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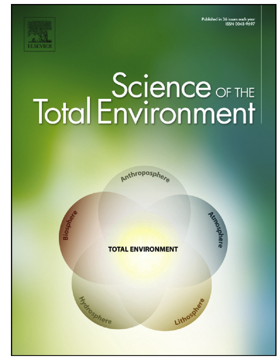

A critical review on Environmental Impacts of Renewable Energy Systems and Mitigation Strategies: Wind, Hydro, Biomass and Geothermal

Enas Taha Sayed, Tabbi Wilberforce, Khaled Elsaid, Malek Kamal Hussien Rabaia, Mohammad Ali Abdelkareem, Kyu-Jung Chae, A.G. Olabi

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A critical review on Environmental Impacts of Renewable Energy Systems and Mitigation Strategies: Wind, Hydro, Biomass and Geothermal

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Abstract

The annual growth of global energy demand and the associated environmental impacts (EIs) has an important role in the large sustainable and green global energy transition. Renewable energy systems have been attracting substantial economic, environmental, and technical attention throughout the last decade, while some have been in the market for almost a century. However, even renewable energy may negatively affect the environment, which is widely considered much less harsh than fossil energy resources. This, in return, more consideration and appropriate precautions should be taken. This work deals with the environmental impacts (EIs) of small and medium-sized wind, hydro, biomass, and geothermal power systems. The approach goes through all stages from planning and conception to constructing and installing and throughout service life and decommissioning. For various circumstances and technically and ecologically viable guidelines for their effect on natural resources and wildlife, clear and comprehensive solutions have been given.

Keywords: Environmental Impacts; Wind energy systems; hydro energy systems; Biomass; Geothermal; Environmental Solutions.

1. Introduction

Through industrial development, energy production is regarded as a major challenge, particularly as the world's population is rising exponentially. Community expansion and migration into formerly uninhabited spaces and technology growth increase the energy demand in general and electricity, particularly [1, 2]. Therefore, for a sustainable, stable society, clean, environmentally friendly, and efficient energy sources are more than ever needed [3, 4]. Fossil fuels and conventional energy production processes dominate coal, crude oil, and natural gas supplies, accounting for more than 80 percent of primary energy sources of 2018 [5]. However, the widespread use of fossil fuels was a double-edged sword, sadly detrimental to the environment and climate [6, 7]. The immense reliance on fossil fuels and their misuse on a wide scale in almost every field of life have brought about many dangerous environmental problems [8, 9], heatwaves, forest fires, elevated sea levels, flooding, etc. [10-12].

Extensive research and development efforts have been undertaken to improve the efficiency of the current processes through waste heat recovery [13-17], developing energy conversion devices that are environmentally friendly and efficient [18-21], and applying sustainable and renewable energy sources with low or no environmental effects (EIs) [22, 23]. Renewable energy resources have been driven to a level that enables advanced countries to turn their existing energy mix into more renewable energy shares, calling for a global carbon reduction and neutralization. Massive diplomatic decisions and, in particular, the Paris Agreement called for global carbon emission reduction [24]. According to the International Renewable Energy Agency (IRENA) report, Climate-Safe Energy Solutions: To effectively achieve such major goals and adequately restrict negative impacts on climate change, maximum decarbonization of energy supply must be achieved in less than 50 years. However, that can not be accomplished without at least seven times the current growth rate of renewable energy sources by 2060, when the world's economy triples [25].

In IRENA 's 2019 statistical report, renewable energies have shown 7.4% capacity growth with a net power growth of 176 GW in 2019, of which 54% are built in Asia alone with 90% for new solar and wind power plants [26, 27]. Renewable energy dominates the new power capacity in 2019 by about 70% [28, 29]. Every kWh created by a renewable system replaced a kWh generated by a conventional power plant. However, renewable energy systems continue to be improved and have not yet replaced conventional systems in full.

Among various renewable energy technologies, solar power generation is the most common and well-known technology and has been actively applied worldwide [30, 31]. Other than solar energy systems, renewable energy resources like wind, geothermal, and biomass energy systems have been getting good attention and promising investments in the past decade, as shown in Fig. 1 [32]. Figure 1 shows the significant increase in renewable energy installed capacity over the last two decades for wind, hydro, biomass, and geothermal energies. Further, hydroelectric and tidal energy have previously seen considerable attention towards them being the first commercialized and mature renewable system compared with the rise of the other renewable systems [32].

The many advantages of renewable energies, specifically those related to being environmentally friendly, have been the driver of extensive research work over the last couple of decades [33]. Figure 2 below shows the number of publications with either the words energy or power in combination with geothermal, biomass, wind and hydroelectric in the title of journal articles, as extracted from the ScienceDirect website by Elsevier, as one of the internationally recognized scientific publishers, throughout 1996-2020. Figure 2.a shows a clear evolution in the publication as a direct output for research work and activities from about 150 in 1996 to more than 1,000 in 2020. The publications related to wind energy are about 21.5-73.3% over the same period, with an overall average of about 60%, as shown in Fig. 2.b. Followed by biomass energy of 17-68%, with an overall average of 23%. Geothermal energy was the third type of renewable energy in this ranking, with about 5.3-17.3% over the study period, with an overall average of 10%. Hydroelectric power, as one of the old and well-established types of clean and renewable energies, has received the least research and development efforts of about 4.4-11% with an overall average of about 7%. It is essential to take proper precautions to the environmental impacts of renewable energy resources. An assessment of the sustainability of such renewable technologies and an evaluation of all technologies and eliminating any possible environmental risk are required to avoid further EIs arising from the newly implemented renewable energy supply systems [34-36].

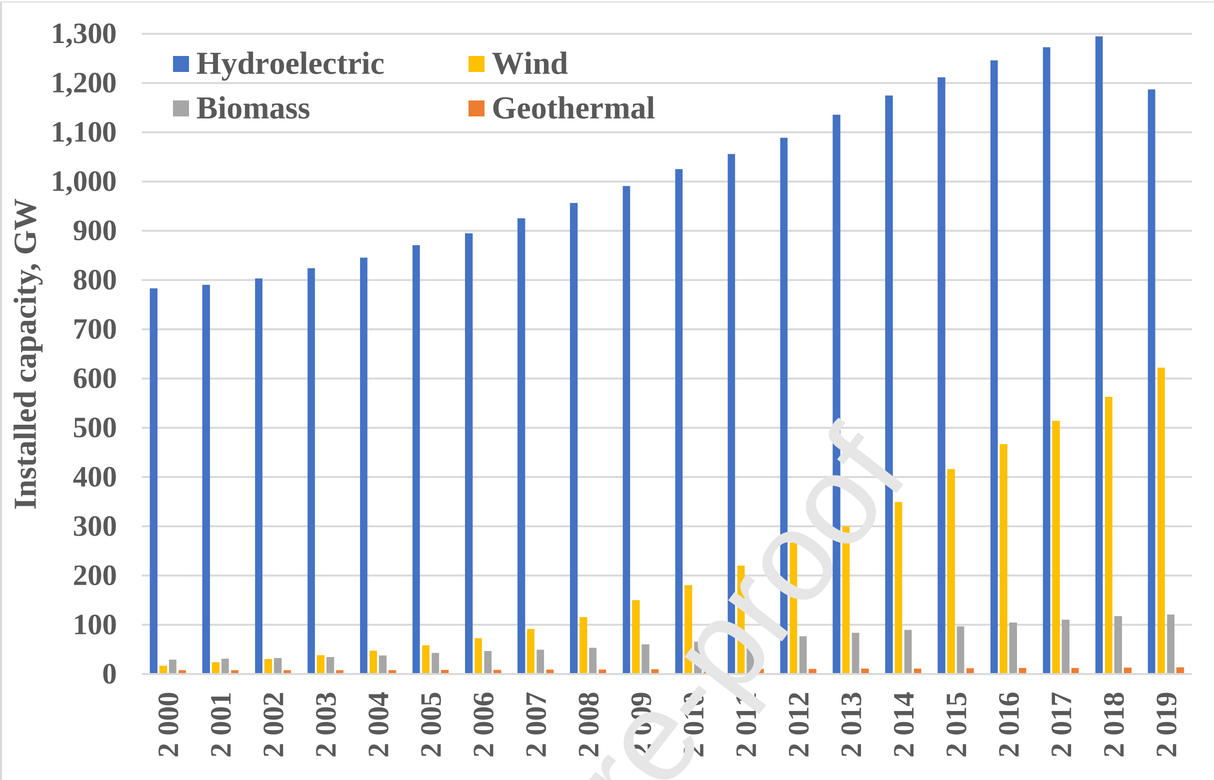
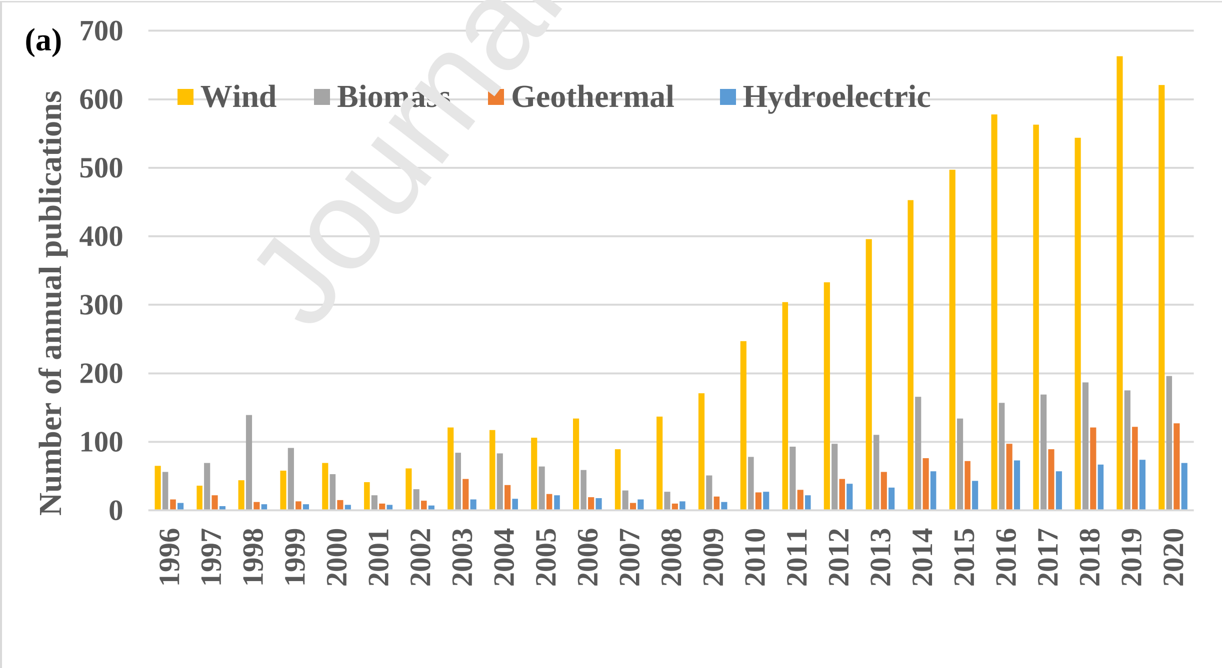


Figure 1: Total installed capacity of different renewable energy systems [32].



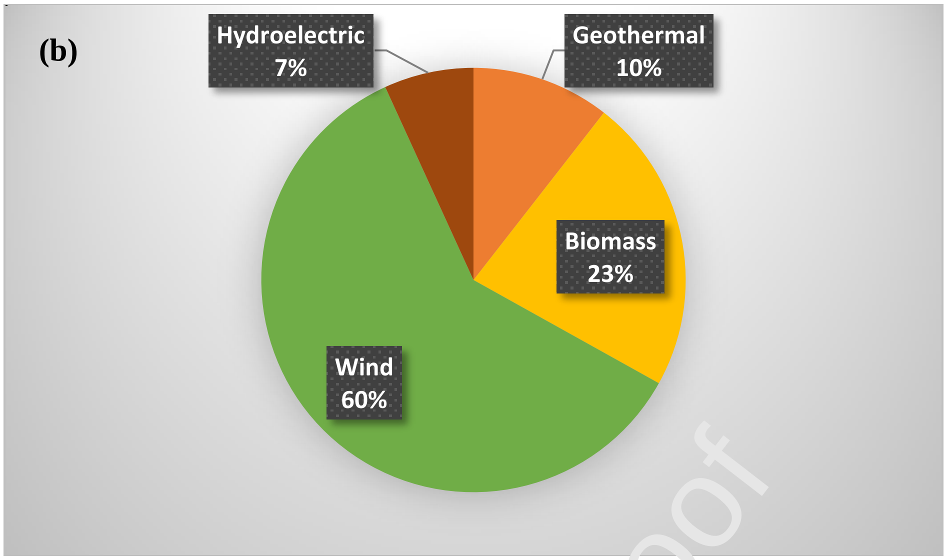


Figure 2: Publications concerning different renewable energies over the period 1996-2020 (a) Number of annual publications, (b) Overall average percentage.

To date, the EIs of solar energy generation has been dealt with relatively more than any other renewable technologies, and in-depth insights have been made on various solar power topics. Therefore, this review addresses the EIs of wind, hydro, i.e., hydroelectric (excluding tidal and wave, due to their relatively low implementation stage), biomass, and geothermal energy systems. It discusses the most recent concerning EIs of these renewable technologies and provides possible mitigation strategies for different environmental scenarios. This review considers the EIs of the operation phase of the renewable energy production stage rather than the whole life cycle assessment in a collective approach. The detailed EIs based on life cycle assessment can be found elsewhere for each individual renewable energy resource [37-43]. This is mainly due to the fact that the main advantage of renewable energy resources over fossil energy resources are mainly associated with the much lower EIs during the operation phase. It is usually not fair to compare renewable energy resources to fossil ones based on a whole life cycle as the utilization of renewable energy resources are still associated with more costly and advanced material, intermittent nature, and small scale will have.

The review discusses first the different EI of fossil energy resources, which serve as a base for comparing the relative EIs of renewable energy resources to fossil fuels and each other. Additionally, due to the intermittent generation nature of most renewable energy resources, it is commonly integrated with other renewable energy resources, fossil energy resources, and energy storage to smooth the power supply capacity. It is ten easier to think of the EIs of such a hybrid system in relation to the specific EIs associated with the main hybrid components, which can be collectively less or more than the sum of both. The review also intensively explains and discusses the possibilities of small activities in different systems that can cause more significant and indirect impacts.

2. Environmental impacts of fossil energy resources

A wide variety of fossil energy resources are readily available and have been exploited since the old days of the bronze and iron ages, utilizing coal, and more recently oil since the mid-19th century, and more recently natural gas in the late 19th century. Figure 3 shows the primary energy sources in mega-ton oil equivalent (Mtoe) since 1990. The figure shows that fossil energy sources have been dominating the energy supply, which has been dropping recently due to the development in renewable energy resources, reaching 81% recently [44]. The current electrical power generation capacity of about 25 PWh is sourced from: coal 37.7%l, natural gas 22.5%, hydropower 16.1%, nuclear power 10.1%, renewable energies 8.5%, oil 3.2%, and biofuels 1.8% [44].

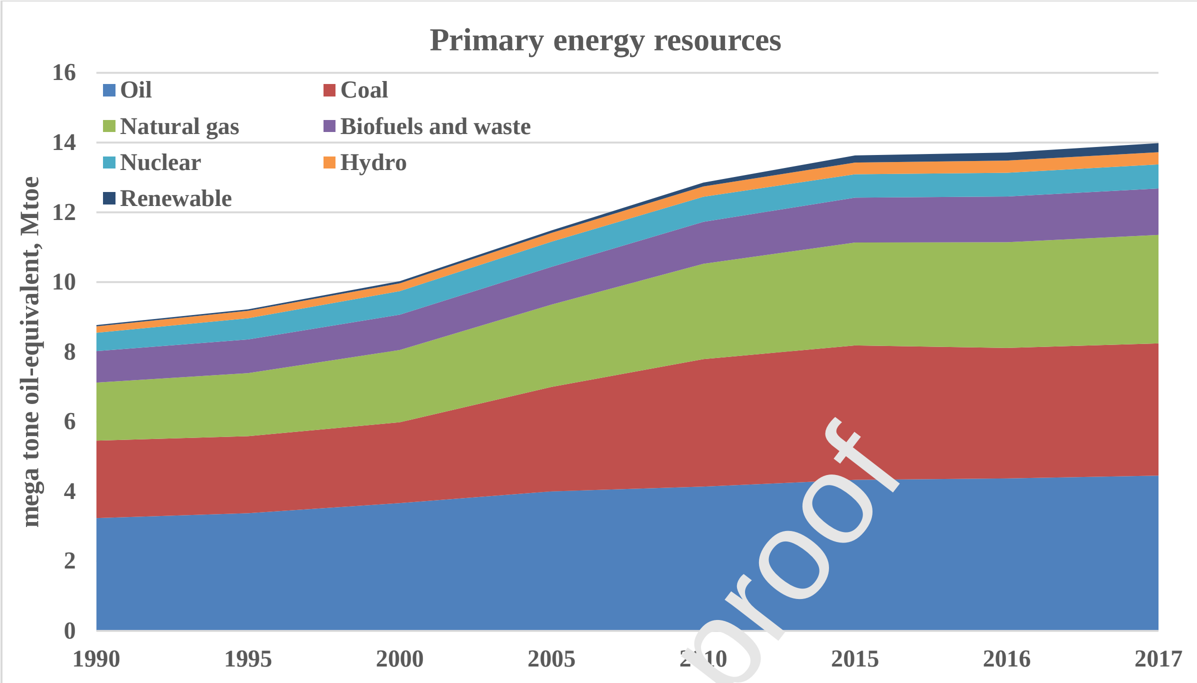


Figure 3: Primary energy resources over the period of 1990-2017 [Source: International Energy Agency IEA, 2020] [44].

Although the notable development and urbanization the utilization of fossil energy resources has brought since the early Industrial Revolution, the costly price and adverse side effects were the associated EIs [45-47]. The most notable EIs of fossil fuels is their impact on air quality and climate change due to the emissions of many combustion flue gases containing significant greenhouse gases (GHGs) [48, 49]. The other main EI is the water resources utilized for energy generation due to what is called the water-energy nexus being two associated streams in any natural process [50-52].

2.1. Gaseous emissions.

The gaseous emissions from power plants can be divided into two groups: Greenhouse gases (GHGs) and aerosols. The GHGs include carbon oxides CO_x (CO and CO_2), sulfur oxides SOx (SO_2 and SO_3), nitrogen oxides NOx (N_2O, NO, and NO_2), and volatile organic compounds

(VOCs). The aerosols include particulate matter (PM) and other aerosols [45, 53]. Figure 4 shows the global GHGs emissions as CO_2-eq, which interestingly follows the same trend shown in Fig. 3 for energy supply, showing the clear interdependence [54]. It is shown most global GHGs emissions are from heat and power 42%, transportation 25%, and industry 19%. It has been estimated that coal is responsible for 72.5% of the global CO_2-eq emissions, despite it only contributes 31.8% of the global power supply. SO_x are also directly related to coal utilization resulting in about two-thirds of the total SO_2 emissions, being the fossil fuel with the highest sulfur content [55]. NO_x are other pollutants that are due to the oxidation of atmospheric nitrogen during combustion or in the atmosphere [56]. The significant detrimental EIs from SO_x and NO_x emissions being gaseous acidic oxides are acidification, leading to acid rains. These acid rains, in return, result in 1) deterioration of crops and forests, 2) corrosion of exposed surfaces and structures, and 3) elevated acidity in water bodies such as oceans, seas, rivers, lakes, and groundwater, which in turn affect aquatic life [57]. Table 1 below shows the approximate gaseous emissions per unit power generated in MWh for different fossil fuels [58]. It is clearly shown that natural gas has the lowest emissions; thus it is widely used for power generation expanded from 14% and 1.75 PWh in 1990 to 22.5 % and 5.9 PWh in 2017 [44].

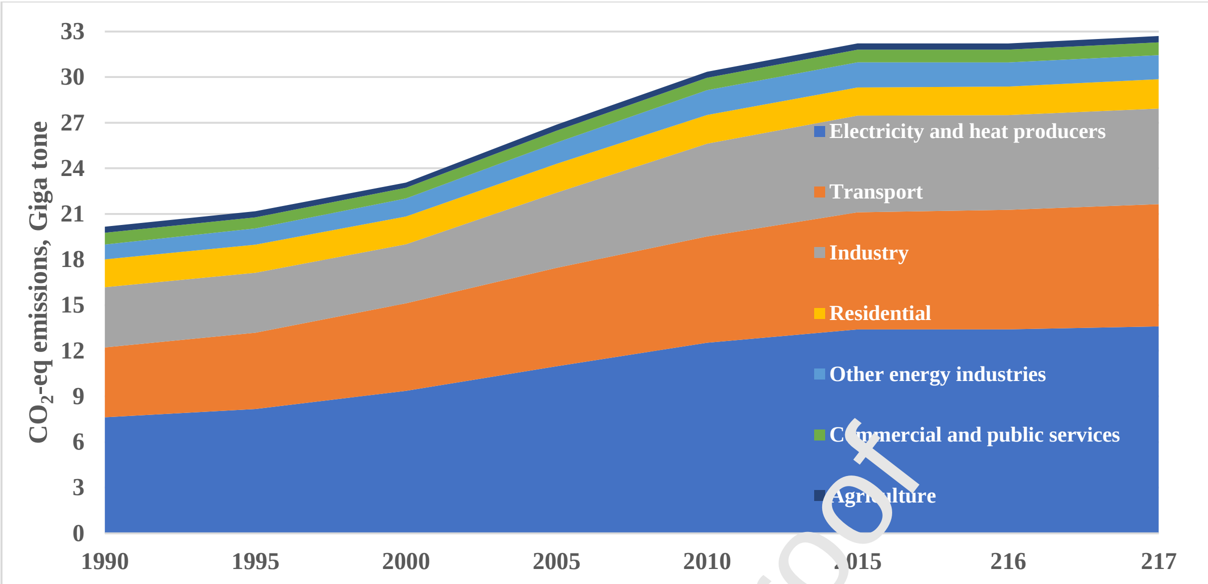


Figure 5: Global GHGs emissions as CO_2-eq emissions per sector [Source: International Energy Agency IEA, 2020] [44].

Table 1 Approximate greenhouse gases for different fossil fuels [58].

Fuel	***Co_2-Eq, Kg/MWh***	***NO_x, Kg/MWh***	***SO_x, Kg/MWh***
Natural Gas	380 - 1,000	0.2-3.8	0.01-0.32
Oil	530 - 900	0.5-1.5	0.85-8
Coal	660 - 1,050	0.3-3.9	0.03-6.7

2.2. Water resources

The power plant requires a huge amount of water during normal operation, mainly for cooling and steam production purposes, which has to be well treated for these specific purposes by adding a wide range of chemicals and undergoing different water treatment processes. This treatment results in changing the whole nature of water, with added chemicals toxic and harmful to water bodies and aquatic life [59]. In the United States US, It was found that almost 200 billion cubic meters, or 40% of the total water withdrawn, was for power generation [60]. Table

2 below shows the approximate water requirement per unit power generated for different fossil fuel types.

Table 2: Cumulative water consumption for power generation using life cycle assessment LCA for different energy resources [61].

Energy Resources	***Water Consumption, m^3/MWh-Operation***
Coal	0-4.5
Coal - with Carbon Capture	1.9-4.5
Nuclear	0.5-3.2
Natural Gas - Conventional	0.3-2.6
Natural Gas - Combined Cycle	0.1-1.9

A wide range of chemicals are added during typical water treatment for heat and power, including biocides and antiscalants to control biofouling and scaling, corrosion inhibitors, coagulants, flocculants, and many others. The EIs due to the discharge of wastewater from power plants, can be summarized as follows [51, 53, 62, 63]:

- Chemical impacts:
  - Formation of disinfection byproducts (DBPs),
  - Introducing foreign materials to the aquatic environment,
  - Discoloration of water bodies due to the use of coagulants (including iron and aluminum salts), which reduces light penetration strength or depth,
  - Increases the concentration of toxic heavy metals.
- Physical impacts:
  - Increases the water turbidity due to discharge of metal oxides and suspended solids reduces the light penetration strength.
  - Increase the salinity, density, and temperature of water bodies.

- Biological impacts: Changes in mortality, metabolic, and growth rates of aquatic organisms due to the above mentioned chemical and physical changes.

3. Wind Energy Systems

Wind energy is regarded from a techno-economic perspective as the most mature source of clean or renewable energy [64]. Being eco-friendly [65], wind energy systems are improving to be the best regarding compatibility with humans and animals among all renewable systems [66]. According to IRENA's yearly reports, wind energy systems are getting the second-highest attention after solar systems among new renewable energy sources, over the last couple of decades, excluding hydropower as a mature technology. This is because it has much less effect on the environment and climate change, along with various benefits to the environment, economy, and society [67]. Generally, as long as there is the sun causing air movement in our atmosphere, wind energy systems will always be viable, whether in the mainland or oceans, as depicted in Fig. 5. Figure 5 shows the direct utilization of wind energy, along with energy storage, as pumped water in a holistic wind energy-based process for power generation and storage. However, like any other technology, wind energy has its own benefits and impacts in several sectors. Therefore, this section presents the environmental and ecological advantages and disadvantages of the wind power system and measures to minimize the EI.

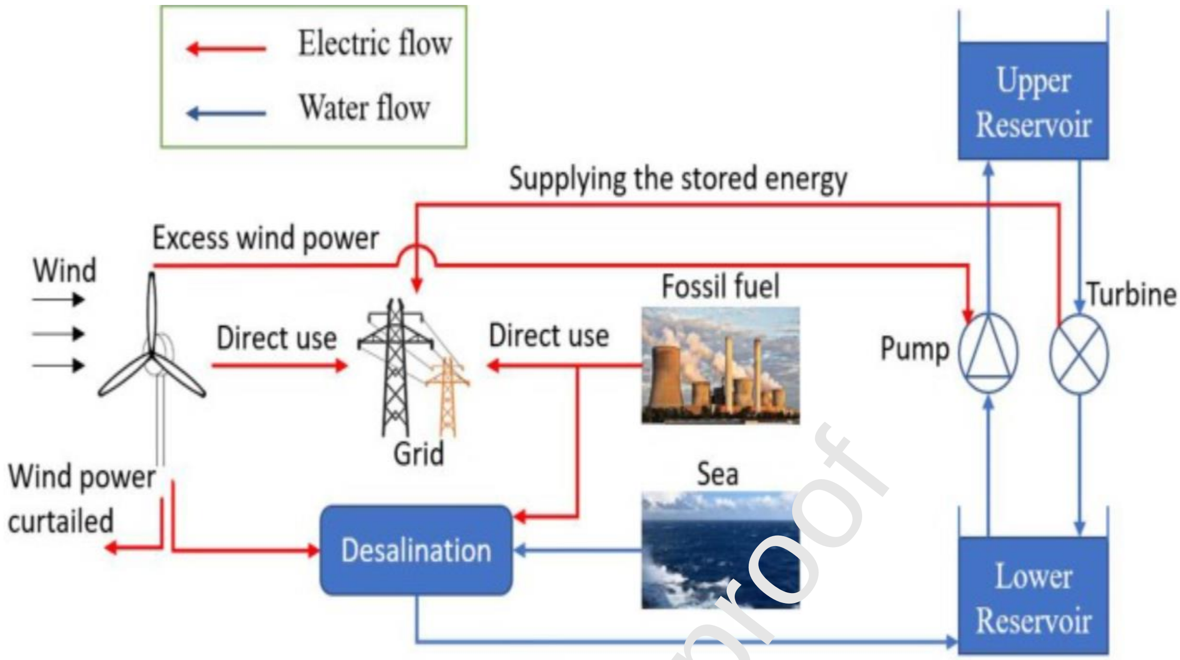


Figure 5: Desalination process using wind energy system coupled with pumped hydro energy storage [68]

3.1. Environmental benefits of wind energy

GHGs emission reduction is the most noticeable feature that gets the most economical and scientific focus among all the possible advantages. Compared to fossil fuel-based power plants, wind energy systems are such a great solution as they do not produce any gaseous emissions such as CO_x, SO_x, NO_x, particulate matter (PM) such as soot, or any other air pollutants during the operation phase [69-71]. Although some of these pollutants might be produced during material fabrication, construction, and maintenance phases, still negligible compared to the significant pollutant emissions from fossil fuel energy systems and can be easily recovered using photosynthesis [72-74]. According to the American Wind Energy Association (AWEA) [75-79], wind turbines avoided 189 million metric tons of CO_2 in the power sector, as depicted in Fig. 6, equivalent to 42 million cars' worth of CO_2 emissions in 2019 alone.

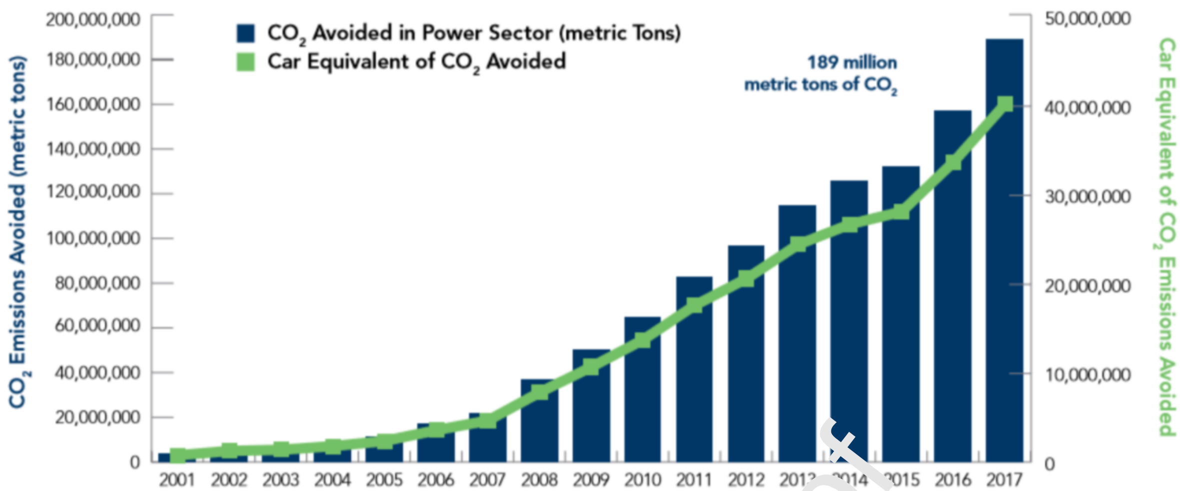


Figure 6: Impact of wind energy on the avoidance of carbon dioxide emissions [75].

It is also noted that a typical wind energy project repays its carbon footprints in less than six months, then provides decades of totally zero-emission energy. While regarding other gaseous emissions like SO_x, NO_x, and PM, which cause smog leading to asthma attacks and other severe health impacts, wind energy systems significantly reduces such pollutants. It was recorded that in 2018 alone, such pollutants reductions had created $9.4 billion in public health savings, leaving a huge positive impact on the environmental and human health sectors. Additionally, wind energy systems do not require a huge amount of process water that is inevitably used to produce electricity in conventional thermal power plants. Therefore, in terms of energy production and water consumption, wind power is an excellent alternative to conventional power plants. Obviously, water is a very vital and limited source, so that any significant reduction of water consumption can allow better water supply for other purposes [80]. AWEA [75, 81] has reported the massive amount of water that can be conserved due to the utilization of wind energy systems, recording that wind energy generation in 2019 alone has reduced water consumption at existing power plants by about 103 billion gallons. Another interesting advantage of wind power plants is that they can provide beneficial lands as reservatories for some species [82].

3.2. Environmental impacts of wind energy

Compared to conventional energy sources, the negative EIs of wind energy systems are relatively negligible [83, 84]. Even compared to other renewable energy systems, it still has less adverse impacts in most, if not all, the impact sectors [85]. Nevertheless, it can affect human life, natural ecosystems, and lifestyles, which must be reviewed carefully [86-88]. In this regard, the main EIs that are intensively introduced and discussed are related to noise pollution [89], visual pollution [90], local climate change [91], and electromagnetic interferences. Other issues are causing ecological concerns regarding bio-system disturbances or wildlife safety for birds [92], bats [93], and marine wildlife [94]. Figure 7 shows the different challenges or impacts associated with harnessing wind energy. The various impacts are 1) noise and visual, 2) bird fatality, 3) soil erosion and deforestation, 4) lightning from towers, 5) electromagnetic radiation, and 6) surrounding neighborhood [64].

3.2.1. Noise and possible mitigations

Noise pollution is the most noticeable negative EI of wind energy systems. Noise is normally identified as any irritating or disturbing sound. In the case of wind turbines, loud, unpleasant sounds can be caused by aerodynamics as the wind with different velocities goes through the wind turbine blades with different sizes [67]. Larger turbines under faster wind speeds will cause louder noises with frequencies of 100 Hz [88]. Generally, aerodynamic noise has various frequencies depending on many factors, and it is considered a broadband noise [95, 96]. Noise from wind turbines can be reduced through proper and more careful designing of the aerofoils and the overall blade shape [97, 98], balancing between the noise radiation and the energy production [99, 100].

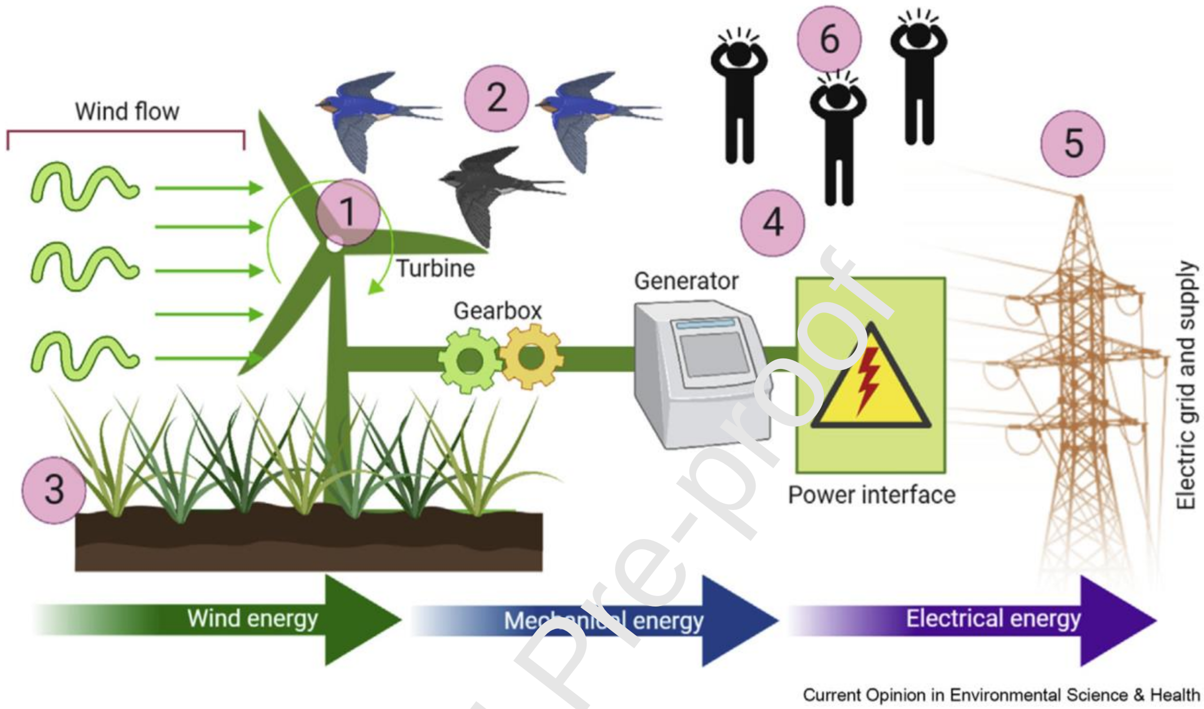


Figure 7: Environmental impacts related to wind energy: 1) noise and visual, 2) bird fatality, 3) soil erosion and deforestation, 4) lightning from towers, 5) electromagnetic radiation, and 6) surrounding neighborhood [64].

Other undesired noises can be due to machinery reasons by the internal parts of the gearbox, the generator, cooling fans, and other auxiliaries like oil coolers, hydraulic power packs for blade pitch [101, 102]. Such noises are typically less than 1 kHz frequency and do not increase with turbine dimensions [102, 103], but they are irritating and noticeable more than the aerodynamic noise [95]. Mechanical noises can be sufficiently reduced using side toothed gear wheels and proper acoustic insulation for the turbine housing interior during the design stage [104, 105]. During the operation phase, it is advised to use acoustic insulation curtains and vibration support structures that properly absorb vibration and do not allow it to reach the turbine's housing [104, 105].

Significant noises come out from the giant turbines with larger dimensions and machinery. Still, such turbines have a height that exceeds 100 m, so it will not have a huge impact on humans or wildlife [64]. Wind farms are further encouraged to be installed 300 m away from homes. The sound disturbance is measured in decibels (dB); wind turbines produce about 105 dB of sound disturbance; hence installing such projects further away from a residential area will significantly reduce the noise effect associated with such projects [64].

3.2.2. Visual impact and Possible Mitigations

Wind energy equipment has a visual impact that varies between color and contrast [106], distance from residential areas [107], and shadow flickering [64, 67, 85]. Regarding the color and contrast, it has been reported that the effect of contrast increases depending on the surrounding environments [108]. Designers try to mix the pixels of the turbine with the background or the surrounding pixels at the edges of the turbine, which enlarges this effect on a long-distance and when there is a larger proportion of pixels on the sides; thus, distance from residential areas can also affect the visual impact although it is more important for the noise impact. The most important and most discussed visual impact of wind energy systems or turbines is the shadow flickering and the so-called disco effect. There are two sides to this impact though all can happen simultaneously, and both are controlled by the distance away from the turbine, operation intervals or working hours, and interaction with sunlight, which also depends on light intensity [109]. The first side is when the light reflects over the turbine blades causing the disco effect or periodic flashes of light; while this effect can depend on the intensity of the produced light, but it can be reduced through smoothening the surface of the blades and using nonreflective coating [110]. The other side is when the shadow of the moving blades casts on the ground and residential areas. This might be minor and subjective and can be resolved by picking sites that are far away from residential areas [111].

The general visual impact of a wind turbine is to make people regard it as a negative machine that destroys beautiful nature, viewing their residences into industrial areas [112]. Especially when wind energy projects are gaining more attention, investments, and improvements for increasing their heights and technical capabilities [113]. Not-In-My-Back-Yard (NIMBY) concept comes from people who are supporting the wind energy systems on a conceptual level since it can replace the conventional power plants for a better atmosphere. Still, at the same time, they are used to live in beautiful landscapes and stunning nature, forcing them to refuse the construction of utility-scale wind projects in such sites but might accept smaller projects [112, 114-117]. Thus sites should always be picked wisely. Regarding sites, offshore wind turbines are constructed on different bodies of water [118, 119]. The construction of such offshore wind farms, if not planned and executed properly, carefully, and quickly might result in dolphin and seals fatalities during the construction phase [120, 121]. Similarly, marine wildlife that lives near the water surface under a wind farm might also be affected by the shadow flickering and less sunlight than needed. Although such impact is minor, it is still under investigation for selecting optimized offshore wind farms.

3.2.3. Birds fatalities

Birds colliding with turbine blades seem to be direct and unavoidable damage associated with wind power. Conversely, other indirect and avoidable impacts such as habitat destruction and displacements can be mitigated by carefully choosing the plant installation site to consider wildlife safety along with other technical site selection criteria. Despite the possibility of bird fatality associated with wind power projects, statistically, it has been deduced that wind farm-related bird death is significantly lower than other factors such as building collision, human activities, and utility projects captured in Fig. 8 below.

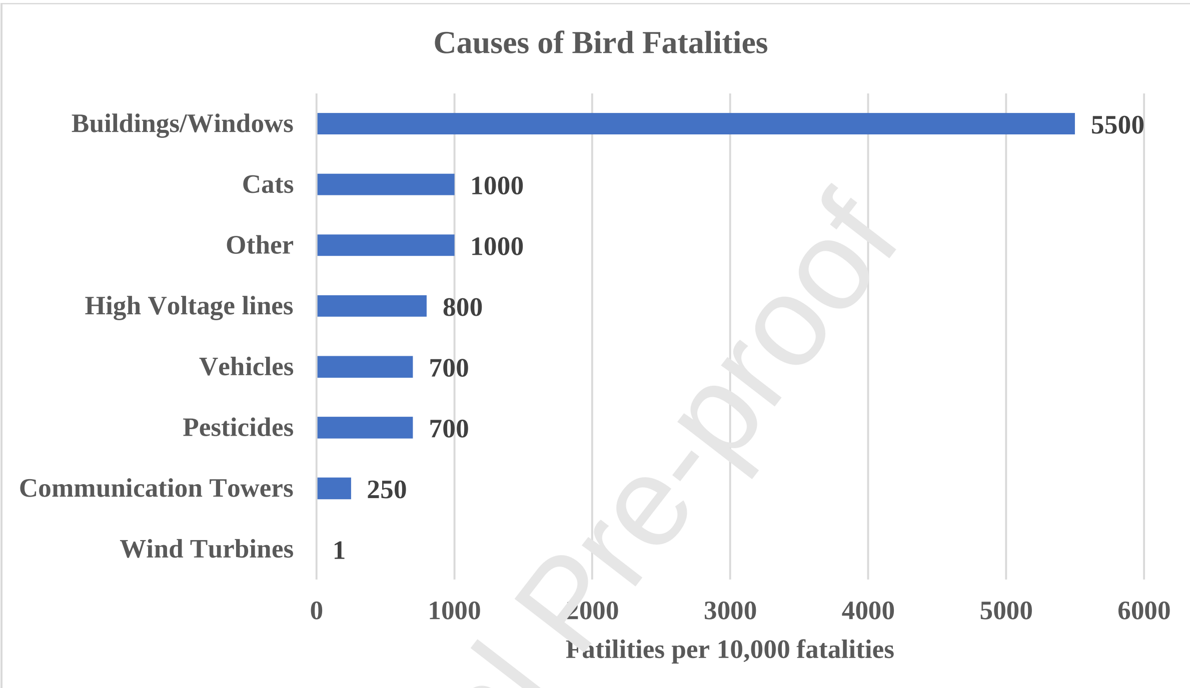


Figure 8: Comparison of bird's mortality of different causes [92].

3.2.4. Electromagnetic interference impacts and possible mitigations

The impact of wind turbines on health in general associated with electromagnetic interferences has not been clearly reported. However, it has been proven that there are some electromagnetic radiations generated from wind turbines, which deforms or changes some radio or television transmissions coming from nearby stations [122]. Randhawa et al. [123] found that wind turbines were degrading radio performance in the Fresnel zone through different mechanisms, including reflection, diffraction, and scattering effects. It was also reported by Sengupta [124] that wind turbines can affect nearby navigation, microwave communication, television, and FM radio systems through modulating radio wave radiations. Such impact gives another importance to site allocation because it is better to avoid sites that might have high electromagnetic interferences with wind turbines such as broadcast stations [122, 125]. Additionally, synthetic materials can be used for blades construction, or even using the wind turbine for communication services improvement by installing antennas on them [122, 125].

3.2.5. Impacts on nature and possible mitigations

Like the butterfly effect concept, small effects of wind farms or their construction might lead to some unforeseen and undesirable results reported to be minor, local, and short-term problems even if their adverse effects last longer than expected. These problems typically happen in wind power systems, especially the conventional ones with higher dramatic results. But we have to ensure that we should prevent even the smallest negative impact on nature when introducing new technologies and avoid past mistakes. Wind impacts nature and the local climate first by removing plants and vegetations of the land during the construction phase. Such activity, along with the foundation's excavations, usage of large machinery, transportation of huge turbine parts, and connecting transmission/feeder lines to the electricity grid, can all cause additional damages to soil and land [126-128]. These effects are reported to result in small climate changes such as a rise in temperature during day and night [129-132].

Contrarily, some other research groups have reported the positive impacts of wind farms like prevention or decrease of sandstorm hazards, which can be further utilized in some sites [133]. Others claimed that wind farms are not negatively affecting the climate as much as thought [134]. Such positive and negative impacts suggest that further detailed investigations and research efforts are needed to have a full understanding of the impact of wind farms on climate change on both the local and regional levels. Regarding possible mitigations, China, as one of the major global investors and developers in wind energy systems, has specific wind turbine construction guidelines. The guidelines recommend minimizing heavy equipment interference by involving as much work as possible in excavations [63]. It also promotes early replantation of trees and plants as soon as possible after construction work is over [64].

As another concern of wind power, potential impacts on biodiversity and wildlife safety has been addressed significantly by many researchers [135-138], with possible mitigations and ways to eliminate the risk as much as possible [139-145]. While birds are reported to be the largest victims of death by wind turbines worldwide [146], the example previously explained about birds and what can be done to some direct and indirect scenarios, as well as the following discussion, will both apply for bats, marine wildlife, and all sorts of wildlife that can be threatened by wind systems. The concerns of the community about wildlife safety are understandable and essential to consider as the possibility of more danger increases with the global growth of wind energy systems; thus, it is highly advised to wisely pick the land that will result in less wind turbine-caused wildlife fatalities, as proper site selection is proven to reduce wildlife mortality significantly.

On the other hand, unlike many other human activities, the number of birds being killed and other sorts of wildlife being threatened in general by wind turbines is almost negligible when compared to such activities [147]. For instance, a study on a wind farm of 1 GW capacity with a proper wildlife-caring site reported a total number of 20 fauna killed by wind turbines, which is negligible compared to the 1,500 avian deaths caused by hunters or the 2,000 deaths caused by collisions with vehicles and electrical causes [64, 148, 149]. Such comparisons are essential for a better understanding of the real EI of wind energy systems or wind turbines in particular. It was studied that birds can get lost in dark nights and foggy weathers, and then they are attracted by the light coming from the wind farm, causing them to directly collide with turbines' blades [150].

A similar relationship can be seen between foraging bats and electromagnetic radiation effects caused by wind turbines [151].

4. Hydro energy systems

Hydroelectric energy or hydropower [152-154], tidal energy [155-157], wave energy [158-160], and ocean thermal energy conversion (OTEC) [161-163] are all considered as water-based energy systems. Hydropower is regarded as the major type in terms of installed capacity and power generation. It is the only mature renewable energy system for almost a century before any other sustainable and renewable energy comes into spot. Thus, many research groups have performed detailed location-specific researches and discussions of the technological state, life cycle assessments, EIs, and possible solutions [164-174], while other groups have globalized their research and covered the EIs of most if not all the water-based energy technologies [82, 175-178].

In general, water-based energy technologies, specifically hydropower, are considered the most effective renewable energy sources [82, 179], as it has the highest efficiency of about 90% among all other technologies [180]. Hydropower provides the largest power generation globally compared to other renewable technologies due to its massive installation over almost a century [181]. According to different global agencies, including the IRENA 2020's renewable capacity statistics report [26], and the International Hydropower Association (IHA) 2020's hydropower status report [182], hydropower alone provides 17% of the total global electricity supply [183]. On the bright side, such technology has a high maturity level; hence, hydropower is incredibly advanced in all aspects, including environmental impacts. On the other hand, hydropower plants have a major sociopolitical problem that forces people to shift away from the construction areas of such plants. They of course provide a huge and significant amount of jobs for local communities which will eventually and importantly support the economic development of these communities [184]. Water-based energy systems still have some ecological impacts to be discussed and mitigated. However, it has been agreed that most, if not all of the ocean/marine/water energy systems have relatively similar environmental impacts.

Like any other renewable energy system, water-based energy systems have some social impacts like public perception and view. Decision-making is affected by public engagements with community ownerships and external costs, especially with the relatively low energy density taken into account, which causes renewable energy systems to be highly visible and spread over many sites compared to conventional energy systems [178, 185]. On the other hand, water-based energy systems have a relatively different class of EIs due to the fact that most renewable energy systems are not employed in oceans and water surfaces as many as their land installations. Their EI can be summarized as follows in a generalized discussion.

Flow changing is simply to alter or block nearshore and ambient flow patterns in different ways, which might affect the marine ecosystem and wave climates as well as the functionality and maintenance of some tidal and wave systems [171, 177, 186-189]. This will also result in minor but still existing transportation of nutrients and sediments due to erosion effects caused by the turbines and their changes over the flow, which will eventually cause direct and indirect biodiversity issues and wildlife safety concerns [178, 189-196]. Such transportation, accompanied by hard materials near a soft sediment system, will create artificial reefs that will alter the natural sediment transportation patterns and the hydrodynamic processes and possibly enhance biodiversity by providing rich food sources. However, it might still have downsides through attracting predators and other species that are originally non-native, forcing another change that might damage the local environment [188, 196-200].

Like the artificial reefs with its advantages and disadvantages, biofouling can come with biodiversity enhancement and cause pollution risks by eutrophicating the benthic systems by increasing the sedimentation rates [189, 196, 201]. Other than its effects on biosystem, biofouling can also affect the efficiency of the water-based energy systems as it will increase the mass and the surface roughness of the devices used in the submerged system, which will eventually make it even harder for maintenance and increase its cost [193, 194, 196, 201]. But it has been reported that this issue will be less damaging on heavily damped systems [202]. There are some concerns regarding electromagnetic radiations from power cables and other emitting devices, which are still pretty minor and relatively low, but it still requires more research [203-205]. Additionally, just like any mechanical based system, water-based energy systems are like wind energy systems; they can cause possible aquatic life threats through collisions and underwater noises. Table 3 below summarizes the different benefits and impacts associated with hydropower.

Table 3: Potential environmental benefits and impacts of hydropower [206-208].

Benefits	Impacts
✓ No/little GHGs emissions during operation, ✓ Less liquid and solid wastes, ✓ Minimal resources requirements (only for construction phase), ✓ Secure water storage and supply for different purposes, ✓ Flood control, ✓ Enhance downstream marine navigation. ✓ Improved tailwater fisheries	❖ change and divert river flow pathways and pattern, ❖ relocation of people and terrestrial wildlife, ❖ Retention of sediment and soil nutrients behind the dams in the reservoir, ❖ Development of aquatic weeds downstream. ❖ Interrupt downstream/upstream passage of aquatic organisms, ❖ Changes in water quality downstream.

For possible mitigations, most EIs of water-based energy systems are not as straightforward as they seem to be since most of them are not as common and mature as hydropower systems; thus, further studies should be performed. Simple common environmental problems shall require known mitigations; for example, mitigations of noise impacts can be through acoustic restraints and sound-reducing materials and techniques [209, 210]. Also, the same concept applies to electromagnetic radiations, pollutions, and contaminations, as proper shielding shall be used along with the use of materials that are not toxic and make sure that hydraulic fluids are properly sealed inside [201]. Finally, proper site allocation shall be the optimal and the most accurate or studied decision criteria for the mitigation of EIs for the sake of biodiversity and wildlife safety [195].

5. Biomass energy systems

Being part of different life cycles and ecosystems, biomass is the primary source of energy or food for all multi-cellular organisms [211, 212]. When thought of biomass-based power producing systems, people either do not know how it works or immediately connect it to conventional energy systems and will have a negative impression. While combustion is not the most optimal way of producing energy from an ecological perspective due to carbon dioxide being released. Biomass-based power plants, as depicted in Fig. 9, are way more useful and renewable when used for electricity generation rather than dumping them or burning them for no use, especially when they are a better replacement for fossil fuels. Biomass can become a better large-scale carbon-neutral energy source if, and only if, utilizing processes were to be improved to be cleaner and economically efficient [213-215]. Such a goal will need more research and development efforts on biomass-based energy systems to enhance the fuel and the process [216-

219]. This will result in several huge benefits that will support several sectors; for example, industrialized economies will receive further developments, oil consumption will significantly decrease, and it will, of course, solve many environmental problems, including greenhouse gas emissions [82].

While previous research groups have performed intensive work to develop biomass-based energy systems over the last decade [220-227], massive work is still needed; thus, EIs should be discussed as necessary as technical designs and specifications matter. Although few research groups have discussed the EIs of biomass systems, it is obvious that the more mature and common the system is, the more attention regarding research and development and further limitations to be exposed, such as environmental impacts. Among several types of biomass large scale systems, the systems depending on aquatic weed farms [228], kelp farms [229], and other less harmful and less common biomass-based systems. It was reported by Abbasi et al. [211] that the land-based biomass systems and mostly the hydrocarbon-rich systems [230, 231] require serious investigations and considerations regarding the EIs. Furthermore, Demirbas et al. [232] have discussed in details several EIs of biofuels, focusing on material-wise and the toxicity or harm of certain materials that have been used for decades, and discussing several analyses that compared different combinations of materials to improve the environmental state of the fuel as well as the economic and political states.

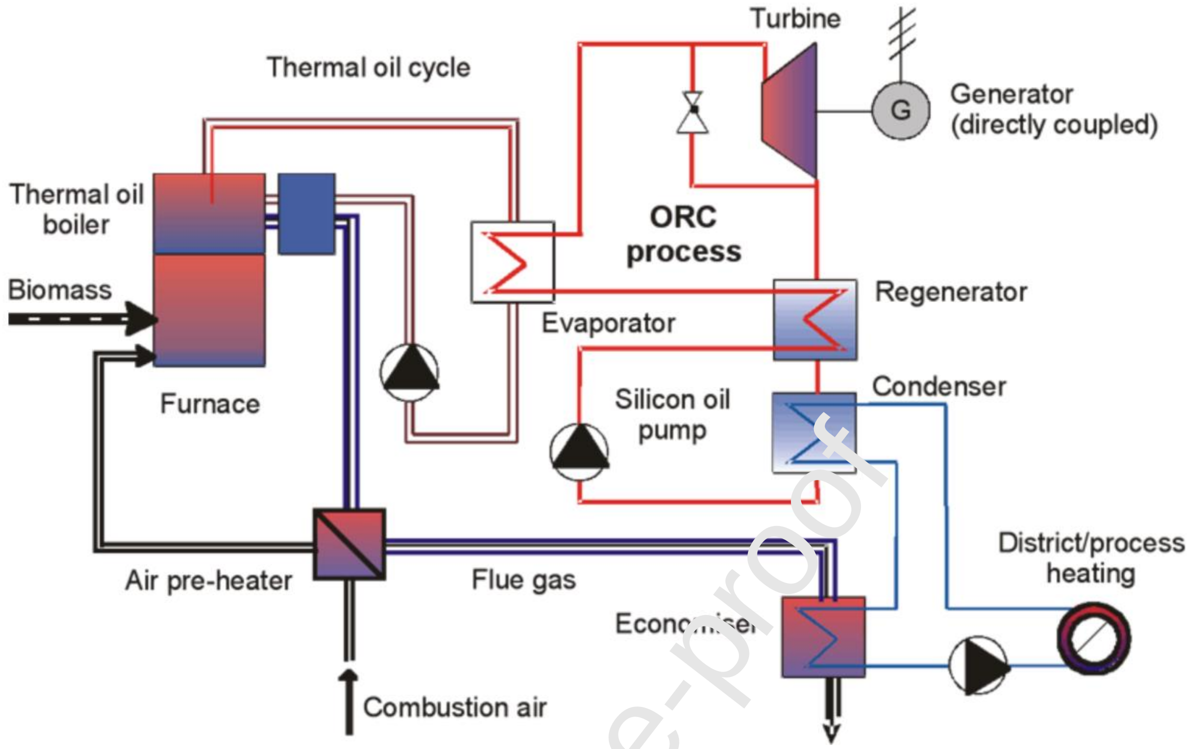


Figure 9: Biomass combined heat and power plant [233].

Generally, the main EIs are related to the large use of water and land resources. It has been reported that biomass energy production programs require way more water than the regular domestic and industrial needs while also requiring larger lands to produce relevant energy [234-238]. Problems of exacerbating soil erosion issues have also been discussed, concluding that certain erosion minimization techniques and technologies should be implemented, but costly and difficult to implement to the point that some countries cannot afford to implement them [239-242]. The whole process of converting a natural ecosystem to the so-called energy-crop plantations will always threaten the wildlife and several biota's safety through the direct destruction of habitats and nutrients or food resources [230, 242-245].

The environmental impacts associated with bioenergy are summarized as follow [241, 246-250]:

- Exhaustive utilization of land and water resources,
- High soil erosion rate due to the displacement of natural forest with croplands,
- High water run-off due to soil erosion, higher water run-off takes place, which renders the recharge of groundwaters.
- Removal of loss of soil nutrients as most energy crops require high nutrient level; hence synthetic fertilizers needs to be added.
- Loss of natural wildlife, habitat, and biota due to the expansion in energy crops planting, which displaces other crops, forests, and natural land, thus reduces the biodiversity.

6. Geothermal Energy systems

With a discouraging efficiency or general performance when compared to other renewable energy sources, geothermal is not the preferred system to go for yet. However, there is a considerable gap when considering the EIs of geothermal energy systems, which indicates substantial encouraging advancements in the technical research and development for this technology that induced environmental investigations. Several research groups have worked on developing the technical state and sustainability of the geothermal energy systems, whether in hybrid configurations or as a standalone [251-259]. Geothermal energy systems are still way more environmentally friendly and clean than conventional energy systems, but no technology is free of adverse EIs, and several research groups have discussed [260-266].

Figure 10 below summarizes the different EIs associated with geothermal energy systems, which include the geological hazardous, land use, impacts on biodiversity, release of contaminated wastewater to the environment, gaseous emissions, solid waste, waste heat, noise, sociological impacts. The main EIs of that limits the development and use of the geothermal technologies are related to several points, including removals of steam and mass fluids resulting in land subsidence [267-269], even operational drilling might result in disturbing the land, creating high noise pollutions, threatening and disturbing wildlife, and gaseous emissions like carbon dioxide, hydrogen sulfide, and solid waste, which will all eventually affect workers' health thus social impacts [266]. Air and water pollutions are huge concerns when it comes to geothermal energy systems as possible ecosystems' degradation causing extra destruction and altering the wildlife and vegetations' habitats [262, 263, 266, 269, 270].

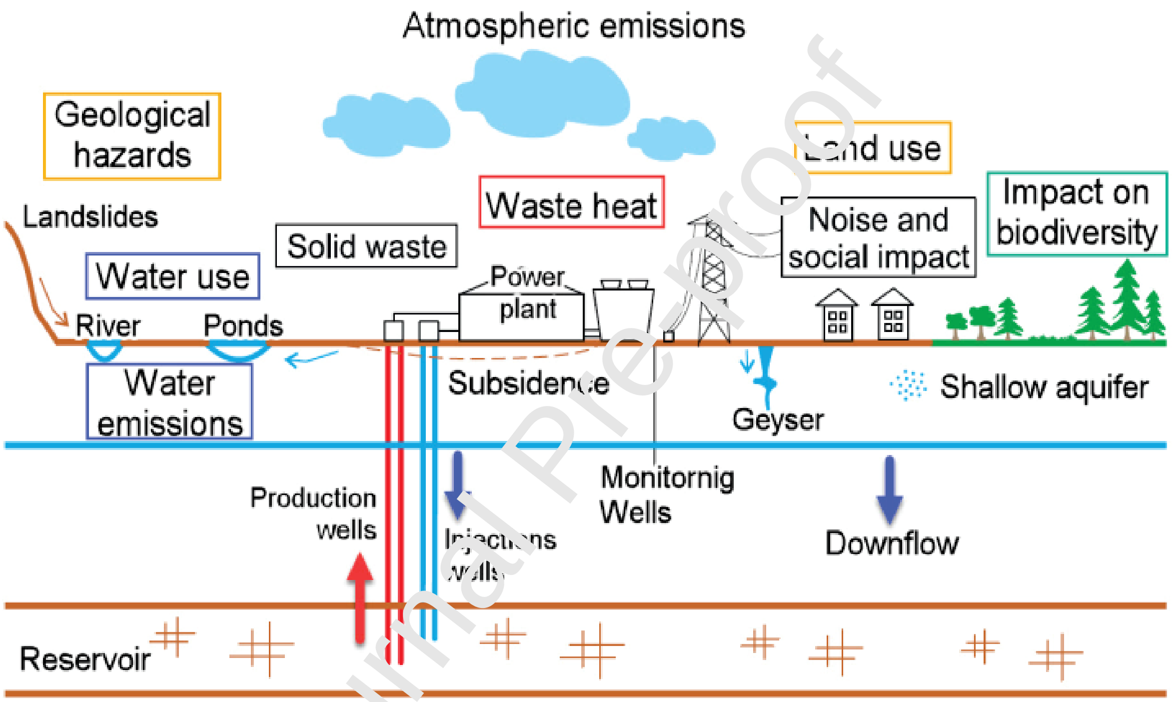


Figure 10: Environmental impacts associated with geothermal energy [266].

Properly enhanced regular mitigations shall be employed for each and every different scenario as extraction depth and site properties will change over plant time. For example, proper waste management must always be employed, but for a forested area must be dealt with extra caution and care as for healthy forests, the healthier they are, the more rain will infiltrate to the reservoirs of the geothermal plant, which is a win-win scenario [263, 271]. Additionally, a good-placed injection well will maintain the reservoir pressure, which will eventually help in reducing potential subsidence [272, 273]. Generally, proper site allocation with appropriate implementation of constructions and operational guidelines customized plants design for each site and its surroundings will eventually end up with a win-win situation, hence, conserving the environment without adding additional impacts whilst improving the efficiency and the performance of the plant. Another common under development way that appears to be the most efficient in improving the performance of the geothermal plant is by combining it with other renewable energy systems. Such hybridization is reported to reduce land-use footprint at added energy generation that can be used in several sectors and for several purposes [274, 275]. For example, combing solar thermal energy systems will supply heat to enhance the reservoirs, while wind or solar photovoltaic energy systems can provide electrical power for pumping fluids [269, 273-276].

The different EIs of geothermal energy are summarized as follow [241, 249, 252, 262, 266, 277, 278]:

- Land subsidence: As a result of the hot water/steam flowing from the underground geothermal field, and due to the different soil responses to the injected fluid, the ground can subject to cracking.
- Induced landslides and seismic activities: The fluid circulation in the geothermal field and variation in the fluid pressure in a stressed ground formation can lead to rock fracture.
- Surface disturbance: Due to the construction and operation of the extraction facility, which depends on the plant and field capacity or size.
- High water demand: Water is the most available and widely used fluid to extract geothermal energy, with a substantial amount lost or wasted in the underground field due to leakage.
- Offensive odor: The fluid abstracted from the geothermal fields usually has some gases (such as hydrogen sulfide) and volatile material.
- Solid waste: The fluid from the geothermal fields is usually saturated with soil/formation constituents, including carbonate/sulfate salts, silica, and silicate salts, which precipitate

upon temperature drop and accumulate as solid waste that requires proper waste management.

- Wastewater: The wastewater from using waster as heat transfer fluid is usually loaded by foreign materials added during operation and salts from soil/formation, which can be hazardous to the environment upon discharge to water bodies.
- Thermal pollution: which is associated with waste heat released to the environment with wastewater or into the air.
- Alteration and contamination of soil nature: Soil washout with water extracted from the geothermal field will change the soil nature; in addition, the foreign material being injected in water will contaminate the soil.
- Noise: Due to machinery and equipment used during the construction and operation of the plant.
- Interruption in natural habitat and biodiversity: Due to the land-use and change in the local site of the geothermal plant.

7. Conclusion

This review has discussed the environmental impacts (EIs)of wind, water-based energy systems (mainly hydropower), bioenergy, and geothermal energy systems. The focus was given to the EIs associated with the operation phase of the energy generation of the renewable energy source. Although many reviews and works consider the life cycle assessment as an effective approach, it considers both manufacturing and operation phases. The main advantage of renewable energy resources over fossil resources is the much less EIs. Specific and detailed discussion and solutions were given for different EIs, and technically and ecologically favorable recommendations for their impacts on natural resources and wildlife. We can see that from a technical and environmental point of view, hydroelectric energy systems were the best option due to their high maturity and well studied environmental impacts. However, it is not the case for other water-based energy systems as they fall behind wind energy systems due to their high cost, complexity, and relatively low performance. Biomass and geothermal energy systems fall behind the previous technologies, respectively, due to their huge impact on the environment and low performance, which did not encourage investments. All of these systems are considered a better option when it comes to conventional energy systems and environmental point of view as they still are way more ecologically friendly.

Finally, further detailed investigations and research are needed to fully understand the impact of wind farms on climate change on both the local and regional levels. Moreover, research efforts are required and advised to be on water-based energy systems other than hydropower systems, with more focus on effects and possible scenarios, and further studies on mitigation of EIs considering marine energy systems, as it has less requirements in terms of lands, with less visual impacts and other ecological and social impacts relative to land-based systems. Furthermore, additional environmental investigations need to be carried out on biomass and geothermal energy systems, which will help expand and further develop these two technologies.

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Author credit

All authors have equal contribution in the current work

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Graphical Abstract

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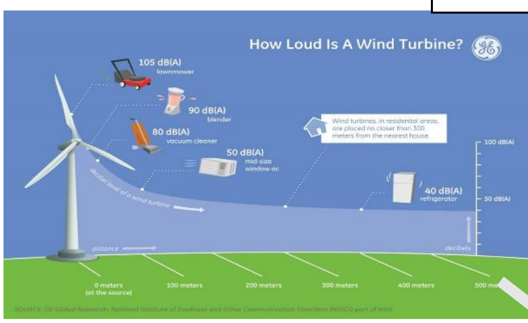
Geothermal energy

Wind energy



Hydro energy

Biomass energy

Highlights

1. Various renewable energy systems are evaluated.
2. Environmental impact of renewable systems is analysed.
3. Prospects of renewable technology is discussed.
4. Limitation of renewable systems are presented.