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Advancements in renewable energy technologies and their impact on environmental sustainability

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Abstract

Concerns about climate change and environmental damage, together with the growing need for energy worldwide, have made the switch from fossil fuels to renewable energy technology imperative. This review looks at new developments in solar, wind, hydropower, biomass, and geothermal energy, highlighting their role in preserving natural resources, lowering greenhouse gas emissions, and enhancing air quality. Innovations such as perovskite-silicon tandem solar cells, hybrid energy storage systems, and smart grid integration have significantly enhanced efficiency and cost-effectiveness. Despite the environmental benefits, challenges such as land use conflicts, resource consumption, and waste management persist. Effective policy frameworks, investment in sustainable materials, and circular economy approaches are critical to maximizing the potential of renewable energy technologies. This review underscores the imperative for continued research and strategic implementation to achieve long-term environmental sustainability.

Keywords: Renewable Energy; Environmental Sustainability; Solar Energy; Wind Power; Hydropower; Biomass Energy; Geothermal Energy; Energy Storage

1. Introduction

The escalating concerns over climate change and environmental degradation have intensified the global pursuit of sustainable energy solutions. Historically, economic development has been closely linked with increased energy consumption and a corresponding rise in greenhouse gas emissions, primarily due to the reliance on fossil fuels [1]. This dependency has led to significant environmental challenges, including global warming, air pollution, and ecosystem disruption. In response, there is a growing imperative to make the switch from energy systems that rely on fossil fuels to renewable energy sources, which provide cleaner and more sustainable alternatives [1, 2].

Technologies for renewable energy, including geothermal, hydroelectric, biomass, wind, and solar, harness natural processes to generate energy with minimal environmental impact [3-5]. These technologies support economic growth and energy security in addition to lowering greenhouse gas emissions. The shift towards renewable energy is essential for achieving environmental sustainability, as it addresses the root causes of environmental degradation associated with traditional energy production [4-6].

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The objectives of this review are threefold: first, to provide an overview of the recent advancements in renewable energy technologies; second, to assess their impacts on environmental sustainability; and third, to identify the challenges and opportunities associated with their implementation. By examining current research and developments, this review aims to elucidate renewable energy's contribution to a sustainable future and to inform policy decisions and strategic planning in the energy sector.

1.1. Overview of Renewable Energy Technologies

Renewable energy technologies have undergone significant advancements, each contributing uniquely to environmental sustainability. This section provides a detailed examination of various renewable energy sources and their technological developments (see Table 1).

1.1.1. Solar Energy

Solar energy harnesses sunlight to generate electricity, primarily through Photovoltaic (PV) cells and Concentrated Solar Power (CSP) systems [3].

Photovoltaic (PV) Cells

PV cells convert light photons into electrical voltage via the photovoltaic effect. Traditional silicon-based PV cells have been the industry standard [7-9]; however, recent innovations have introduced perovskite materials, which have demonstrated higher efficiency rates. According to Khatoon et al., [10], consequent to their great efficiency and versatility, perovskite solar cells (PSCs) have become a potential technology for turning solar energy into electrical power. To improve energy conversion efficiency, research has recently turned to the creation of concentrator or tandem systems [11-13].

Concentrated Solar Power (CSP)

With CSP technology, sunlight is focused onto a receiver using mirrors or lenses, where it is transformed into heat to create electricity [14-16]. Innovations in CSP have focused on enhancing efficiency and cost-effectiveness. Recent developments include hybrid systems that combine photovoltaic and energy storage-integrated Stirling engines, optimizing energy production per unit area [14-16]. These systems employ beam splitters to thermally decouple modules, directing different spectral ranges to appropriate receivers, thereby improving overall efficiency [17-19].

1.1.2. Wind Energy

Wind energy exploits air currents to generate electricity, with technological advancements enhancing both onshore and offshore applications.

Onshore Wind Turbines

Onshore wind turbines are installed on land and have seen improvements in design and materials, leading to increased capacity factors [20-22]. The U.S. Department of Energy reports that research efforts have elevated the average capacity factor from 22% for turbines installed before 1998 to nearly 35% today, while reducing energy costs to under 3 cents per kilowatt-hour [23,24].

Offshore Wind Turbines

Offshore wind turbines are situated in bodies of water, benefiting from stronger and more consistent winds. The offshore segment had significant expansion, adding 10.85 million kilowatts, a 24% increase over the previous year. Global offshore capacity was 75.2 GW at the end of the year. With 6.3 GW in 2023, accounting for 58% of the worldwide growth, China dominated the world in yearly new installations for the sixth year in a row. European nations contributed a total of 3.8 GW, increasing the continent's total to 34 GW, particularly due to strong developments in the Dutch market [25].

1.1.3. Hydropower

Hydropower generates electricity by harnessing the energy of flowing water through various systems.

Large-Scale Dams

Traditional hydropower involves large dams that create reservoirs, providing a stable energy supply [26-28]. However, these structures can disrupt local ecosystems and displace communities. Recent approaches aim to balance energy production with environmental considerations, optimizing reservoir management to mitigate adverse impacts [27].

Run-of-River Systems

Run-of-river hydropower generates electricity without significant water storage, reducing ecological disruption. These systems divert a portion of river flow through turbines, returning it downstream [29-32]. Their smaller footprint makes them suitable for regions where large reservoirs are impractical [32].

Tidal Energy

Tidal energy exploits the gravitational pull of the moon and sun on Earth's oceans. Technologies such as tidal stream generators and barrages convert tidal movements into electricity [33-35]. While still emerging, tidal energy offers a predictable and sustainable energy source with minimal greenhouse gas emissions [33].

1.1.4. Biomass and Bioenergy

Biomass energy derives from organic materials, offering a renewable alternative to fossil fuels.

Biogas

Biogas is produced through anaerobic digestion of organic matter, including agricultural residues and municipal waste. This process yields methane-rich gas, which can be used for heating, electricity generation, or as a vehicle fuel [36, 37]. Implementing biogas systems reduces waste and lowers greenhouse gas emissions.

Biofuels

Biofuels, such as ethanol and biodiesel, are liquid fuels derived from biomass. They can replace conventional fuels in transportation, decreasing reliance on oil and reducing emissions. Advances in second-generation biofuels utilize non-food crops and agricultural residues, enhancing sustainability [38-42].

Waste-to-Energy Conversion

Waste-to-energy technologies convert municipal solid waste into electricity and heat through combustion or gasification. This approach reduces landfill use and recovers energy from waste materials, contributing to a circular economy [43-46].

E. Geothermal Energy

Geothermal energy utilizes Earth's internal heat for direct use applications and electricity generation.

Direct Use

Direct use of geothermal energy involves harnessing heat from geothermal reservoirs for applications such as district heating, greenhouse cultivation, and industrial processes. This method provides a consistent and efficient energy supply with a low environmental footprint [47-50].

Electricity Generation

Geothermal power plants convert hydrothermal fluids into electricity. Enhanced Geothermal Systems (EGS) expand potential by creating artificial reservoirs in hot rock, enabling energy extraction in regions lacking natural hydrothermal resources [47, 51-53]. EGS technology increases geothermal energy's viability as a renewable resource.

Table 1 Comparative Advancements in Renewable Energy Technologies

Energy Source	Technological Advancement	Efficiency Improvement	Cost Reduction (%)	Key Benefits
Solar Photovoltaic (PV)	Development of perovskite-silicon tandem cells	Increased efficiency from ~21% to 28.6%	Significant reduction in installation costs due to higher efficiency	Reduced space requirements for installations
Wind Energy	Enhanced turbine blade designs and taller towers	Increased capacity factors by up to 50%	40% cost reduction over the past decade	Higher energy output and reduced cost per kWh
Green Hydrogen	Ultra-efficient electrolysers achieving 95% efficiency	Reduction in energy loss from 25% to 5%	Potential for cost-competitive green hydrogen production	Decarbonization of hard-to-electrify sectors

1.2. Environmental Benefits of Renewable Energy

There are several environmental advantages of switching to renewable energy sources, significantly contributing to the mitigation of climate change and the enhancement of public health [54-56] (see Table 2). This section explores the primary advantages, including the reduction of greenhouse gas emissions and air pollution, conservation of natural resources, improvements in public health, and water conservation [57-59].

Table 2 Life Cycle Environmental Impact of Renewable Energy Technologies

Technology	Carbon Footprint (g CO_2e/kWh)	Water Consumption (L/MWh)	Resource Use	End-of-Life Waste Management
Solar PV	20	Low water usage during operation	Requires silicon, silver, and other metals	Recycling programs emerging to handle panel disposal
Wind Energy	12	Minimal water use	Utilizes steel, copper, and rare earth elements	Turbine blades pose recycling challenges; research into sustainable materials ongoing
Hydropower	24	High water usage due to reservoir evaporation	Significant land use for reservoirs	Long lifespan reduces frequency of waste generation

1.3. Reduction in Greenhouse Gas Emissions and Air Pollution

One of the most profound environmental benefits of renewable energy is its capacity to substantially reduce greenhouse gas emissions (see Table 3) [57, 59]. Traditional energy production, predominantly reliant on fossil fuels, is a major contributor to carbon dioxide (CO_2) emissions, exacerbating global warming [60-63]. In contrast, renewable energy sources such as wind, solar, and hydroelectric power generate minimal to no direct CO_2 emissions during operation [3,4,12,27]. According to a review by Olabi et al. [64], implementing wind, water, and solar technologies could lead to a significant decrease in global CO_2 emissions, thereby playing a crucial role in climate change mitigation.

In addition to reducing CO_2 emissions, renewable energy technologies significantly diminish air pollutants that adversely affect air quality and public health [60,62]. Fossil fuel combustion releases various harmful pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter, which are linked to respiratory and cardiovascular diseases [65-66]. A study by Jaiswal et al. [67] emphasizes that renewable energy sources emit little to no air pollutants, leading to cleaner air and a reduction in health issues associated with air pollution.

Table 3 Impact of Renewable Energy on Greenhouse Gas Reduction and Air Quality

Energy Source	CO_2 Reduction (Million Tons/Year)	Reduction in Air Pollutants	Health Benefits	Data Source
Solar PV	700	Decreases SO_2 and NO_x emissions	Lower incidence of respiratory diseases	International Energy Agency
Wind Energy	500	Reduces particulate matter (PM2.5)	Improved cardiovascular health	International Energy Agency
Hydropower	1,000	Lowers CO and NO_x levels	Decreased asthma cases	International Energy Agency

1.3.1. Conservation of Natural Resources and Reduced Dependence on Fossil Fuels

Renewable energy sources are inherently sustainable, relying on natural processes that are replenished constantly [55,61,64]. This characteristic reduces the dependence on finite fossil fuel resources, which are associated with environmental degradation through extraction processes such as mining and drilling [68,69]. By harnessing energy from the sun, wind, water, and geothermal heat, societies can preserve natural ecosystems and reduce the ecological footprint associated with energy production [3,15,64].

Rabbi et al. [70] note that the adoption of renewable energy not only conserves natural resources but also promotes energy security by diversifying the energy supply. This diversification reduces vulnerability to fuel price fluctuations and geopolitical tensions related to fossil fuel imports.

1.3.2. Positive Impacts on Public Health and Air Quality Improvement

The deployment of renewable energy technologies has a direct positive impact on public health by improving air quality [58,67]. When fossil fuels are used in power plants and automobiles, pollutants are released which contribute to smog and respiratory problems [71-73]. In contrast, renewable energy generation produces negligible air pollutants, leading to cleaner air and associated health benefits [46,59,72].

The U.S. Environmental Protection Agency [74] reports that air pollution from fossil fuel-based energy production is linked to numerous health issues, including asthma, heart attacks, and premature deaths. The occurrence of these health issues can be decreased by renewable energy by lowering harmful pollutants, which will enhance quality of life and save healthcare expenditures.

1.3.3. Water Conservation Compared to Fossil Fuel Power Plants

Water is an important resource in energy generation, especially in thermoelectric power plants that use water for cooling. Fossil fuel-based power generation consumes substantial amounts of water, contributing to water scarcity and impacting aquatic ecosystems [75-77]. Renewable energy technologies, especially wind and solar photovoltaic systems, require minimal to no water for operation, thereby conserving water resources [28,78].

Ahmadi et al. [79] highlight that transitioning to renewable energy can alleviate pressure on water resources, making it a vital strategy in regions facing water scarcity. This conservation of water not only benefits ecosystems but also ensures the availability of water for agricultural and domestic use [80,81].

1.4. Potential Environmental Challenges

While renewable energy technologies offer substantial benefits for environmental sustainability, their deployment is not without challenges. These challenges encompass land use and habitat disruption, effects on biodiversity, resource consumption for manufacturing, and waste management of decommissioned systems [4,30,35,55,64].

1.4.1. Land Use and Habitat Disruption

The large-scale implementation of renewable energy infrastructures often necessitates significant land use, which can lead to habitat disruption. For instance, utility-scale photovoltaic solar farms require extensive land areas, potentially resulting in habitat degradation for terrestrial wildlife [82,83]. According to research, these installations can fragment or eliminate high-quality habitats, adversely affecting species that rely on these regions for migration and breeding [84,85].

Similarly, the development of biomass energy has been linked to deforestation, particularly in regions like Indonesia [86]. The increasing global demand for biomass has led to the clearing of pristine forests to produce wood pellets for export, primarily to countries aiming to reduce their carbon emissions. This practice not only contributes to habitat loss but also undermines the ecological balance of these forested areas [86-88].

1.5. Effects on Biodiversity

Renewable energy installations can have unintended consequences on biodiversity. Wind energy, while a clean power source, poses risks to avian species. Studies have shown that wind turbines, both onshore and offshore, are responsible for the mortality of millions of migratory birds and bats annually due to collisions [89-91]. This highlights the need for careful site selection and technological innovations to mitigate such impacts.

Moreover, the placement of renewable energy facilities in ecologically sensitive areas can threaten various species [90]. Research indicates that over 2,000 renewable energy facilities worldwide are situated in regions of environmental significance, potentially disrupting the natural habitats of numerous plant and animal species [84,85].

1.5.1. Resource Consumption for Manufacturing

The production of renewable energy technologies necessitates the extraction and utilization of various raw materials, some of which are scarce or environmentally intensive to procure [92]. For example, the manufacturing of photovoltaic panels and wind turbines requires metals and minerals, the mining of which can lead to habitat destruction and pollution [7,8,13,93]. A study published in Nature Communications emphasizes that the demand for these materials could exacerbate mining threats to biodiversity, particularly if not managed sustainably [94]. This calls for the adoption of responsible sourcing practices and the development of recycling technologies to minimize environmental impacts.

1.5.2. Waste Management of Decommissioned Systems

As renewable energy systems reach the end of their operational lifespan, the disposal of components presents environmental challenges. Solar panels, for instance, contain hazardous materials that, if not properly managed, can lead to soil and water contamination [95]. The recycling of these panels is still in its nascent stages, necessitating advancements to handle the anticipated increase in photovoltaic waste [96.97].

Similarly, wind turbine blades, often constructed from composite materials, pose disposal challenges due to their size and durability. Current recycling methods are limited, leading to concerns about landfill accumulation. Research and development efforts are ongoing to improve recycling processes and develop sustainable materials for future turbine blades [98,99].

1.6. Innovations and Future Trends

Incorporating renewable energy sources in the current electricity systems necessitates continuous innovation to address challenges such as intermittency, grid stability, and environmental impact. The efficiency and sustainability of renewable energy systems are greatly improved by recent developments in energy storage, smart grid technology, environmentally friendly materials, and circular economy strategies (see Table 4).

Table 4 Comparative Analysis of Energy Storage Technologies for Renewable Integration [100]

Storage Technology	Efficiency (%)	Cost ($/kWh)	Lifespan (Years)	Suitability for Renewable Integration
Lithium-ion Batteries	85-95	137 (as of 2020)	10-15	Ideal for short-term storage; widely used for solar and wind integration
Pumped Hydro Storage	70-85	5-100 (site-dependent)	50+	Suitable for large-scale, long-duration storage; limited by geographical requirements
Hydrogen Storage (via electrolysis)	30-40	High initial costs; decreasing with technological advancements	20-30	Promising for long-term, large-capacity storage; useful for seasonal storage and grid stability

1.6.1. Advances in Energy Storage

Efficient energy storage systems are essential for mitigating the variability inherent in renewable energy sources like wind and solar power. Recent research has focused on hybrid energy storage systems (HESS), which combine multiple storage technologies to leverage their complementary strengths. For instance, Adeyinka et al. [101] discuss how HESS can enhance grid stability by providing rapid response capabilities and sustained energy supply, thereby facilitating smoother integration of renewables into the grid. Their findings indicate that implementing HESS can reduce grid instability incidents by up to 35%, highlighting its potential in modern energy systems [101].

In addition to hybrid systems, advancements in battery technology have been significant. The development of long-duration energy storage (LDES) solutions, such as e-Zinc's batteries capable of storing energy for 12 to 100 hours, offers promising avenues for addressing extended periods of low renewable output [102]. These batteries enable the recapture of curtailed energy and provide resilience during grid outages, effectively replacing traditional peaking power plants and supporting infrastructure [103].

1.6.2. Smart Grids and Artificial Intelligence

The modernization of power grids through smart technologies and artificial intelligence (AI) is crucial for managing the complexities introduced by renewable energy integration. AI enhances grid resilience by optimizing energy distribution and predicting demand patterns [104,105]. The U.S. Department of Energy [106] identifies key opportunities in AI-accelerated power grid models, which can improve capacity planning and transmission studies. These models facilitate the efficient incorporation of variable renewable energy sources, thereby enhancing grid reliability.

Moreover, AI-driven forecasting tools have been developed to predict renewable energy production with greater accuracy [105]. These tools assist grid operators ...in maintaining supply and demand equilibrium and lowering dependency on backup systems that rely on fossil fuels. For example, AI applications in smart grids have demonstrated a 20% improvement in forecasting accuracy, leading to more efficient energy management and reduced operational costs [107].

1.6.3. Development of Eco-Friendly Materials

The environmental footprint of renewable energy technologies is influenced by the materials used in their construction. Recent advancements have focused on developing eco-friendly materials that reduce environmental impact throughout the product lifecycle. For instance, research into biodegradable materials for solar panels and wind turbine components aims to minimize waste and facilitate easier recycling at the end of their operational life [20,22,98].

1.6.4. Circular Economy Approaches

Adopting circular economy principles in the renewable energy sector involves designing systems with end-of-life considerations, promoting reuse, refurbishment, and recycling of components. This approach not only reduces waste but also conserves resources and lowers production costs. For example, implementing take-back programs for decommissioned solar panels and wind turbines ensures that valuable materials are recovered and repurposed, contributing to environmental sustainability [7, 96].

1.7. Policy and Global Perspectives

The advancement and adoption of renewable energy technologies are profoundly influenced by policy frameworks, international agreements, and collaborative efforts among nations. This section explores the role of government incentives, highlights case studies of countries leading in renewable energy adoption, and discusses the challenges faced in policy implementation and financial constraints.

1.7.1. Government Incentives and International Agreements Promoting Renewable Energy

Government incentives play a pivotal role in accelerating the deployment of renewable energy technologies. These incentives often manifest as tax credits, subsidies, and grants aimed at reducing the financial burden on investors and consumers. For instance, the United States has implemented federal tax incentives such as the Renewable Electricity Production Tax Credit (PTC) and the Investment Tax Credit (ITC), which provide financial benefits to entities generating electricity from renewable sources. These incentives have been instrumental in promoting investments in wind and solar energy projects across the country [108].

In the European Union, the "Clean Industrial Deal" has been proposed to enhance the competitiveness of EU industries while reducing carbon emissions. This comprehensive package includes measures such as lowering energy costs through guarantees for renewable energy purchase agreements, easing access to state aid and financial incentives for carbon-reducing projects, and simplifying public procurement rules to boost demand for locally produced clean technologies. These initiatives aim to create a conducive environment for renewable energy investments and facilitate the transition to a low-carbon economy [109,110].

1.7.2. Case Studies of Countries Leading in Renewable Energy Adoption

Several countries have emerged as exemplars in the adoption and integration of renewable energy into their national energy portfolios.

Germany's Energiewende, or "energy transition," is a notable example of a comprehensive policy framework aimed at shifting from conventional energy sources to renewables. This initiative has led to substantial investments in wind and solar power, resulting in a significant reduction in the nation's carbon footprint. From 2013 to 2018, Germany increased its wind power capacity from 1% to 34% of its electricity mix, demonstrating the effectiveness of sustained policy support and investment in renewable technologies [111].

Uruguay has also achieved remarkable success in its renewable energy endeavors. As of 2022, the country generated 91% of its electricity from renewable sources, including wind, solar, and hydropower. This transformation was facilitated by favorable regulatory frameworks, long-term power purchase agreements, and a clear governmental vision prioritizing energy diversification and sustainability. The rapid expansion of wind energy, in particular, underscores Uruguay's commitment to improving energy security and decreasing dependency on foreign fossil fuels [111].

China's approach to renewable energy adoption offers insights into large-scale implementation in developing countries. By 2018, approximately 27% of China's installed electricity capacity was derived from renewable sources such as water, wind, and solar energy. This shift was driven by substantial investments in renewable infrastructure and policies aimed at reducing dependence on coal. China's experience highlights the importance of strategic planning and government support in achieving a diversified energy mix [112-115].

1.7.3. Challenges in Policy Implementation and Financial Constraints

Despite the progress observed in various nations, several challenges persist in the implementation of renewable energy policies, particularly concerning financial constraints and policy execution. One significant challenge is the financial investment required for the energy transition. The United Nations Conference on Trade and Development (UNCTAD) reported a substantial increase in the Sustainable Development Goals (SDG) investment gap, surpassing $4 trillion annually in developing countries alone. Specifically, energy investment needs are estimated at $2.2 trillion per year. This financial shortfall poses a considerable barrier to the widespread adoption of renewable energy technologies, especially in regions lacking access to substantial capital and investment frameworks [116].

Policy implementation can also be hindered by regulatory complexities and administrative hurdles. In the European Union, efforts to promote renewable energy have led to proposals for easing state aid regulations to facilitate public and private investments in decarbonization projects. The proposed "Clean Industrial Deal" includes measures such as tax breaks and simplified public procurement rules to encourage the adoption of clean technologies. However, balancing the need for rapid deployment with regulatory oversight remains a delicate task, requiring careful policy design and stakeholder engagement [117].

Additionally, geopolitical dynamics can influence the effectiveness of renewable energy policies. For example, European countries have been criticized for sourcing renewable energy from North African nations like Morocco and Egypt to enhance their own green credentials. This practice has raised concerns about environmental justice, as it may impede the decarbonization efforts of the exporting countries and lead to environmental degradation. Such scenarios underscore the necessity for equitable and mutually beneficial energy partnerships that consider the environmental and socio-economic impacts on all parties involved [118].

2. Conclusion

This review has elucidated the significant advancements in renewable energy technologies and their profound impact on environmental sustainability. The transition from fossil fuels to renewable energy sources has been shown to markedly reduce greenhouse gas emissions, thereby playing a crucial role in mitigating climate change. Additionally, the adoption of renewables contributes to the conservation of natural resources and the enhancement of air and water quality. However, the deployment of these technologies is not without challenges. Issues such as land use conflicts, potential biodiversity impacts, resource consumption during manufacturing, and waste management of decommissioned systems have been identified as areas requiring careful consideration and management.

To fully harness the environmental benefits of renewable energy technologies while addressing the associated challenges, a multifaceted approach is recommended. Strategic planning and environmental impact assessments are essential to minimize land use conflicts and protect biodiversity. For instance, selecting appropriate sites for renewable energy installations can reduce habitat disruption. Moreover, the development of sustainable supply chains and recycling programs is imperative to address the environmental impacts of resource extraction and waste management. Implementing policies that promote the use of environmentally friendly materials and the recycling of decommissioned components can further enhance the sustainability of renewable energy systems.

Future research should focus on several key areas to advance the sustainability of renewable energy technologies. Innovations in energy storage solutions are critical to solve renewable energy sources' erratic performance and guarantee a steady supply of electricity. Additionally, exploring the environmental impacts of emerging technologies can provide insights into potential challenges and mitigation strategies. Research into the development of circular economy approaches, such as designing renewable energy components for disassembly and recycling, can significantly reduce waste and resource consumption. Furthermore, studies on the socio-economic impacts of renewable energy deployment can inform policies that promote equitable and sustainable energy transitions.

Compliance with ethical standards

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The authors declare that they have no conflict of interest to be disclosed.

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