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Environmental impacts of renewable energy systems and strategies for mitigation

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Abstract
The transition to renewable energy systems is critical to combating climate change and reducing reliance on fossil fuels, but it is not without environmental challenges. World is in the urgency of increasing the renewable energy generation to fulfil the climate goals. The real challenge is use of renewable energy towards combating the climate change really sustainable or not. This paper examines the environmental impacts of key renewable energy sources hydropower, geothermal, wind, solar, and bioenergy and explores innovative strategies to mitigate these effects. Hydropower projects can disrupt aquatic ecosystems and displace local communities, while geothermal energy may lead to land subsidence and emissions of greenhouse gases. Wind turbines, particularly horizontal-axis designs, impact bird and bat populations and contribute to noise pollution. Solar energy systems can result in habitat destruction and rely on resource-intensive manufacturing processes. Bioenergy production poses risks such as deforestation, soil degradation, and increased water usage if not managed sustainably. To address these challenges, the paper explores emerging technologies and strategies for mitigation. Vertical-axis wind turbines (VAWTs) offer more compact, wildlife-friendly designs, while air gen technology in which humid air in the nanopores, provide opportunities for sustainable energy generation with minimal impacts. Alternative sustainable energy solutions, including advanced nuclear energy, are highlighted as essential complements to renewables. Nanotechnology innovations, such as high-efficiency solar cells and advanced biofuel catalysts, enhance the performance and sustainability of energy systems. Additionally, sustainable bioenergy practices, such as integrating agroforestry and using non-food biomass, are discussed to reduce ecological trade-offs. Through a combination of technological advancements, ecosystem restoration, policy interventions, and integrated energy planning, the paper presents a comprehensive approach to achieving a sustainable energy future with minimal environmental impact.

Keywords: Nano technology, renewable energy, vertical-axis wind turbines, bioenergy, nuclear energy

Introduction

Energy is the driving force behind all forms of life and activities in the universe. It allows things to happen from the growth of plants, functioning of our bodies to movement of vehicles. Various forms of energy are existing such as kinetic energy, potential energy, thermal energy and many more. Ability to do work is called as energy, mainly energy comes in two main types i.e. renewable energy and non-renewable energy. Renewable energy is an energy derived from natural sources that are replenished at a higher rate than they are consumed (UNO). Renewable energy Cannot be exhausted because replenishment rate is greater than the consumption rate. Examples for renewable energy is sunlight, wind, water, geothermal energy etc. Non- renewable energy can be exhausted because their replenishment rate is less than consumption rate hence, they are limited in nature. Example for non-renewable energy is fossil fuels, crude oil, mineral resources etc. The planet earth facing catastrophic events frequently in one or the other parts of the world. Ready answer for all these is global warming and climate change. Renewable energy systems, such as solar, wind, hydroelectric, geothermal, and bioenergy, are critical in transitioning to sustainable energy sources and combating climate change. Unlike fossil fuels, these systems generate energy with lower greenhouse gas emissions, reducing their overall environmental footprint. However, renewable energy systems are not without environmental impacts. From land use changes and habitat disruption to resource extraction and waste generation, the deployment and operation of renewable energy technologies can pose challenges to ecosystems and communities (Dhar *et al.*, 2020) [18]. For instance, large-scale solar farms may result in land degradation and loss of biodiversity, while wind turbines can impact bird and bat populations (Hamed *et al.*, 2022) [25].

Similarly, hydropower Dams alter river ecosystems, affecting aquatic habitats and water quality (Gracey *et al*., 2016) [21]. Moreover, the extraction of materials like lithium, cobalt, and rare earth elements required for renewable energy technologies often leads to environmental degradation in mining areas (Igogo *et al*., 2021) [30]. To address these challenges, strategies for mitigation are essential. These include adopting sustainable design practices, improving energy efficiency, implementing robust environmental impact assessments, and fostering innovation in materials and recycling technologies. Additionally, integrating renewable energy projects with land conservation efforts and engaging local communities in decision-making processes can help minimize negative impacts while maximizing social and environmental benefits. India being a leader nation in making climate pledges voluntarily and moving towards the sustainability, trying to install more renewable energy capacity to reduce dependence on the fossil fuels and crude oil imports. India is the world's third largest producer of renewable energy with 40% of its installed electricity capacity coming from non-fossil fuel sources (Dey *et al*., 2022) [17]. This balance between expanding renewable energy and protecting ecosystems is crucial to ensuring a sustainable and equitable energy future. The following sections will explore the specific environmental impacts of various renewable energy systems and the strategies that can be employed to mitigate these effects.

Table 1: Myths and truths about renewable energy generation

MYTHS	TRUTHS
Renewable energy is 100% sustainable	Renewable energy also have negative impacts on environment
Reliable	Not available round the clock
Permanency	Requires a lot of space
Less cost	Less efficient
Highly eco friendly	E- waste
Power generated using natural resource	Repair and maintenance Existing resources + extra inputs

Environmental impacts of solar energy

Utility-Scale Solar Farms require significant land, often ranging from 5 to 10 acres per megawatt (MW) of installed capacity. This land use can compete with agriculture, forestry, and other land-based activities. Clearing land for solar farms can disrupt natural habitats and lead to the loss of biodiversity leads to Habitat Loss and Fragmentation. Some species may be displaced, while others may struggle to adapt to the altered environment. Habitat fragmentation can occur when roads and infrastructure are built to support solar installations also. The installation of solar panels often involves clearing vegetation and altering the soil structure, which can lead to reduced soil stability and increased erosion, altered water infiltration and drainage patterns, loss of vegetation cover which impacts local flora and fauna (Dhar *et al*., 2020) [18]. In areas with high solar potential, utility-scale solar farms may compete with agricultural activities for fertile land (Guerin *et al*., 2019) [22]. Although solar energy has lower water requirements than fossil fuel-based power generation, some land use practices associated with solar farms may indirectly affect water resources such as cleaning solar panels requires water, especially in arid regions (Hernandez *et al*., 2014) [28]. Alterations to land may affect local hydrology, potentially impacting groundwater recharge and surface water flow. Large solar farms may alter the visual character of landscapes, especially in scenic or culturally significant areas. The glare from solar panels, though minimal with modern anti-reflective coatings, may still affect nearby residents or drivers. Impacts of hazardous waste like emissions of hazardous materials like Cd, Pb and Se during, manufacturing, accidental leakage, life after use, carcinogenic elements and pressure on mineral resources.

Environmental impacts of wind energy

Collisions with turbine blades can lead to bird and bat fatalities. Migratory species and those that fly at the height of the blades are most at risk (Cryan *et al*., 2009) [14]. Bats are particularly affected due to barotrauma i.e. pressure changes near the blades (Lawson *et al*., 2020) [34]. Construction and operation of wind farms can disturb local habitats, especially in ecologically sensitive areas. Offshore wind farms may affect marine ecosystems, altering habitats for fish, marine mammals, and seabirds. Shadow flickering i.e. the movement of the turbine blades through the sunshine causes adverse visual impacts on birds (Nazir *et al*., 2020) [41]. Aerodynamic noise comes from turbine blades passing through the air, mechanical noise comes from the turbine's internal gears, the generator, and other auxiliary parts. South and east of the places were typically warmer than those west of the wind farm, local temperature increased 0.72 ºC and increased night temperature was more evident (Wang *et al*., 2023) [55]. Wind turbine blades also alter radio wave signals and affect televisions, FM radios, microwave communication systems, and navigational systems.

Environmental impacts of hydro power generation

Dams and reservoirs disrupt river ecosystems, affecting aquatic species and their habitats (Alla *et al*., 2021) [4]. Fish populations, especially migratory species like salmon, are significantly impacted by blocked migration routes. Reservoir flooding can submerge forests, wetlands, and other critical habitats, leading to biodiversity loss (Fjelstad *et al*., 2018) [20]. Regulated water flow changes natural river dynamics, impacting sediment transport and nutrient distribution downstream. Reduced sediment flow can degrade downstream ecosystems, including estuaries and deltas. While reservoirs in tropical regions can release methane and CO_2 from submerged vegetation decomposition. These emissions can offset the climate benefits of hydropower in some cases (Gunkel *et al*., 2009) [23]. Large areas of land, including forests, agricultural fields, and human settlements, are often submerged to create reservoirs. This results in habitat loss and displacement of wildlife and people (Chakraborty *et al*., 2021) [12]. Construction of dams and reservoirs often requires clearing vegetation, reducing carbon storage capacity and altering local climates (Alla *et al*., 2021) [4]. Reservoirs can cause stratification of water layers, affecting temperature and oxygen distribution. These changes can harm aquatic life and disrupt ecosystems downstream. Accumulation of organic matter in reservoirs can lead to eutrophication, resulting in algal blooms and degraded water quality.

Environmental impacts of bioenergy

Expanding bioenergy crop production can lead to deforestation, wetland drainage, and grassland conversion, resulting in habitat loss and reduced biodiversity (Petermann *et al*., 2021) [43]. Growing bioenergy crops on arable land may displace food production to other areas, indirectly causing deforestation or habitat conversion (Abreu *et al*., 2022) [1]. Bioenergy crops like corn, sugarcane, and soy may compete with food crops for arable land, water, and nutrients, potentially contributing to food insecurity (Liaqat *et al*., 2023) [35]. Irrigation for bioenergy crops can strain local water resources, particularly in arid regions. Fertilizers and pesticides used in cultivating bioenergy crops can lead to water pollution, causing eutrophication in nearby water bodies (Mishra *et al*., 2023) [40]. Emissions from cultivating, harvesting, transporting, and processing bioenergy crops can reduce its overall carbon savings (Holmotov *et al*., 2021) [29]. Decomposing organic matter in bioenergy production can release methane, a potent greenhouse gas, if not properly managed. Combustion of biomass for energy can produce air pollutants like particulate matter, nitrogen oxides (NOx), and volatile organic compounds (VOCs), affecting air quality. Intensive cultivation of bioenergy crops can deplete soil nutrients, reducing long-term soil productivity (Cherubin eta l., 2021) [13]. Large-scale monoculture of bioenergy crops can increase soil erosion, especially on sloped lands. Large-scale monoculture plantations of bioenergy crops can reduce biodiversity by replacing diverse ecosystems with single-species crops.

Environmental impacts of geothermal energy

Construction of geothermal power plants and infrastructure can lead to land disturbance, particularly in ecologically sensitive areas. Drilling and exploration activities may impact local vegetation and wildlife habitats. The visual footprint of geothermal plants, including pipelines, cooling towers, and drilling rigs, can affect the aesthetics of natural landscapes. Open-loop systems may consume significant amounts of water, especially in dry regions, potentially straining local water resources (Ouerghi *et al*., 2024) [42]. Improper management of geothermal fluids, which may contain salts, heavy metals, and toxic elements, can contaminate surface and groundwater (Kara *et al*., 2022) [32]. Some geothermal reservoirs release trace amounts of gases such as H_2S and CH_4. Drilling and fluid injection into geothermal reservoirs can cause minor earthquakes, a phenomenon known as induced seismicity. These seismic events are generally low in magnitude but can raise concerns in populated areas. Over-extraction of geothermal fluids can cause land subsidence, leading to sinking ground levels that may affect infrastructure and ecosystems. Development of geothermal fields in natural areas can disrupt ecosystems, particularly in areas with unique geothermal features i.e. hot springs, geysers.

Mitigation strategies

Sustainable use of renewable energy should focus on minimizing environmental impact while maximizing efficiency and sustainability. Site selection should prioritize waste lands and degraded lands to prevent unnecessary disruption of ecosystems. Conducting thorough environmental impact assessments ensures potential risks are identified and mitigated. Minimizing land disruption by avoiding forested areas helps preserve biodiversity, while wildlife protection measures, such as deterrents to prevent bird collisions at wind turbines, safeguard local fauna. Proper waste management, especially during decommissioning, is essential to handle materials responsibly (Adebisi *et al*., 2023) [3]. Choosing eco-friendly materials in manufacturing reduces the environmental footprint, and integrating powerwalls for energy storage decreases dependency on grid electricity (Baus *et al*., 2017) [8]. Innovative technologies like vertical axis wind turbines (VAWT), which harness energy from vehicle wakes, and Air-Gen technology, helps in generating additional renewable energy (Casini *et al*., 2016) [11]. Dry cooling of PV panels reduces water consumption compared to wet cooling, and the application of anti-reflective agents on solar panels minimizes water requirements while enhancing panel longevity (Hajjaj *et al*., 2022) [24]. Shadow flickering from wind turbines can be reduced by optimizing rotor blade smoothness and using materials with low reflectivity. Mechanical noise can be controlled through proper insulation during manufacturing, and communication services can be improved by installing antennas on wind turbine towers or avoiding locations prone to broadcast signal interference (Dai *et al*., 2015) [15]. Lastly, the use of nanotechnology can significantly increase the efficiency of renewable energy systems, making them more sustainable and effective (Apoorva *et al*., 2023) [5].

Other alternative energy technologies

1. Nuclear energy

Nuclear energy is considered a sustainable alternative to renewable energy due to its ability to produce large amounts of low-carbon electricity with high reliability. Unlike solar and wind power, which depend on weather conditions, nuclear power plants provide a stable and continuous energy supply, making them a reliable baseload energy source (Mathew *et al*., 2022) [39]. Additionally, nuclear energy has a high energy density, meaning a small amount of uranium can produce a significant amount of electricity, reducing resource consumption and land use compared to some renewable sources. From an environmental perspective, nuclear power emits virtually no greenhouse gases during operation, helping to combat climate change. Advances in nuclear technology, such as next-generation reactors and small modular reactors (SMRs), improve safety, efficiency, and waste management. Furthermore, innovations in nuclear fuel recycling and breeder reactors have the potential to extend fuel availability and reduce radioactive waste (Malerba *et al*., 2022) [37]. While nuclear energy is not classified as "renewable" because it relies on finite uranium resources, it is considered sustainable due to its efficiency, low emissions, and potential for long-term fuel supply through advanced technologies (Asif *et al*., 2024) [6]. By complementing renewable energy sources, nuclear power helps ensure a stable and clean energy transition.

Table 2: Advantages and disadvantages of nuclear energy

Advantages of nuclear energy	Disadvantages of nuclear energy
Carbon-free electricity	Uranium is technically non-renewable
Small land footprint	Very high costs
High power output	Nuclear waste
Reliable energy source	Malfunctions can be catastrophic

2. Air – Gen technology

According to a new study published “in Advanced Materials”, engineers at the University of Massachusetts Amherst have demonstrated a novel “air generator” (Air-gen) film that relies on microscopic holes smaller than 100 nanometres. This technology uses the charge imbalance created in nanopores due to air’s humidity. As humid air passes through Air-gen material’s miniscule holes, the water molecules come into direct contact with first an upper, then lower chamber in the film. This creates a charge imbalance, i.e. electricity. This technology currently has not potential of catering to huge needs of the renewable energy sector, but in future definitely contribute to electricity generation.

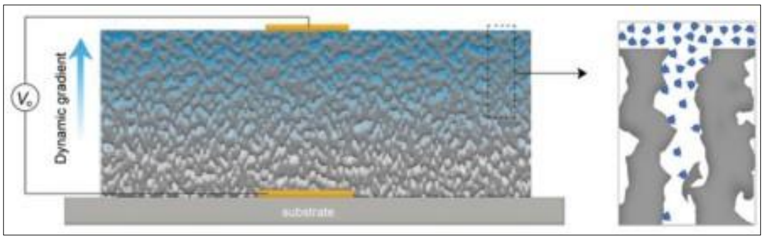

Fig 1: Representation of air gen technology depicting nanopores with humid air (Source: Liu *et al*., 2024)

3. Vertical axis wind turbine technology (VAWT)

Wind energy generated from the wake of moving cars has a large energy potential that has not yet been utilized. The turbine was designed to be planted by the side of the car lane and driven by the wake produced by the car. Current VAWT designs lag behind the Horizontal Axis Wind Turbine (HAWT) counterparts in terms of efficiency, as measured by their power coefficient (Kassa *et al*., 2024) [33]. However, new research suggests that these types of wind turbines may be better suited for wind farm installations than previously thought. In India, VAWT is not much in use. Recently (2022) Mumbai has become India's first airport to launch a one-of-its-kind. Vertical axis wind turbines (VAWTs) offer several advantages that make them a compelling choice for harnessing wind energy. One key benefit is their omnidirectional nature, allowing them to capture wind from any direction without requiring reorientation. This makes them particularly effective in turbulent or changing wind conditions. Additionally, VAWTs can be placed closer together than horizontal axis turbines, maximizing land use efficiency (Barnes *et al*., 2021) [7]. They also operate at lower starting wind speeds, making them suitable for areas with less consistent wind patterns (Hand *et al*., 2021) [26]. Another advantage is their lower environmental impact, as they pose fewer risks to birds and wildlife compared to traditional turbines (Docrat *et al*., 2023) [19]. Furthermore, their design allows for easier installation and maintenance since many components are positioned closer to the ground (Liu *et al*., 2019) [36]. Lastly, VAWTs have a striking and modern appearance, making them a visually appealing option for urban and residential settings.

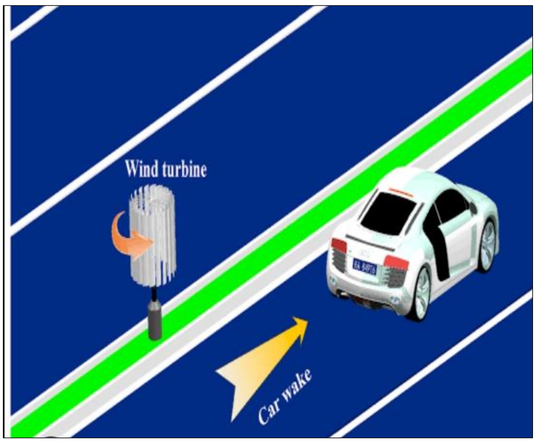

Fig 2: Picturization of VAWT activation by wakes of car and striking representation of VAWT respectively (Source: Tian *et al*., 2017)

Fig 3: VAWT at Mumbai airport

4. Nano technology

Nano technology applications were numerous in the field of renewable energy technology. Graphene panel of solar system reaches a 92% efficiency compared to conventional silicon-based PV panels (Das *et al*., 2019) [16]. Nanoscale heat and corrosion protection layers used on turbine blades in power plants enhances the efficiency (Bonu *et al*., 2022) [10]. Ice cleaning self-cleaning surfaces of wind turbine. Nanotechnology also helps in producing better lithium ion batteries with improved energy density, charge and discharge efficiency (Adak *et al*., 2022) [2]. Carbon nano tubes, graphene, nano composites, fuel cells, solar cells etc. helps in enhancing the efficiency.

Conclusion

To minimize these impacts, effective mitigation strategies must be implemented. These include sustainable site selection, improved recycling and circular economy approaches for materials, technological advancements to enhance efficiency, and policies that promote responsible resource management. Additionally, integrating a diverse mix of renewable sources and adopting energy storage solutions can optimize grid stability while reducing ecological footprints. By balancing the benefits of clean energy with responsible environmental management, renewable energy systems can continue to support global sustainability goals without compromising ecological integrity.

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