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Article

Energy resources: Their causal relationship with ecology and environments

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Abstract: Energy resources are critical drivers of economic development and societal progress, but their extraction, conversion, and use have profoundly impacted ecological systems and the environment. Therefore, it is essential to explore the relationships between energy resources and the environment throughout history. This paper examines the causal relationships between energy resource utilization and environmental changes, addressing both renewable and non-renewable energy sources. We analyze the environmental consequences of energy extraction and consumption, including pollution, habitat destruction, and climate change, and evaluate sustainable approaches to mitigate these effects. Fossil fuels have been the primary source of energy and are major contributors to greenhouse gas emissions, air and water pollution, and habitat destruction, all of which exacerbate global climate change. On the other hand, renewable energy sources such as wind, solar, and hydroelectric power are considered more sustainable. However, they also have environmental impacts, such as habitat disruption and high resource consumption. Researchers argue that trade-offs must be managed between increasing energy use, facilitated by technological advancements, and achieving sustainability. Energy generation and ecological goals should not be viewed as opposing or irreconcilable. With the implementation of appropriate policies, measures, and guidelines, energy production can be aligned with efforts to mitigate climate change and promote sustainability.

Keywords: energy resources; environmental impact; climate change; sustainability; renewable energy

1. Introduction

Energy is a key element in achieving economic growth and development in any society. However, energy resources are more than just enablers of development, as their collection, transformation, and use significantly impact ecological systems and the environment at large. Therefore, it can be said that energy resources and their use have the potential to cause environmental consequences. Since the Industrial Revolution, fossil fuels—including coal, oil, and natural gas—have been the dominant sources of energy and key drivers of industrialization and urbanization. Nonetheless, their extraction and use emit large amounts of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), which contribute to global warming and climate change [1]. The detrimental use of fossil fuels contributes to air, water, and land pollution, as well as habitat destruction and species extinction [2]. More effective and environmentally friendly alternatives to fossil fuels include solar, wind, and hydroelectric energy sources. The use of renewable energy provides benefits such as reduced greenhouse gas emissions and the preservation of biodiversity. However, it is important to note that renewable energy technologies also have their own environmental impacts. For example, the construction of wind turbine farms can negatively affect bird and bat populations [3] or hydroelectric dams, while providing renewable energy can adversely affect aquatic ecosystems [4].

Nuclear energy generates power with minimal greenhouse gas emissions, making it a low-carbon alternative to fossil fuels. However, it poses significant challenges, including the management of radioactive waste and the risk of catastrophic accidents, as demonstrated by events like Chernobyl and Fukushima [5]. The long-term management of radioactive waste and the high expense of nuclear safety measures continue to be serious concerns [6]. Global energy demand is projected to increase by over 50% in the next 20 years [7], making it imperative to consider the environmental implications. Sustainable energy practices must be developed to meet energy needs without compromising the environment.

This review paper aims to analyze the environmental impacts of energy resource utilization, considering both renewable and non-renewable energy sources. It examines energy use and its ecological effects to identify strategies that can mitigate negative impacts and promote ecological sustainability.

2. Literature review

Search platforms such as Google Scholar, Web of Science, and ScienceDirect were utilized for the literature review. Many relevant papers identified during the search were cited in this study due to their importance to the topic. The close relationship between energy resources and the environment has been a central focus of numerous research studies over the past few decades. With the increasing global demand for energy, it is essential to understand the environmental implications of various energy resources to develop sustainable and long-term solutions. This review explores the ways in which energy resource consumption contributes to environmental changes, with a particular focus on both renewable and non-renewable sources. It discusses the environmental impacts of energy consumption and patterns of energy use, aiming to identify strategies that minimize negative effects and promote environmental sustainability.

2.1. Non-renewable energy resources and environmental impacts

2.1.1. Fossil fuels and environmental impact

For centuries, humanity has depended on fossil energy sources such as coal, oil, and gas for primary energy production and industrial growth, owing to their abundance and affordability. However, the excessive use of fossil fuels has caused significant damage to ecosystems. Their combustion releases large quantities of greenhouse gases, including CO_2 and CH_4, which contribute to global warming and climate change worldwide [1]. The long-term effects of climate change pose severe threats to biodiversity, food security, and human health [8]. Another major drawback of relying on fossil fuels is air pollution and its associated health impacts. Emissions such as particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) are significant contributors to air pollution [9]. These pollutants are harmful to human health, causing respiratory and cardiovascular diseases [10] as seen in **Figure 1**. According to the Global Burden of Disease study, air pollution from fossil fuels accounts for millions of premature deaths annually [11]. Furthermore, large-scale extraction of fossil fuels destroys habitats and reduces biodiversity, as vast areas of land are excavated for oil and gas drilling and mining operations [12].

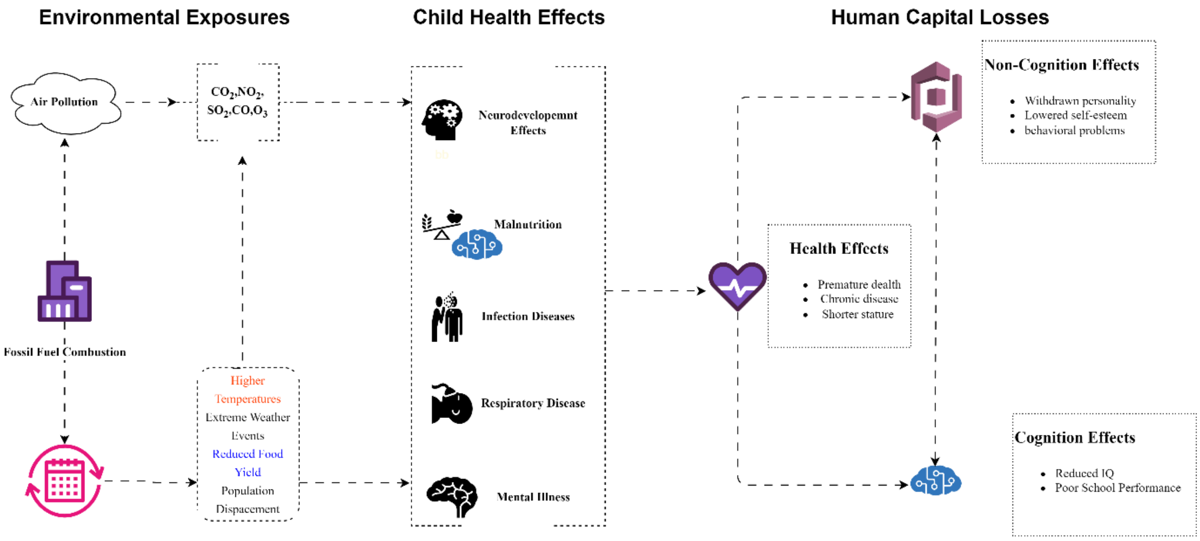

Figure 1. Routes from burning fossil fuels to potential effects on children's health and related losses in human capital [13].

Some studies have documented that water resources are increasingly under threat due to pollution caused by oil spills, coal mine drainage, and hydraulic fracturing fluids (fracking), all of which are harmful to both humans and the environment as shown in **Table 1**. Aquatic ecosystems are particularly vulnerable to these threats [14]. Additionally, the extraction of fossil fuels often results in significant land degradation and biodiversity loss. Coal mining, especially through mountaintop removal, can permanently alter landscapes and ecosystems [15]. Similarly, oil and gas drilling disrupts natural environments, leading to habitat fragmentation and species loss [16].

For example, air pollution from fossil fuels accounts for millions of premature deaths annually, with an estimated 8.7 million deaths globally linked to fossil fuel-related air pollution (PM2.5) in 2018 [17]. Additionally, 74% of the greenhouse gas (GHG) emissions in the United States in 2019 came from fossil fuels [18]. With global CO_2 emissions reaching 36.8 billion metric tons in 2022, the primary cause of human-induced climate change continues to be the burning of coal, oil, and natural gas for energy production [19].

The usage of fossil fuels has a significant financial cost in addition to its negative effects on the environment. Fossil fuel-related air pollution is predicted to cost the world $2.9 trillion a year, or 3.3% of Gross Domestic Product (GDP), in lost productivity and medical costs [20].

Comparisons of energy efficiency also draw attention to the drawbacks of fossil fuels. For example, combined-cycle natural gas plants can achieve efficiencies of over 60%, but coal-fired power plants only operate at 33%–40% efficiency [21]. However, in terms of sustainability and efficiency, renewable energy sources like solar and wind perform better than fossil fuels. While solar photovoltaic (PV) efficiency has increased to about 20%–25%, modern wind turbines have a capacity factor of 35%–50%, with offshore installations reaching even greater levels [22,23].

There are major financial advantages to switching to renewable energy as well. In 2021, the renewable energy industry employed 12.7 million people globally, and forecasts suggest that number will continue to rise as clean energy investments increase [24,25]. Additionally, the levelized cost of electricity (LCOE) for solar PV has decreased by 89% and for onshore wind by 70% since 2010, indicating a significant drop in the cost of renewable energy over the last ten years [26,27]. In comparison, the worldwide cost of fossil fuel subsidies, including explicit subsidies, health care expenses, and environmental harm, was $7 trillion in 2022 [28].

Table 1. Environmental and ecological impact of fossil fuels.

Impact Type	Description	Data/ Statistic	References
Greenhouse Gases	CO_2 and CH_4 emissions contribute to global warming and climate change.	Fossil fuels accounted for 74% of U.S. GHG emissions in 2019	[29]
Air Pollution	Release of SO_2, NOx, PM, and other pollutants.	Air pollution from fossil fuels is linked to millions of premature deaths annually	[30]
Water Pollution	Contamination from oil spills and fracking fluids	Fracking wells use 1.5–16 million gallons of water, potentially contaminating groundwater	[14]
Land Degradation	Habitat destruction and soil erosion from mining and drilling activities	Coal mining leads to acid mine drainage, impacting aquatic ecosystems	[15]
Ocean Acidification	CO_2 absorption by oceans changes their chemistry, harming marine life.	Ocean acidity has increased by 30% over the last 150 years	[31]
Ecosystem disruption and Biodiversity Loss	Habitat destruction leads to loss of species and ecosystems	Significant biodiversity loss due to habitat fragmentation and pollution	[32]
Resource Depletion	Finite nature of fossil fuels necessitates sustainable alternatives.	Fossil fuels are non-renewable and contribute to resource depletion	[33]

2.1.2. Nuclear energy and environmental risks

Nuclear energy is one of the few resources that does not emit carbon dioxide when used to produce electricity, making it an alternative to fossil fuels. However, nuclear energy also has its disadvantages, particularly concerning environmental and safety issues. One of the major challenges is the disposal of radioactive waste, which remains hazardous for thousands of years to ecosystems and human health [34]. The United States alone produces over 2000 metric tons of nuclear waste annually, and as of 2020, more than 80,000 metric tons of spent nuclear fuel had accumulated in temporary storage at sites like the Yucca Mountain repository [35]. The disposal of this waste has been a contentious issue, with limited progress in developing permanent repositories.

The risk of severe accidents, such as the Chernobyl disaster in 1986 and the Fukushima Daiichi plant incident in 2011, highlights the dangers of nuclear power [36]. These accidents resulted in significant ecological and human consequences, including radioactivity and the contamination of surface and groundwater sources [37]. Moreover, the high costs of constructing and operating nuclear power plants, coupled with stringent safety regulations, present economic challenges [38]. Public concern about the safety and environmental impacts of nuclear power has led to resistance against new nuclear plants in many countries. A survey conducted by the Pew Research Center in 2019 found that only 49% of Americans supported the use of nuclear energy, compared to 78% support for solar power and 71% for wind power [39].The long-term management of nuclear energy requires robust safety protocols, efficient waste management systems, and public acceptance.

2.2. Renewable energy and environmental challenges

Renewable energy sources, such as solar, wind, and hydroelectric power, have emerged as potential substitutes for fossil fuels. These sources generate energy without emitting greenhouse gases during operation, thereby reducing the overall carbon footprint [40,41]. However, renewable energy technologies also present environmental challenges. Only publications discussing the trade-offs or effects of renewable energy types on the environment and nature conservation were considered relevant.

Changes in land use and resource extraction for renewable energy development can disturb the environment and are usually not sustainable. For instance, wind energy farms have been linked to increased bird and bat deaths due to strikes with turbine blades [42]. Likewise, extensive solar farms can change the cover of the land and subsequently affect the local ecosystems by fragmenting habitats [43]. Even though hydropower energy is more constant and reliable, it comes at the cost of altered water flows, which via loss of biodiversity and the Riverine species, habitat damage, and river degradation [44]. Increased energy production from renewable sources forces and transforms their sources from forests, wetlands, and crop areas, resulting in a reduced capability of renewable energy sources to sustain ecosystems. Also, the studies have addressed that the construction of renewables will produce a lot of biodiversity loss, and this has greatly concerned conservationists.

The types of impacts examined include air, soil, and water pollution, greenhouse gas emissions, hydrological changes, landslides, soil erosion, deforestation, habitat fragmentation, and biodiversity loss, as listed in **Table 2**. The most common renewable energy sources in Tanzania—solar, wind, bioenergy, hydro, and geothermal—are the primary focus of this article.

Table 2. Summary of effects of nature protection and the environment from renewable energy sources [40].

Type	Air Pollution	GHG Releases	Water Contamination	Land Slide	Soil Pollution	Deforestation	Biodiversity and Habitat loss
Solar	X	X	X	X	X	?	?
Wind	?	X	X	X	X	X	?
Hydro	√	√	√	√	√	√	√
Bioenergy	√	√	√	X	√	√	√
Geothermal	√	X	√	√	√	√	√

√: Existing data and theoretical connections.
?: There is a theoretical connection but no supporting data in this field of study.
X: no proof was discovered.

Solar power is considered a low-emission energy source, but its long-term environmental impact is significant. According to studies, the production of photovoltaic (PV) panels creates hazardous waste, including silicon tetrachloride as a byproduct that leads to land and water pollution [45,46]. Large-scale solar arrays also sometimes need significant changes in land use, which fragments habitat. In Arid regions, the installation of solar farms has been shown to reduce natural plant cover by 25% [47,48]. Furthermore, because of its material-intensive components, high-temperature plumbing (HTP) in concentrated solar power (CSP) facilities may result in higher emissions [49]. In countries like India and China, where solar power expansion is accelerating, there are growing concerns about waste management and land degradation [50]. India's ambitious solar farm projects in Rajasthan have been criticized for disrupting fragile desert ecosystems [51,52]. Similarly, in China, the rapid deployment of PV plants has led to increased concerns about silicon mining and water usage, particularly in arid regions [48,53].

Wind power is one of the most ecologically harmless renewable energy technologies in terms of carbon footprint, producing just 11 g CO_2-equivalent per kWh as opposed to coal's 820 g CO_2-equivalent per kWh [54,55]. However, wind turbines have been linked to biodiversity concerns, particularly bird and bat mortality. A study in the United States found that up to 500,000 bird fatalities per year can be attributed to wind farms [56]. Furthermore, building wind turbines changes the morphology of the ground and causes soil erosion, particularly in areas with unstable soil [43]. Changes in the behavior of nearby wildlife populations have also been linked to wind farm noise pollution and electromagnetic disruptions [57]. Concerns over offshore wind farms' effects on marine ecosystems have been raised throughout Europe, especially in Germany and Spain. Studies indicate that fish movement patterns and bottom ecosystems are impacted by turbine foundations [58]. By including artificial reef structures to offset habitat loss, the UK, on the other hand, has been at the forefront of sustainable wind farm design [59–61].

Hydropower projects, despite providing a consistent electricity supply, are coupled with considerable ecological impacts. It has been demonstrated that in some river ecosystems, changes to upstream and downstream water flows can reduce fish populations by as much as 60% [62,63]. For instance, the construction of the Belo Monte dam in Brazil has been correlated with much lower fish diversity and abundance [64]. Large-scale dam projects also contribute to deforestation, with the Amazon region losing over 1 million hectares of forest owing to hydropower expansion [65]. Furthermore, methane emissions from reservoirs might counteract the climate benefits of hydropower; in certain tropical reservoirs, methane emissions can reach 1000 mg/m^2/day [66]. Countries such as Brazil and China have significantly invested in large-scale hydropower. More than 1.3 million people have been displaced by China's Three Gorges Dam, the world's largest hydropower project, which has also caused extensive geological instability [67,68]. Scandinavian nations like Sweden and Norway, on the other hand, have created small-scale run-of-river hydropower plants that preserve energy production while minimizing environmental disruptions [69,70].

Bioenergy is frequently marketed as a sustainable alternative to fossil fuels, although its environmental impact varies depending on the feedstock and land use. The conversion of forests to bioenergy crops has caused a 20% decline in biodiversity in some locations [71]. Furthermore, biomass energy production releases pollutants such as nitrogen oxides and particulate matter, contributing to air quality degradation

[72]. Life-cycle assessment research indicated that bioenergy combustion can produce up to 70 g of CO_2-equivalent per kWh, making its carbon savings largely dependent on sustainable feedstock supply [73]. In the United States, the rise of corn-based ethanol production has caused increasing nitrogen runoff into aquatic bodies, contributing to dead zones in the Gulf of Mexico [74]. Similarly, in Southeast Asia, palm oil biofuel plants have been directly related to deforestation, causing serious habitat loss for endangered species such as orangutans in Indonesia and Malaysia [75].

It is important to note that while certain renewable energy technologies may have negative impacts on biodiversity, others may have positive effects, as shown in **Table 3**.

Table 3. Biodiversity benefits of different renewable energy pathways.

Renewable pathway	Biodiversity benefit	References
Solar energy	Solar energy plants can provide habitat and feeding grounds, such as grazing, for specific animals. This includes photovoltaic panels installed on roofs and building facades	[76]
Wind Energy	Wind power projects may benefit terrestrial wildlife by reducing traffic, increasing food availability, and reducing predators	[77]
Hydropower	Hydroelectric projects can provide new homes for some iconic species	[78]
Bioenergy	Bioenergy landscapes, such as miscanthus and switchgrass, may offer ecosystem services such as habitat and food, in contrast to intensive monoculture farming approaches	[79–82]

2.3. End-of-life of renewable energy systems

Driven by the worldwide movement toward greener energy sources, the fast expansion of renewable energy infrastructure presents the management of the end-of-life (EOL) disposal and recycling of components like wind turbines, solar panels, and energy storage batteries as a difficulty. While these technologies offer lower carbon emissions and a cleaner environment, disposal presents distinct issues. These issues are exacerbated by the difficulty of recycling important minerals like lithium, rare earth elements (REEs), and cadmium, which are essential to these systems. Addressing these concerns is critical to ensure that renewable energy sources are actually sustainable, without causing additional environmental problems as they age.

Wind turbines are crucial for renewable energy production, but their disposal and recycling pose significant challenges. The blades, made from lightweight, durable materials like fiberglass or carbon fiber, pose a significant challenge. The International Renewable Energy Agency (IRENA) predicts a global waste of up to 50 million tons of blades by 2050 [83]. Despite efforts, the scale of wind turbine waste continues to grow. The average lifespan of a wind turbine is 20 to 25 years, after which blades need to be replaced. As wind energy expands globally, efficient, cost-effective, and environmentally friendly recycling solutions are needed.

Solar panels, composed of silicon, glass, aluminum, and sometimes cadmium and lead, have a lifespan of 25–30 years [84]. The recycling process is complex and costly due to the presence of hazardous materials [85]. Less than 10% of solar panels are recycled globally, attributed to difficulties in material separation, lack of proper recycling infrastructure, and low economic incentives. The growing solar energy market leads to a potential waste crisis in the future. The recycling process involves disassembly, material separation, and recovery of valuable components. Recovery of rare materials like cadmium and indium is challenging, necessitating advanced techniques like hydrometallurgical processes.

Rising global demand for energy storage solutions, especially lithium-ion batteries (LIBs), is causing a growing challenge in battery disposal and recycling. Lithium, cobalt, and nickel are critical minerals in LIBs, but their extraction can have significant environmental and social impacts [86]. Currently, only 5% of batteries are recycled, involving costly and energy-intensive processes. The shortage of recycled lithium and other critical minerals has led to concerns about "mining" electronic waste, e-waste, to recover valuable metals. With the growing demand for renewable energy systems, recycling these critical materials becomes even more urgent.

2.4. Case studies illustrating the impacts of renewable and non-renewable energy on ecology and environment

Coal mining and other non-renewable energy sources have been linked to widespread habitat loss and pollution, which ultimately results in the extinction of species, according to some case studies. For example, the loss of habitats vital to species such as the eastern hellbender salamander (Cryptobranchus alleganiensis) due to mountaintop removal mining in Appalachia, USA, has contributed to the fall in biodiversity [87]. In a similar fashion, the Colombian Cerrejón coal mine has drastically reduced habitat, putting species like the jaguar in jeopardy [88,89] and negatively affecting indigenous populations. Due to habitat loss, species like the black-throated finch (Poephila cincta) and bilby (Macrotis lagotis) are under danger from the Adani Carmichael coal mine in Australia [90]. In Bulgaria, coal mining along the Black Sea coast has also destroyed coastal ecosystems and eroded soil, which has an impact on migratory bird species [91]. In the Kuzbass region of Russia, coal mining has contaminated the air and water, harming aquatic life and local ecosystems [92].

However, renewable energy initiatives like solar and wind may also have an impact on biodiversity, but frequently in different ways. Collisions with turbines in wind farms, like those in the UK, have killed birds and bats [93]. In the North Sea, offshore wind farms have an effect on marine ecosystems, despite the fact that certain species benefit from the constructions [94]. There are worries regarding habitat destruction when solar power plants are implemented in environmentally delicate regions, such as the Amazon rainforest [95]. In order to reduce the effects of both energy forms on biodiversity, these case studies emphasize the necessity of meticulous planning and mitigation techniques. Additionally, research shows that in 2012, wind turbines killed over 600,000 bats in the United States, with the Appalachian Mountains seeing the highest fatality rate [96]. According to estimates, wind turbines cause the loss of less than 0.4 birds every gigawatt-hour (GWh) of energy produced, while fossil fuel power plants cause the loss of more than 5 birds per GWh [97].

3. Technological advancements and sustainable energy practices

To link energy generation with environmental preservation, technical advances and regulatory adjustments are necessary. Smart grids, for example, can enhance energy efficiency and reduce environmental impacts. Green product and service innovation includes the development of new items, such as energy-efficient appliances and building designs [98]. Integrating energy storage solutions, such as batteries and pumped hydro storage systems, can improve the reliability of renewable energy sources by addressing intermittency issues [99]. Storage also allows excess energy produced during high production periods to be stored and used when production is low but demand is high. Research and development in the battery field, particularly in lithium-ion and solid-state batteries, have improved their energy density, efficiency, and lifespan, making their commercial use more feasible [100]. Research into carbon capture and storage (CCS) technologies can prevent greenhouse gas emissions from fossil fuel power plants. CCS involves capturing carbon dioxide emissions from fossil fuels and transportation and storing the gas in geological formations. Over time, the economic aspects of this technology have been refined, and the cost of CCS has decreased significantly, making it a more feasible method for reducing carbon emissions [101]. For example, the Petra Nova project in Texas, USA, has been operational since 2017 and is among the largest CCS projects, successfully reducing CO2 emissions from a coal-fired power plant [102].

In terms of policies related to renewable energy sources, the deployment of measures such as carbon pricing, incentives for renewable energies, and emission reduction targets has been identified as crucial in accelerating the transition to sustainable energy systems [103]. Governments and international organizations need to collaborate to design and implement policies that favor the adoption of clean energy sources. For instance, the Green Deal outlines specific objectives, such as reducing greenhouse gas emissions by 2030 and addressing the low share of renewables in the energy supply [104]. Additionally, decentralized energy systems and smarter grids play a significant role in transforming energy generation, transmission, and consumption. Smart grids and decentralized energy systems detect areas with high energy demand and send more electricity to those grids. Local generation within microgrid systems, as well as distributed generation units, reduces reliance on larger-scale power plants and enhances resiliency [105,106].

To meet the world's energy needs economically, continuous innovation and improvement of renewable energy technologies are essential. For example, the development of perovskite solar cells could increase solar energy conversion efficiency at a lower cost than current silicon cells [107]. Furthermore, increased competition in the wind energy market is driven by advancements in wind turbine technology and materials, which have improved energy capture and structural integrity [108]. Technological advances, strategies, and innovative plans are supported by countries through international collaborative initiatives. Setting low-carbon energy policy targets, such as those outlined in the Paris Agreement, represents a global effort to combat climate change [109]. By sharing accumulated knowledge, technologies, and best practices, countries can overcome technical and financial challenges in integrating clean energy solutions. **Figure 2** below shows the advancements and innovations in energy technologies that have significantly influenced resource efficiency and ecological balance.

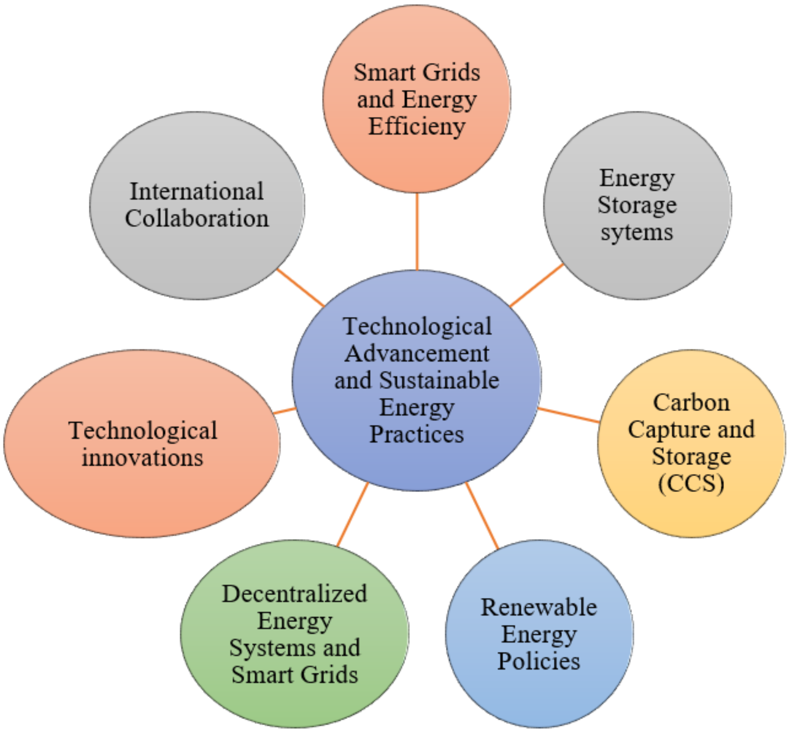

Figure 2. Advancements and innovations in energy technologies.

4. Conclusion

The relationship between energy resources and the environment is complex, with both renewable and non-renewable sources having significant ecological consequences. While fossil fuels have long been the dominant energy source, their extraction and combustion contribute to climate change, air and water pollution, and biodiversity loss. The depletion of non-renewable resources also presents economic and sustainability challenges, necessitating a transition toward cleaner energy alternatives. Renewable energy sources, including solar, wind, hydro, and bioenergy, offer solutions to reduce greenhouse gas emissions and mitigate climate change. However, they are not without drawbacks. Wind farms impact bird and bat populations, large-scale solar farms lead to habitat fragmentation, and hydropower projects disrupt aquatic ecosystems. Therefore, an integrated approach is essential to balance energy production with ecological preservation. Technological advancements, such as smart grids, energy storage solutions, and carbon capture, are critical in improving energy efficiency and reducing negative environmental impacts. Policy measures, including carbon pricing and incentives for renewable energy adoption, can accelerate the transition to sustainable energy systems. International collaboration and investment in research and development will further enhance the viability of clean energy solutions. To achieve a sustainable future, a holistic approach is required, integrating renewable and low-carbon technologies while mitigating their environmental risks. By prioritizing careful planning, impact assessments, and technological innovations, energy production can align with ecological conservation. This balance is vital to ensuring economic development while preserving biodiversity and mitigating climate change.

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References

1. Intergovernmental Panel on Climate Change. Climate change 2014: synthesis report: longer report. Intergovernmental Panel on Climate Change; 2015.
2. Osman AI, Chen L, Yang M, et al. Yap, Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. Environ Chem Lett. 2023; 21(2023): 741-764. doi: 10.1007/s10311-022-01532-8
3. Kiesecker JM, Copeland H, Pocewicz A, et al. Development by design: blending landscape-level planning with the mitigation hierarchy. Frontiers in Ecology and the Environment. 2009; 8(5): 261-266. doi: 10.1890/090005
4. Rosenberg DM, McCully P, Pringle CM. Global-scale environmental effects of hydrological alterations: Introduction. Bioscience. 2000; 50(2000): 746-751. doi: 10.1641/0006-3568(2000)050[0746:GSEEOH]2.0.CO;2
5. Yang H, Feng Q, Xu W, et al. Unraveling the nuclear isotope tapestry: Applications, challenges, and future horizons in a dynamic landscape. Eco-Environment & Health. 2024; 3(2): 208-226. doi: 10.1016/j.eehl.2024.01.001
6. Kurniawan TA, Othman MHD, Singh D, et al. Technological solutions for long-term storage of partially used nuclear waste: A critical review. Annals of Nuclear Energy. 2022; 166: 108736. doi: 10.1016/j.anucene.2021.108736
7. Ahmad T, Zhang D. A critical review of comparative global historical energy consumption and future demand: The story told so far. Energy Reports. 2020; 6: 1973-1991. doi: 10.1016/j.egyr.2020.07.020
8. Boykoff M, Luedecke G. Elite News Coverage of Climate Change. Oxford Research Encyclopedia of Climate Science. 2016. doi: 10.1093/acrefore/9780190228620.013.357
9. Ambient (outdoor) air pollution, (n.d.). Available online: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health?gad_source=1&gclid=CjwKCAiA34S7BhAtEiwACZzv4UCKjjJNs3QNsXXwG8_xTfwlGPe31WmcMarJivuve03UHb9hHpjKKBoCWCAQAvD_BwE (accessed 17 December 2024).
10. Lelieveld J, Evans JS, Fnais M, et al. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature. 2015; 525(7569): 367-371. doi: 10.1038/nature15371
11. Vohra K, Vodonos A, Schwartz J, et al. Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. Environmental Research. 2021; 195: 110754. doi: 10.1016/j.envres.2021.110754
12. Finer M, Jenkins CN, Pimm SL, et al. Oil and Gas Projects in the Western Amazon: Threats to Wilderness, Biodiversity, and Indigenous Peoples. PLoS ONE. 2008; 3(8): e2932. doi: 10.1371/journal.pone.0002932
13. Zhang Y, Han A, Deng S, et al. The impact of fossil fuel combustion on children’s health and the associated losses of human capital. Global Transitions. 2023; 5: 117-124. doi: 10.1016/j.glt.2023.07.001
14. Vengosh A, Jackson RB, Warner N, et al. A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. Environmental Science & Technology. 2014; 48(15): 8334-8348. doi: 10.1021/es405118y
15. Palmer MA, Bernhardt ES, Schlesinger WH, et al. Mountaintop Mining Consequences. Science. 2010; 327(5962): 148-149. doi: 10.1126/science.1180543
16. Mudumba T, Stimpson B, Jingo S, et al. The implications of global oil exploration for the conservation of terrestrial wildlife. Environmental Challenges. 2023; 11: 100710. doi: 10.1016/j.envc.2023.100710
17. Vohra K, Vodonos A, Schwartz J, et al. Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. Environmental Research. 2021; 195: 110754. doi: 10.1016/j.envres.2021.110754
18. Domke GM, Walters BF, Nowak DJ, et al. Greenhouse Gas Emissions and Removals from Forest Land, Woodlands, and Urban Trees in the United States, 1990-2017. U.S. Department of Agriculture, Forest Service, Northern Research Station;

2019. doi: 10.2737/fs-ru-178
19. Executive Summary - CO2 Emissions in 2023 - Analysis - IEA. Available online: https://www.iea.org/reports/co2-emissions-in-2023/executive-summary (accessed 27 December 2024).
20. Myllyvirta L. Quantifying the Economic Costs of Air Pollution from Fossil Fuels Key messages. CREA; 2020.
21. Gonzalez-Salazar MA, Kirsten T, Prchlik L. Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. Renewable and Sustainable Energy Reviews. 2018; 82: 1497-1513. doi: 10.1016/j.rser.2017.05.278
22. Zappa W, van den Broek M. Analysing the potential of integrating wind and solar power in Europe using spatial optimisation under various scenarios. Renewable and Sustainable Energy Reviews. 2018; 94: 1192-1216. doi: 10.1016/j.rser.2018.05.071
23. Tyagi VV, Kaushik SC, Tyagi SK. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. Renewable and Sustainable Energy Reviews. 2012; 16(3): 1383-1398. doi: 10.1016/j.rser.2011.12.013
24. Renewable Energy and Jobs - Annual Review 2022. Available online: https://www.irena.org/publications/2022/Sep/Renewable-Energy-and-Jobs-Annual-Review-2022 (accessed 27 December 2024).
25. International Renewable Energy Agency, International Labour Organization. Renewable Energy & Jobs Annual Job Review. 2021; 1-98.
26. Renewable Power Generation Costs in 2023. Available online: https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023 (accessed 27 December 2024).
27. The drop in the LCOE of renewable energies over the past decade drives the energy transition - AleaSoft Energy Forecasting. Available online: https://aleasoft.com/drop-lcoe-renewable-energies-past-decade-drives-energy-transition/ (accessed 27 December 2024).
28. Black S. IMF Fossil Fuel Subsidies Data: 2023 Update. IMF Working Papers. 2023; 2023(169): 1. doi: 10.5089/9798400249006.001
29. Epa U, Change Division C. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019 - Data Highlights. 1990.
30. Air pollution. Available online: https://www.who.int/health-topics/air-pollution?form=MG0AV3#tab=tab_1 (accessed 18 December 2024).
31. Shue H. Responsible for what? Carbon producer CO2 contributions and the energy transition. Climatic Change. 2017; 144(4): 591-596. doi: 10.1007/s10584-017-2042-9
32. Kuipers KJJ, Hilbers JP, Garcia-Ulloa J, et al. Habitat fragmentation amplifies threats from habitat loss to mammal diversity across the world's terrestrial ecoregions. One Earth. 2021; 4(10): 1505-1513. doi: 10.1016/j.oneear.2021.09.005
33. Kirsch S. Running out? Rethinking resource depletion. The Extractive Industries and Society. 2020; 7(3): 838-840. doi: 10.1016/j.exis.2020.06.002
34. Ramana MV. Nuclear power and the public. Bulletin of the Atomic Scientists. 2011; 67(4): 43-51. doi: 10.1177/0096340211413358
35. Review of the Department of Energy's Plans for Disposal of Surplus Plutonium ... - National Academies of Sciences, Engineering, and Medicine, Division on Earth and Life Studies, Nuclear and Radiation Studies Board, Committee on Disposal of Surplus Plutonium at the Waste Isolation Pilot Plant - Google Books. Available online: https://books.google.co.tz/books?hl=en&lr=&id=BErpDwAAQBAJ&oi=fnd&pg=PR1&dq=U.S.+Department+of+Energy+(DOE).+(2020).+Nuclear+Waste+Disposal.&ots=ARHo0MYyMk&sig=DIAF06zq7LRfoTUBpsc5jeI75J8&redir_esc=y#v=onepage&q=U.S.%20Department%20of%20Energy%20(DOE).%20(2020).%20Nuclear%20Waste%20Disposal.&f=false (accessed 27 December 2024).
36. Perrow C. Fukushima and the inevitability of accidents. Bulletin of the Atomic Scientists. 2011; 67(6): 44-52. doi: 10.1177/0096340211426395
37. Yasunari TJ, Stohl A, Hayano RS, et al. Yasunari, Cesium-137 deposition and contamination of Japanese soils due to the Fukushima nuclear accident. Proc Natl Acad Sci USA. 2011; 108(2011): 19530-19534. doi: 10.1073/pnas.1112058108
38. Lovering JR, Yip A, Nordhaus T. Historical construction costs of global nuclear power reactors. Energy Policy. 2016; 91: 371-382. doi: 10.1016/j.enpol.2016.01.011
39. Majority of Americans support more nuclear power in the US | Pew Research Center. Available online: https://www.pewresearch.org/short-reads/2024/08/05/majority-of-americans-support-more-nuclear-power-in-the-country/

(accessed 27 December 2024).

40. Pratiwi S, Juerges N. Review of the impact of renewable energy development on the environment and nature conservation in Southeast Asia. Energy, Ecology and Environment. 2020; 5(4): 221-239. doi: 10.1007/s40974-020-00166-2
41. Li X, Gu Q, Wang Q, et al. Renewable energy in the mining industry: Status, opportunities and challenges. Energy Strategy Reviews. 2024; 56: 101597. doi: 10.1016/j.esr.2024.101597
42. Voigt CC, Straka TM, Fritze M. Producing wind energy at the cost of biodiversity: A stakeholder view on a green-green dilemma. Journal of Renewable and Sustainable Energy. 2019; 11(6). doi: 10.1063/1.5118784
43. Dhar A, Naeth MA, Jennings PD, et al. Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. Science of The Total Environment. 2020; 718: 134602. doi: 10.1016/j.scitotenv.2019.134602
44. He F, Zarfl C, Tockner K, et al. Hydropower impacts on riverine biodiversity. Nature Reviews Earth & Environment. 2024; 5(11): 755-772. doi: 10.1038/s43017-024-00596-0
45. Stamford L, Azapagic A. Environmental Impacts of Photovoltaics: The Effects of Technological Improvements and Transfer of Manufacturing from Europe to China. Energy Technology. 2018; 6(6): 1148-1160. doi: 10.1002/ente.201800037
46. Tawalbeh M, Al-Othman A, Kafiah F, et al. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. Science of The Total Environment. 2021; 759: 143528. doi: 10.1016/j.scitotenv.2020.143528
47. Gómez-Catasús J, Morales MB, Giralt D, et al. Solar photovoltaic energy development and biodiversity conservation: Current knowledge and research gaps. Conservation Letters. 2024; 17(4). doi: 10.1111/conl.13025
48. Lafitte A, Sordello R, Ouédraogo DY, et al. Existing evidence on the effects of photovoltaic panels on biodiversity: a systematic map with critical appraisal of study validity. Environmental Evidence. 2023; 12(1). doi: 10.1186/s13750-023-00318-x
49. Pitz-Paal R, Amin A, Oliver Bettzuge M, et al. Wagner, Concentrating solar power in Europe, the middle east and North Africa: A review of development issues and potential to 2050. Journal of Solar Energy Engineering, Transactions of the ASME. 2012; 134(2012). doi: 10.1115/1.4006390
50. Degraded lands can aid achieve four times India's 2030 renewable. Available online: https://www.tncindia.in/what-we-do/our-insights/stories-in-india/renewableenergy/ (accessed 27 December 2024).
51. Kumar K, Malhotra Baxi S. Desert Solar Power India: A Systematic Study of Potential Development of Solar Power in The Indian Desert. International Journal of Advanced Research. 2021; 9(10): 1411-1414. doi: 10.21474/ijar01/13700
52. Shokrgozar S, Girard B. "The companies are powerful, people are weak": India's solar energy ambitions and the legitimation of dispossession in Rajasthan. Journal of Political Ecology. 2024; 31(1). doi: 10.2458/jpe.5410
53. Wu H, Hou Y. Recent Development of Grid-Connected PV Systems in China. Energy Procedia. 2011; 12: 462-470. doi: 10.1016/j.egypro.2011.10.062
54. Wang Y, Sun T. Life cycle assessment of CO2 emissions from wind power plants: Methodology and case studies. Renewable Energy. 2012; 43: 30-36. doi: 10.1016/j.renene.2011.12.017
55. Dolan SL, Heath GA. Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization. J Ind Ecol. 2012; 16(2012). doi: 10.1111/j.1530-9290.2012.00464.x
56. Gradolewski D, Dziak D, Martynow M, et al. Comprehensive Bird Preservation at Wind Farms. Sensors. 2021; 21(1): 267. doi: 10.3390/s21010267
57. Estellés-Domingo I, López-López P. Effects of wind farms on raptors: A systematic review of the current knowledge and the potential solutions to mitigate negative impacts. Animal Conservation. 2024.
58. Maxwell SM, Kershaw F, Locke CC, et al. Potential impacts of floating wind turbine technology for marine species and habitats. Journal of Environmental Management. 2022; 307: 114577. doi: 10.1016/j.jenvman.2022.114577
59. Püts M, Kempf A, Möllmann C, et al. Trade-offs between fisheries, offshore wind farms and marine protected areas in the southern North Sea – Winners, losers and effective spatial management. Marine Policy. 2023; 152: 105574. doi: 10.1016/j.marpol.2023.105574
60. Afzal MS, Tahir F, Al-Ghamdi SG. Recommendations and Strategies to Mitigate Environmental Implications of Artificial Island Developments in the Gulf. Sustainability. 2022; 14(9): 5027. doi: 10.3390/su14095027
61. Edwards-Jones A, Watson SCL, Szostek CL, et al. Stakeholder insights into embedding marine net gain for offshore wind farm planning and delivery. Environmental Challenges. 2024; 14: 100814. doi: 10.1016/j.envc.2023.100814
62. Bunn SE, Arthington AH. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity, Environ Manage. 2002; 30(2002): 492-507. doi: 10.1007/s00267-002-2737-0

63. Rolls RJ, Leigh C, Sheldon F. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. Freshwater Science. 2012; 31(4): 1163-1186. doi: 10.1899/12-002.1
64. Winemiller KO, McIntyre PB, Castello L, et al. Sáenz, Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science. 1979; 351(2016): 128-129. doi: 10.1126/science.aac7082
65. Castello L, Macedo MN. Large-scale degradation of Amazonian freshwater ecosystems. Global Change Biology. 2015; 22(3): 990-1007. doi: 10.1111/gcb.13173
66. Bambace LAW, Ramos FM, Lima IBT, et al. Mitigation and recovery of methane emissions from tropical hydroelectric dams. Energy. 2007; 32(6): 1038-1046. doi: 10.1016/j.energy.2006.09.008
67. Gleick PH. The World's Water, undefined 2008, Three Gorges Dam Project, Yangtze River, China, Researchgate. Available online: https://www.researchgate.net/profile/Peter-Gleick/publication/265238648_Three_Gorges_Dam_Project_Yangtze_River_China/links/55f890c908aeafc8ac137fe4/Three-Gorges-Dam-Project-Yangtze-River-China.pdf (accessed 7 December 2024).
68. Chang CYA, Gao Z, Kaminsky A, Reames TG. Michigan Sustainability Case: Revisiting the Three Gorges Dam: Should China Continue to Build Dams on the Yangtze River? Sustainability (United States).2018; 11(2018): 204-215. doi: 10.1089/sus.2018.29141.cyac
69. Köhler B, Ruud A. How are environmental measures realized in European hydropower? Available online: https://brage.nina.no/nina-xmlui/handle/11250/3060086 (accessed 7 December 2024).
70. Ferrier RC, Jenkins A. Handbook of Catchment Management; Wiley Online Library; 2009.
71. Núñez-Regueiro MM, Siddiqui SF, Fletcher RJ. Effects of bioenergy on biodiversity arising from land-use change and crop type. Conservation Biology. 2020; 35(1): 77-87. doi: 10.1111/cobi.13452
72. Tomlin AS. Air Quality and Climate Impacts of Biomass Use as an Energy Source: A Review, Energy and Fuels. 2021; 35(2021): 14213-14240. doi: 10.1021/acs.energyfuels.1c01523
73. Kulas D, Winjobi O, Zhou W, Shonnard D. Effects of Coproduct Uses on Environmental and Economic Sustainability of Hydrocarbon Biofuel from One- and Two-Step Pyrolysis of Poplar, ACS Sustain Chem Eng. 2018; 6(2018): 5969-5980. doi: 10.1021/acssuschemeng.7b04390
74. Davis JE. Booms, Blooms, and Doom: The Life of the Gulf of Mexico Dead Zone. Alabama Review. 2017; 70(2): 156-170. doi: 10.1353/ala.2017.0011
75. Waller MT. Ethnoprimatology. Springer International Publishing; 2016.
76. Hernandez RR, Easter SB, Murphy-Mariscal ML, et al. Environmental impacts of utility-scale solar energy. Renewable and Sustainable Energy Reviews. 2014; 29: 766-779. doi: 10.1016/j.rser.2013.08.041
77. Pearce-Higgins JW, Stephen L, Douse A, et al. Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. Journal of Applied Ecology. 2012; 49(2): 386-394. doi: 10.1111/j.1365-2664.2012.02110.x
78. Palmeirim AF, Peres CA, Rosas FCW. Giant otter population responses to habitat expansion and degradation induced by a mega hydroelectric dam. Biological Conservation. 2014; 174: 30-38. doi: 10.1016/j.biocon.2014.03.015
79. Werling BP, Dickson TL, Isaacs R, et al. Landis, Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes, Proc Natl Acad Sci USA. 2014; 111(2014): 1652-1657. doi: 10.1073/pnas.1309492111
80. Semere T, Slater F. Ground flora, small mammal and bird species diversity in miscanthus (Miscanthus × giganteus) and reed canary-grass (Phalaris arundinacea) fields. Biomass and Bioenergy. 2007; 31(1): 20-29. doi: 10.1016/j.biombioe.2006.07.001
81. Timo T, Lyra-Jorge M, Gheler-Costa C, et al. Effect of the plantation age on the use of Eucalyptus stands by medium to large-sized wild mammals in south-eastern Brazil. iForest - Biogeosciences and Forestry. 2015; 8(2): 108-113. doi: 10.3832/ifor1237-008
82. Dotta G, Verdade LM. Medium to large-sized mammals in agricultural landscapes of south-eastern Brazil. Mammalia. 2011; 75(2011): 345-352. https://doi.org/10.1515/MAMM.2011.049
83. IRENA - International Renewable Energy Agency. Available online: https://www.irena.org/ (accessed 27 December 2024).
84. Ofoegbu O, Ajakaye OJ, Onche E, et al. Recycling of Solar Panel Cells: Past, Present and Future. Paper Publications; 2024.
85. Badran G, Lazarov VK. From Waste to Resource: Exploring the Current Challenges and Future Directions of Photovoltic Solar Cell Recycling. Solar. 2025; 5(1): 4. doi: 10.3390/solar5010004
86. Wagner-Wenz R, van Zuilichem AJ, Göllner-Völker L, et al. Recycling routes of lithium-ion batteries: A critical review of

the development status, the process performance, and life-cycle environmental impacts. MRS Energy & Sustainability. 2022; 10(1): 1-34. doi: 10.1557/s43581-022-00053-9
87. Price SJ, Muncy BL, Bonner SJ, et al. Effects of mountaintop removal mining and valley filling on the occupancy and abundance of stream salamanders. Bellard C, ed. Journal of Applied Ecology. 2015; 53(2): 459-468. doi: 10.1111/1365-2664.12585
88. Cerrejón-Glencore's coal mine continues to make unfulfilled promises to the communities it has affected for decades in Colombia. The Roche community speaks up - London Mining Network. Available online: https://londonminingnetwork.org/2024/11/cerrejon-glencores-coal-mine-continues-to-make-unfulfilled-promises/ (accessed on 27 December 2024).
89. Oliveira MLS, Akinyemi SA, Nyakuma BB, et al. Environmental Impacts of Coal Nanoparticles from Rehabilitated Mine Areas in Colombia. Sustainability. 2022; 14(8): 4544. doi: 10.3390/su14084544
90. Black-throated finch GP fact sheet 2014. "Black-throated finch GP fact sheet 2014", Accessed: Feb. 28, 2025. [Online]. Available: https://www.banktrack.org/download/impacts_of_the_proposed_carmichael_coal_mine_project_on_the_black_throated_finch
91. Prodanov B, Dimitrov L, Kotsev I, et al. Spatial distribution of sand dunes along the Bulgarian Black Sea Coast: inventory, UAS mapping and new discoveries. Nature Conservation. 2023; 54: 81-120. doi: 10.3897/natureconservation.54.105507
92. Osintseva M, Ishutin I. Influence of Natural, Climatic, and Industrial Factors on Air and Water Quality in The Kemerovo Region (Kuzbass, Russia). Qubahan Academic Journal. 2023; 3(3): 1-10. doi: 10.48161/qaj.v3n3a149
93. Pearce-Higgins JW, Stephen L, Langston RHW, et al. The distribution of breeding birds around upland wind farms. Journal of Applied Ecology. 2009; 46(6): 1323-1331. doi: 10.1111/j.1365-2664.2009.01715.x
94. Slavik K, Lemmen C, Zhang W, et al. Wirtz, The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. Hydrobiologia. 2019; 845 (2019): 35-53. https://doi.org/10.1007/s10750-018-3653-5
95. Hampl N. Energy systems for Brazil's Amazon: Could renewable energy improve Indigenous livelihoods and save forest ecosystems? Energy Research & Social Science. 2024; 112: 103491. doi: 10.1016/j.erss.2024.103491
96. Hayes MA. Bats Killed in Large Numbers at United States Wind Energy Facilities. BioScience. 2013; 63(12): 975-979. doi: 10.1525/bio.2013.63.12.10
97. Smallwood KS. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin. 2013; 37(1): 19-33. doi: 10.1002/wsb.260
98. Ürge-Vorsatz D, Cabeza LF, Serrano S, et al. Heating and cooling energy trends and drivers in buildings. Renewable and Sustainable Energy Reviews. 2015; 41: 85-98. doi: 10.1016/j.rser.2014.08.039
99. Worku MY. Recent Advances in Energy Storage Systems for Renewable Source Grid Integration: A Comprehensive Review. Sustainability. 2022; 14(10): 5985. doi: 10.3390/su14105985
100. Dunn B, Kamath H, Tarascon JM, Electrical energy storage for the grid: A battery of choices. Science. 1979; 334 (2011): 928-935. doi: 10.1126/science.1212741
101. Lee H, Lee J, Koo Y. Economic impacts of carbon capture and storage on the steel industry–A hybrid energy system model incorporating technological change. Applied Energy. 2022; 317: 119208. doi: 10.1016/j.apenergy.2022.119208
102. Jenkins J. Financing Mega-Scale Energy Projects: A Case Study of The Petra Nova Carbon Capture Project Prepared for the CEO Council for Sustainable Urbanization October 2015. Available online: http://english.cciee.org.cn (accessed on 27 December 2024).
103. Kartal MT, Pata UK, Alola AA. Renewable electricity generation and carbon emissions in leading European countries: Daily-based disaggregate evidence by nonlinear approaches. Energy Strategy Reviews. 2024; 51: 101300. doi: 10.1016/j.esr.2024.101300
104. Vela Almeida D, Kolinjivadi V, Ferrando T, et al. The "Greening" of Empire: The European Green Deal as the EU first agenda. Political Geography. 2023; 105: 102925. doi: 10.1016/j.polgeo.2023.102925
105. Massoud Amin S, Wollenberg BF. Toward a smart grid: power delivery for the 21st century. IEEE Power and Energy Magazine. 2005; 3(5): 34-41. doi: 10.1109/mpae.2005.1507024
106. Babanazarov NSH, Matkarimov AI, Ilyasov IS. Advancing energy efficiency: Harnessing machine learning for smart grid management. E3S Web of Conferences. 2024; 524: 01003. doi: 10.1051/e3sconf/202452401003
107. Hu Z, Ran C, Zhang H, et al. The Current Status and Development Trend of Perovskite Solar Cells. Engineering. 2023; 21:

15-19. doi: 10.1016/j.eng.2022.10.012

108. Leung DYC, Yang Y. Wind energy development and its environmental impact: A review. Renewable and Sustainable Energy Reviews. 2012; 16(1): 1031-1039. doi: 10.1016/j.rser.2011.09.024
109. Dwivedi YK, Hughes L, Kar AK, et al. Climate change and COP26: Are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action. International Journal of Information Management. 2022; 63: 102456. doi: 10.1016/j.ijinfomgt.2021.102456