64 GW by 2023 [19]. The prospects for offshore wind offer an aquaculture-friendly option, with further improvements in floating turbine technology ensuring a future-proof coastal community. Offshore wind turbines provide a consistent renewable energy source for marine aquaculture farms. Innovations in 3D printing have been instrumental in creating durable and cost-efficient components for these systems [20], [21]

C. Bioenergy and Waste-to-Energy Systems

Anaerobic digestion in particular provides a sustainable mechanism of managing aquaculture wastes while producing renewable energy through the bioenergy technologies. This process converts organic wastes, for example, fish feces and feed residues, to power or biogas. Bioenergy offers a twin solution for operational efficiency as well as environmental sustainability while dealing with waste management as well as energy production. By converting trash into useful energy and nutrient-rich manure, bioenergy systems have the potential to cut pollution by 50-70% [22]. Bioenergy derived from organic waste products can power recirculating aquaculture systems (RAS). IoT-based solenoid-controlled pressure regulation systems have shown promise in enhancing bioenergy utilization [23].These systems not only save money but also reduce the number of pollutants in the environment. For instance, biogas generation solves waste disposal problems and allows aquaculture companies to use organic waste for the generation of energy that can be used on site. In addition, using nutrient-rich leftovers as fertilizers promotes the circular economy. Examples from the real world demonstrate the feasibility and benefits of these systems. Bioenergy technologies have helped fish farms in Brazil reduce their waste disposal costs by 40% [24]. Similarly, a Danish fish farm used the biogas produced to meet 25% of its energy requirements and reduced waste disposal costs by 45% [25]. These examples illustrate how bioenergy systems can enhance operational economics and sustainability. Despite these advantages, there are still challenges. Setting up a waste-to-energy system requires specialized knowledge and infrastructure that can be very resource-intensive in the beginning. But there are major potential benefits. For example, 50–70% of organic waste can be converted with anaerobic digesters, generating energy worth about $10,000 per hectare per year [26]. New integrated systems that combine aquaculture and agricultural waste streams further enhance biogas production, offering creative opportunities for sustainability and resource efficiency. In conclusion, bioenergy and waste-to-energy systems with associated energy demands and waste management are very suitable for the business of aquaculture in terms of environmental and financial goals (Figure 2).

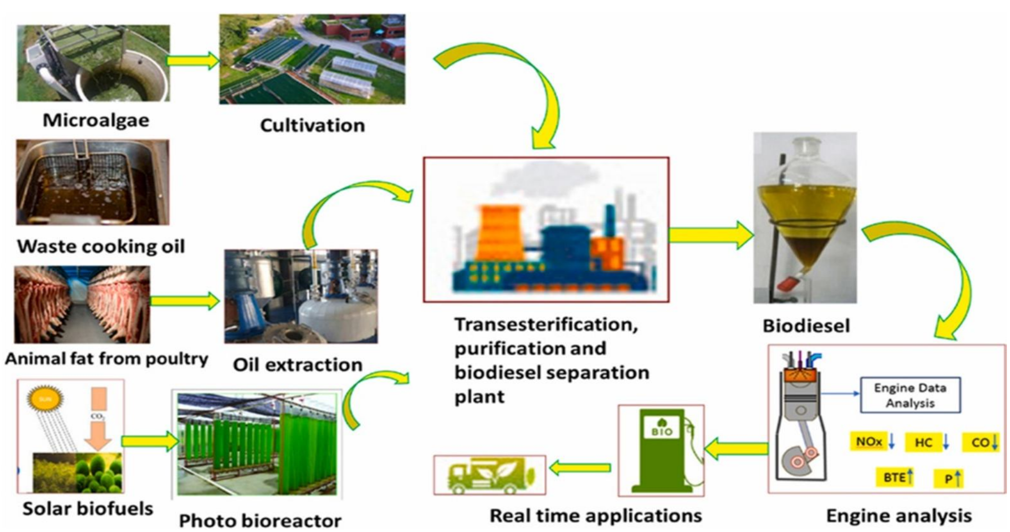

Figure 2. Showing waste-to-biogas conversion

D. Hybrid Renewable Energy Systems

Aquaculture businesses can count on hybrid renewable energy systems that bring together solar, wind (WE), and bioenergy technology for a regular and dependable power source [27]. These systems are particularly useful in regions that have unpredictable weather patterns since they offset the unpredictability of individual renewable sources. For vital aquaculture functions such as lighting, aeration, and surveillance systems in offshore farms, they can provide continuous electricity. For aquatic species, this reliability is crucial in maintaining ideal conditions, especially in environments where power failure may compromise animal health or productivity. According to case studies, a hybrid of solar and wind technology in Vietnam decreased energy costs for aquaculture operations by 45% [28], while hybrid systems helped shrimp farms in Indonesia save 40% on electricity [29]. But there are some drawbacks associated with deploying hybrid systems: they require careful system design and hefty upfront expenses. These barriers are being overcome by technological advancement; hybrid systems increase energy reliability by 50–70%. The sustainability and economic viability of hybrid renewable energy solutions for aquaculture are further improved by AI-driven hybrid systems [30], [31], [32], which utilize predictive analytics to dynamically balance energy supply and demand. In conclusion, hybrid renewable energy systems are an innovative way to satisfy aquaculture's energy needs since they offer sustainability, dependability, and financial advantages while adapting to the difficulties presented by irregular energy supplies (Figure 3).

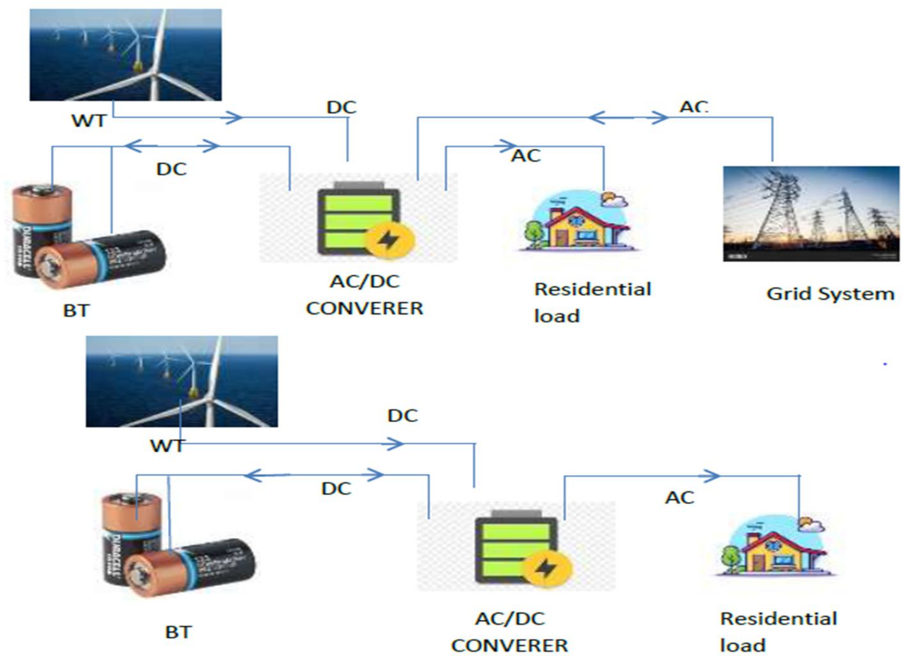

Figure 3. Hybrid Renewable Energy system

E. Role of Renewable Energy in Automation of Aquacultural Engineering

Renewable energy and efficient, sustainable energy sources for a variety of processes are key drivers of aquaculture engineering automation. Aquaculture's automated water quality, feeding, and oxygenation monitoring systems require a steady supply of dependable electricity, which renewable energy sources like sun, wind, and hydropower will provide very well. Solar panels are the most widely utilized power sources for feeders, sensors, and aerators at remote locations [33]. On the other hand, coastal aquaculture businesses are more suited for wind turbines. IoT and smart technology may also be employed with renewable energy. It makes possible to utilize AI-driven optimization, automated feeding systems, and real-time water quality monitoring, all of which increase productivity and reduce waste. Automation in aquaculture is driven by renewable energy integration. Studies on automation trends in India [34] reveal the potential for combining AI-driven automation with renewable energy to enhance operational efficiency.

Renewable energy reduces the operating cost, reduces dependence on fossil fuels, and encourages energy independence, especially in far-flung places. Further automation of filtration and aeration is also carried out using systems like RAS through solar power (Li et al., 2023). Renewable energy promotes sustainability because it reduces the generation of greenhouse gases and supports environmentally friendly aquaculture practices like biofloc systems and integrated multi-trophic aquaculture (IMTA) [36].

Hybrid renewable systems and battery storage solutions address the issues of intermittent energy supply, ensuring uninterrupted operation. Despite the initial investment costs and integration challenges, advancements in renewable technology are expected to drive wider adoption, making aquaculture automation both more efficient and environmentally sustainable.

III. ENVIRONMENTAL AND ECONOMIC IMPACTS

Incorporating renewable energy technology into aquaculture systems offers many economic and environmental benefits in solving critical issues facing the sector. Such impacts include reduced greenhouse gas emissions (GHG), better water and waste management, financial savings, and increased sustainability. These effects can be further examined in the dimensions below.

A. Environmental Impacts

Aquaculture's use of renewable energy is fundamental to improving environmental sustainability. Aquaculture operations can reduce greenhouse gas (GHG) emissions by 40–70% depending on the configuration by substituting renewable energy sources such as solar photovoltaic (PV) systems and wind power for conventional fossil fuel-dependent systems such as diesel generators [37]. This adjustment reduces the carbon footprint of the industry in addition to mitigating climate change. Renewable energy also improves water quality by using sun and wind-powered water circulation devices, which increase dissolved oxygen levels and prevent water stagnation. Bioenergy technologies reduce pollution by 50–70% and promote healthier aquatic ecosystems through the conversion of organic waste from fish excrement and feed residues to energy [38]. Aquaculture cages and offshore wind farms are examples of renewable infrastructure that integrates to minimize habitat disruptions, preserve natural surroundings, and promote biodiversity. Aquaculture's use of renewable energy has the potential to reduce greenhouse gas emissions by 1.2 million tonnes a year worldwide, in addition to decreasing dependence on fossil fuels and increasing ecosystem health. It is, therefore, an integral part of sustainable industrial development, which reduces the environmental impacts of industrial operations, including aquaculture [39].

B. Economic Impacts

Major economic benefits accrue from the adoption of renewable energy technologies in aquaculture, which decreases the cost of operations, increases profitability, and enhances energy self-sufficiency. Renewable energy technologies, such as solar PV and wind turbines, lower energy costs by half or even more, and that typically constitutes 30 to 50 percent of total expenses. For example, photovoltaic water pumps in Kenya pay back in four years with annual savings of up to 30% [40], while hybrid systems in Vietnam lowered energy costs by 45% [41]. The increased profit margins from the savings enable the operators to invest back into expansion, feed quality, and technological advancement. For instance, solar aerators increased the profitability of shrimp producers in India by 25%, while offshore aquaculture in Norway reduced the production costs by 40% to increase global competitiveness [42]. As demonstrated by solar PV systems in Nigeria, which has stabilised the supply of energy and increased dependability on the production by 35% [43], renewable energy also ensures that it is independent in terms of energy, which is crucial to far-flung or off-grid operations. While renewable energy systems have high initial costs, they reduce long-term operational expenses. Collaborative marketing strategies in agriculture [44] can also support economic sustainability in aquaculture.These developments have set aquaculture up for a stronger, more sustainable, and efficient future.

IV. INNOVATION AND FUTURE DIRECTIONS

A. Innovations

Aquaculture and renewable energy have converged in response to the growing global demand for sustainable food systems, changing the industry by boosting environmental sustainability, productivity, and profitability. Among these innovations are co-cultivating seaweed and shellfish with renewable energy infrastructure and vertical aquaculture farms powered by renewable energy, which optimize space and energy use through stacked tank systems. Carbon offset programs may increase adoption rates by 40 percent, according to studies [45]. Carbon credit programs can promote sustainable practices for aquaculture farms by installing renewable energy systems. The use of 3D printing for developing aquacultural components [21] and biogenic nanoparticles for water quality enhancement [46] represent cutting-edge innovations. Floating renewable energy technologies such as solar photovoltaic systems and offshore wind energy integration improve space utilization and productivity. Because AI and IoT are now integrated, aquaculture has seen an acceleration in renewable energy management, from cost reduction to predictive maintenance and optimization of energy demand [7]. Battery storage systems as well as hydrogen storage systems are now being developed in order to reduce the intermittence of renewable energy sources and cut grid dependency in half.

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Regions such as Southeast Asia are developing blue bonds and other financial and regulatory innovations to support maritime sustainability programs and speed up the deployment of hybrid renewable energy systems [47]. Tidal energy systems, floating wind turbines, microbial fuel cells, and geothermal systems may help develop the aquaculture industry in the future. Such progress illustrates how aquaculture and renewable energy technologies may be integrated into a more resilient and sustainable industry.

B. Blockchain in Aquaculture: Monitoring and Optimizing Renewable Energy

Blockchain technology has shown promise in improving the renewable energy systems of aquaculture management and monitoring [48]. AI-driven smart aquaculture systems [49] uses blockchain for energy monitoring and optimization. Its decentralized ledger allows for real-time recording of energy production and consumption data, making reliable access to data on energy usage possible for stakeholders. This is particularly useful when keeping track of renewable energy sources such as wind, solar PV, and biofuels. Smart contracts powered by blockchain technology enable automatic energy distribution based on real-time data, maximizing energy use and ensuring sustainability goals (Li & Kassem, 2021). Blockchain also makes it easier to verify carbon offset and renewable energy credits, ensuring aquaculture firms meet sustainability goals. Blockchain-powered AI-driven energy management systems can automatically adjust energy flow, enhancing system efficiency and reducing operating costs. These developments provide a viable route boosting aquaculture's sustainability and cost effectiveness (Figure 4).

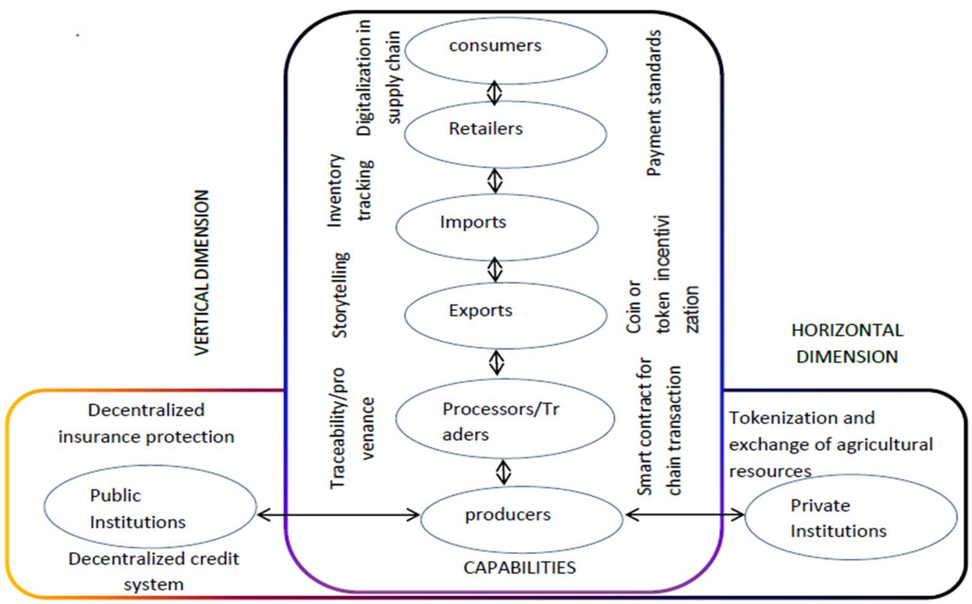

Figure 4. Use cases of block chain using the vertical and horizontal dimensions of GVC.

C. Future Roadmap

Integrating renewable energy systems is one of the futures for aquaculture. To reduce dependence on fossil fuel, hybrid system which involves a combination of solar, wind, and bioenergy technologies will feature predominantly in the near future [51]. Blue bonds and other forms of subsidy will support small-scale farmers to implement renewable energy systems. Important information and insights will be gained from extending offshore wind farms and pilot projects of floating solar PV systems. AI and IoT systems will maximize the use of renewable energy in the medium future by offering real-time monitoring and administration [52]. Regional energy storage centers will be built to store excess energy during periods of peak production. Growing algae-based biofuels can help meet energy demands and lessen aquaculture's carbon impact by generating renewable energy and absorbing CO_2 (Li & Yao, 2024). Combining several renewable energy sources including solar, wind, tidal, and bioenergy can lead to the long-term objective of creating carbon-neutral aquaculture. The industry will go from pilot projects to the widespread commercial use of hydrogen and tidal energy systems. International cooperation shall ensure technology transfer and equitable access to the renewable sources of energy that will be good for all regions, especially the developing ones. Future developments should focus on integrating AI, IoT, and renewable energy in aquacultural engineering [54].

IV. POLICY AND ADOPTION TRENDS

Funding by Horizon Europe, scheme of Kisan Urja Suraksha Evam Utthan Mahabhiyan (KUSUM) in India [55], federal tax credit of Investment Tax Credit programs of United States, 13th Five-Year Plan of Renewable Energy Development Plan in China [56], etc. are encouraging global policy towards incorporating renewable energy into aqua. These policies push the change to sustainable aquaculture by providing funds for research, providing incentives, and promoting international cooperation. For aquaculture to thrive sustainably and for renewable energy technologies to be incorporated, environmental rules are vital. Significant environmental benefits accrue from the Coastal Aquaculture Authority Act of 2005 in India [57], as it promotes sustainable practices and promotes renewable energy technology. Through the regulation of emissions and waste management in aquaculture operations, Norway's Aquaculture Act (2005) incorporates environmental sustainability [58]. Hydropower makes up more than 90% of the nation's energy mix, making the Norwegian Energy Act (1991) encourage renewable energy sources. The Renewable Energy Law of 2006 promotes the utilization of renewable energy, such as solar and wind, in aquaculture systems [59], whereas China's Environmental Protection Law of 2015 ensures rigorous environmental impact as-sessments for all aquaculture projects. Pilot projects that installed floating solar panels above fish farms have been successful in Guangdong province, maximizing land utilization and reducing energy costs by 40% [60].

A. *Challenges to Policy Implementations*

There are a variety of barriers to aquaculture using renewable energy that require policy interventions. Adoption is often discouraged by the high capital costs, especially for small-scale farmers, thus they require tailor-made blue bonds or interest-free loans [61]. It is further limited by a lack of information about renewable technologies, which can be addressed through focused training initiatives and extension services. The policy fragmentation between aquaculture and energy sectors throws into relief the need for integrated frameworks that bring together sectoral goals. Further, infrastructure constraints in distant locations of aquaculture hinder the deployment of renewable energy, and increasing the grid connectivity or encouraging off-grid renewable alternatives assumes greater importance here [62]. For the aquaculture sector to be economically and sustainably supported by renewable energy, several barriers need to be removed. Challenges include high upfront costs and regulatory barriers. Several researchers suggest that policies promoting renewable energy adoption can accelerate aquaculture development [63].

B. *Opportunities for Policy Innovation*

Innovative policies that incorporate digital tools, international collaborations, and financial mechanisms are driving the global aquaculture sector toward sustainability. An important opportunity is represented by blue bonds and green financing, which offer targeted funding for aquaculture renewable energy projects. In coastal aquaculture, for example, Seychelles' Blue Bond has helped raise funds to integrate solar energy, mitigating the carbon footprint of the industry while increasing energy autonomy and resilience to changes in supply (Bosmans & Mariz, 2023). Assisting in scaling up such renewable technologies as wind and solar electricity helps areas meet sustainability goals and boost their economies. International collaborations enable the exchange of technology and capacity building, which accelerates this transition even further. A great example of the transfer of renewable technologies, such as solar energy systems, to Indian aquaculture farms is the Norway-India partnership under the Norwegian Fish for development program [65]. This has significantly reduced their dependence on fossil fuels, reduced operational costs, and promoted the use of renewable energy in developing countries. Digital tools are also implemented and monitored in aquaculture to ensure the implementation of renewable energy systems. The internet of things and artificial intelligence are some of the innovations being used to enhance efficiency in energy use and observe environmental regulations. AI-powered monitoring systems in China offer real-time data on the efficiency of solar energy in aquaculture ponds [66]. This enables operators and policymakers to make informed changes. The technological advancements ensure long-term sustainability of renewable sources because they enhance their efficiency and effectiveness. When these strategies combine, they promote a stronger, cleaner aquaculture sector that supports international sustainability goals.

C. *Roadmap for Policy Advancement*

For aquaculture to achieve sustainability goals and maintain its economic viability, a clear policy progression roadmap is essential. Short-term subsidies for small-scale farms' renewable energy systems can help them switch from fossil fuel-based energy systems to more economical and sustainable renewable technology [67]. In order to promote the long-term economic and environmental advantages of adopting renewable energy, governments should also run educational programs to increase public understanding.

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Harmonizing rules between the aquaculture and renewable energy sectors can facilitate the smooth incorporation of renewable energy systems in the medium term [68]. This might entail creating mandated renewable energy integration targets for all aquaculture facilities, increasing access to international investment, and amending zoning laws to permit renewable energy installations. A roadmap for policy advancement includes integrating renewable energy technologies into mainstream aquacultural practices and utilizing membrane technologies to treat wastewater [69]. Mandatory renewable energy integration goals for all aquaculture operations are crucial in the long run (10+ years). To achieve these objectives and ensure carbon-neutrality at the end of the period, aquaculture businesses need to utilize renewable energy in their practices. This will reduce the industry's carbon footprint while allowing the industry to achieve its long-term sustainability and the sustainable production of food worldwide.

V. CONCLUSION

Aquacultural engineering combined with renewable energy technologies represents an unusual, innovative solution to sustainable food systems. This exhaustive analysis highlights how aquaculture might tap into solar, wind, and bioenergy technologies to optimize operations, reduce carbon footprints, and support the conservation of the environment. A glance at frameworks for a number of the world's superpower nations such as China, Norway, and India readily indicates that the most up-to-date technologies, including solar power RAS, offshore wind-aquaculture structures, and floating solar power stations are making it possible for a better-stocked aquaculture. China's floating solar systems and Nor-way's offshore wind integration are models India and other developing countries can imitate in terms of scalability and energy efficiency. India's policy-driven initiatives like the Coastal Aquaculture Authority Act and NAPCC form a base for renewable energy adoption, but their constraints, like financial barriers for small-scale farmers, highlight the need for global insights. Environmental laws aimed directly at encouraging the use of renewable energy by aquaculture, while solving environmental issues also present a source of economic benefit. Aquaculture is going to play a vital role in securing the global food system because prices are likely to come down, and sustainability measures improve due to technology investments driven by legislation. To take innovations to scale, future strategies will focus on public-private collaborations, the promotion of cheap renewable technologies, and international practice harmonization. Aquaculture and renewable energy may work together to promote a sustainable and climate-resilient global food chain by utilizing cross-sectoral synergies.

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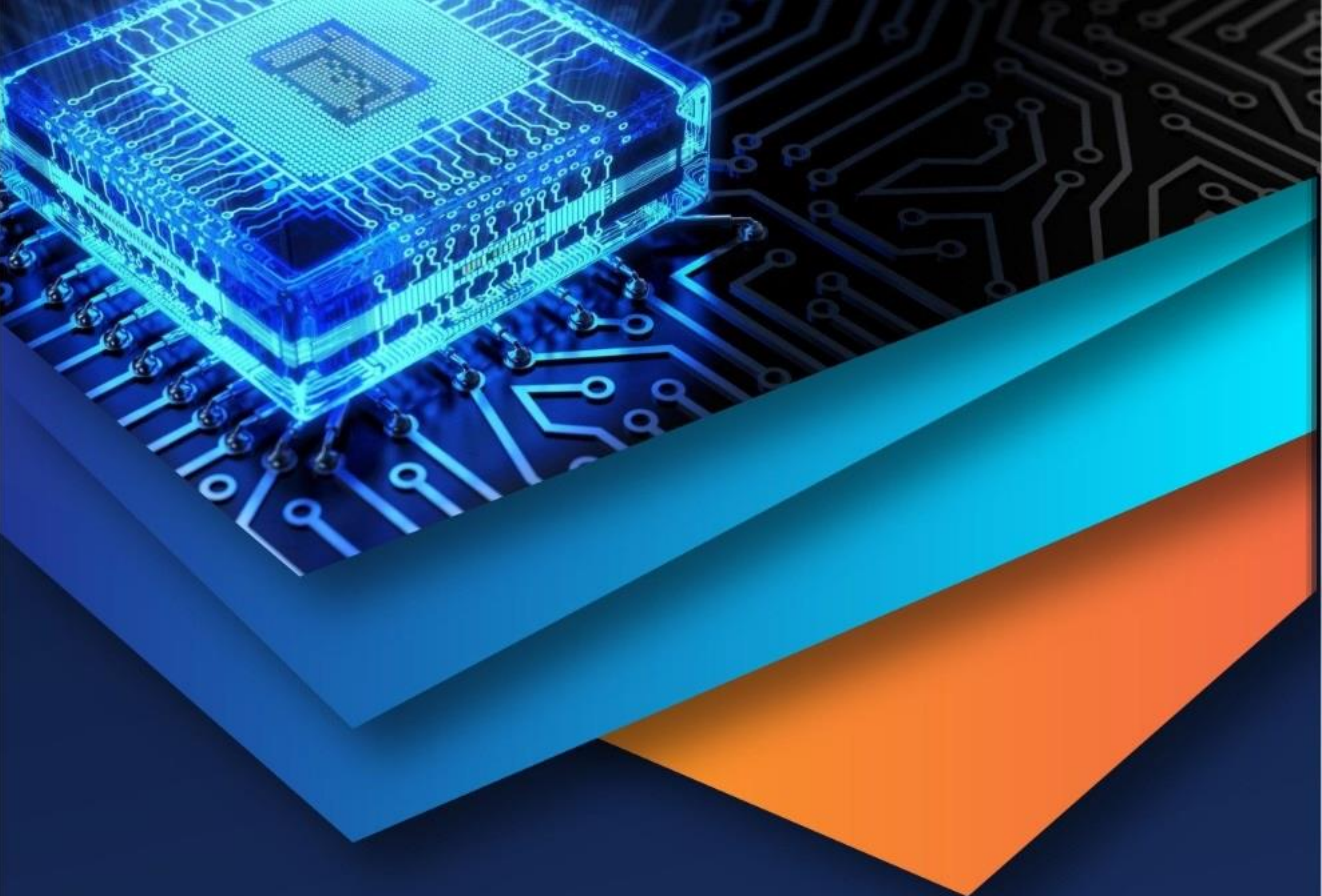

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