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Environmental Impacts and Social Cost of Non-Renewable and Renewable Energy Sources: A Comprehensive Review

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ABSTRACT

Rising energy production and consumption, particularly from fossil fuels, pose substantial threats to both global climate and human well-being. Conventional fossil fuel technologies, as primary energy sources in power plants, predominantly generate pollutants during power generation. Conversely, renewable energy technologies are anticipated to contribute to pollution primarily during equipment manufacturing. The combustion of traditional fuels gives rise to significant volumes of greenhouse gases (GHGs) and hazardous substances, leading to escalated costs for individuals and the worldwide populace. External costs attributed to coal-fired power plants range from 4.0 to 9.5 cents per kilowatt-hour, nearly three times higher than those of gas-fired power plants, and multiple times greater than the expenditures linked with renewable energy technologies. The substitution of non-renewable fuels with clean energy sources stands as an efficacious approach to curtailing atmospheric pollution and the concomitant external expenses. On a global scale, an annual savings of up to 230 billion dollars is potentially attainable by achieving a 36% share of clean energy within the global energy mix by 2030. This topic has garnered the attention of policymakers worldwide. Consequently, this study undertakes an examination of the environmental ramifications and social costs associated with diverse energy sources.

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1. INTRODUCTION

Energy serves as an integral cornerstone of socio-economic development, driving progress across centuries. As depicted in Figure 1, traditional fossil fuels, encompassing coal, oil, and gas, emerged as the dominant energy sources for the global economy in 2019. Fossil fuels commanded a share exceeding 84% of the worldwide primary energy consumption, with oil assuming a predominant role in transportation at 33.1%. Coal followed as the second significant contributor, comprising 27%, while gas and low-carbon sources such as renewables and nuclear energy collectively constituted 24.3% and 15.7%, respectively.

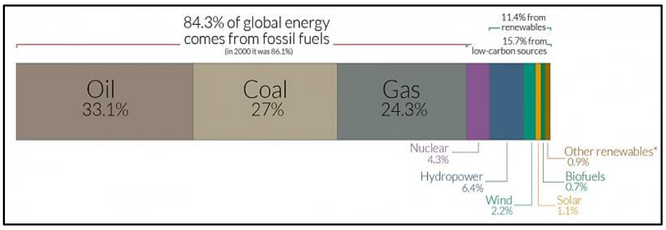

Figure 1. Global primary energy consumption by origin in 2019 (Ritchie, 2020). Source: data provided by BP.

The trajectory of global energy consumption exhibits a persistent upward trend, with aggregate production escalating from 116,214 terawatt-hours (TWh) in 2000 to 136,761 TWh in 2019. Concurrently, the progression of alternative and low-carbon energy sources is poised to reduce the dependency on fossil fuels as primary energy sources (Ritchie, 2020; Shahsavari & Akbari, 2018).

Anticipated global primary demand is set to surge by 1.5 to 3 times by 2050 in response to heightened requirements across diverse sectors, notably the energy domain (Shahsavari & Akbari, 2018). Concomitant with population expansion, the ongoing enhancement of global living standards is poised to fuel this elevation in primary energy requisites. As energy production and consumption escalate, the deleterious environmental consequences of human activities intensify. On average, a 1% increase in human population growth necessitates a corresponding 0.519% elevation in energy production, which, in turn, culminates in amplified carbon dioxide (CO2) emissions (Saidi & Hammami, 2015). CO_2, constituting the foremost greenhouse gas (GHG) emitted during the combustion of carbon-based fuels, contributes to around two-thirds of global anthropogenic greenhouse gas emissions. Approximately 25% of global CO_2 emissions can be attributed to agricultural practices and land-use alterations, encompassing activities such as deforestation, desertification, and land clearing for cultivation (BP, 2015). Over the last century, human activities have emerged as more potent agents

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of destruction than natural phenomena, marking the Anthropocene era. Human factors play a pivotal role in the onset and expansion of desertification, including both direct desertification and conditions conducive to its proliferation. Often, reckless land utilization leads to phenomena such as land conversion, soil erosion, deforestation, and contamination of water and soil resources (Akbari et al., 2019; Akbari et al., 2023; Kashtabeh et al., 2023).

The past two centuries have witnessed a significant surge in atmospheric CO_2 concentrations due to industrial undertakings and alterations in land use. By the close of 2017, atmospheric CO_2 levels reached 32.5 gigatons (GT), marking a 460-million ton (Mt) escalation compared to pre-industrial levels. Correspondingly, global energy-related CO_2 emissions witnessed a 1.4% upswing in the same year. The major contributors to CO2 emissions within the energy sector stem from heat and energy generation. Moreover, fossil fuels stand as principal sources of methane (CH_4) emissions, responsible for over 60% of global anthropogenic methane production. In the energy sector, methane predominantly emanates from natural gas leaks, active and inactive coal mines, and coke production. In 2016, methane emissions accounted for 9.2 Gt CO_2 equivalent, a matter of concern considering methane's substantial contribution to non-CO_2 GHG emissions (IEA, 2017). Despite its shorter atmospheric lifespan compared to carbon dioxide, methane exhibits a heightened capacity to trap solar radiation.

GHG emissions, particularly CO_2 from fossil fuel power plants, have instigated profound environmental predicaments such as global warming and climate change. Climate change stands as the driving force behind surges in extreme weather events, shifts in disease patterns, and agricultural damages. It is estimated that climate change annually accounts for over 150,000 fatalities worldwide (WHOb, 2018). Conventional energy sources also release additional pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), tropospheric ozone (O_3), particulate matter (PM), carbon monoxide (CO), and heavy metals (HMs). Studies reveal that air pollution contributes to 2.7-3 million premature deaths annually, encompassing 5-6% of total global mortality (Qurashi & Hussain, 2015).

Coal emerges as the most abundant and carbon-intensive fossil fuel. Notably, coal serves as the chief source of pollution and GHG emissions in countries like China, India, and South Africa (Wang et al., 2018). Pollutants and GHGs are released into the environment during the complete lifecycle of coal, encompassing mining, processing, consumption, and disposal. Of particular concern is coal's potential to harbor heavy metals, which pose serious threats to human health and the environment (Shahsavari & Akbari, 2018). The use of polluting fuels like coal or biomass for heating or cooking in open fires or traditional stoves results in hazardous levels of indoor air pollution, stemming from the release or production of substances such as CO, particulate matter (PM), and toxic organic compounds (Wang et al., 2018; WHO, 2006). Significant GHG emissions and air pollution, involving compounds like CO_2, SO_2, NO_x, PMs, and non-methane volatile organic compounds (NMVOCs), emanate from power plants fueled by fossil fuels. This has led to climate change and poses health risks. Notably, nearly 2.7 million preterm births are linked to $PM_{2.5}$ pollutions annually, accounting for 18% of all premature births. Such pollution primarily stems from the combustion of fossil fuels and biomass, disproportionately affecting developing nations (Perera, 2018).

The detrimental health outcomes tied to conventional fuel consumption have imposed substantial burdens on governments, yet these costs are typically absent from market prices (Owen & Hanley, 2004; Streimikiene & Alisauskaite-Seskiene, 2013). By the late 20th century, the global economic toll of major climate change consequences was estimated to range between 4 and 20% of the global gross domestic product (GDP) (Liano-Paz et al., 2015). Conventional energy sources, primarily fossil fuels, impose the highest external costs on electricity generation compared to other alternatives (EEA, 2007; NEA, 2003).

Furthermore, non-renewable energy sources like oil and gas are confronting dwindling reserves, necessitating their eventual replacement with alternative energy sources (Shahsavari & Akbari, 2018). Unlike fossil fuels, renewable sources possess the potential for sustained viability over extended periods, releasing substantially fewer pollutants due to their non-reliance on combustion for energy generation. In 2012, the integration of renewable energies led to reductions of global CO_2, NO_x, and SO_2 emissions by 38%, 13%, and 70%, respectively (NRC, 2010; Novacheck & Johnson, 2015). The adoption of renewable energy sources (RESs) is on an upward trajectory, with renewable energy technologies (RETs) evolving and GHG emissions being managed. Projections suggest that by 2100, RESs could cater to 30-80% of the global energy demand (Panwar et al., 2011). In comparison to fossil fuels, air pollution stemming from renewables inflicts 3-10 times less harm (Science Daily, 2015).

However, the adoption of RETs entails specific environmental and social challenges that warrant attention. Many RETs necessitate substantial land areas for facility construction. Among renewables, biomass yields the highest GHG emissions and atmospheric pollution. Direct biomass combustion for electricity generation results in greater air pollutant emissions compared to most other renewable sources (Treyer et al., 2014). To date, over 3 billion people rely on conventional fuels like biomass, kerosene, and coal to meet their energy needs (WHO, 2006). While RESs like hydroelectricity, wind, and solar power do not release GHGs during operation, minor GHG emissions occur during their construction. Additionally, renewable energy projects can impact wildlife and natural landscapes negatively. For instance, bird-turbine collisions leading to bird mortality can be a concern in certain scenarios. Furthermore, mining for materials used in RET manufacturing can generate adverse impacts (Vallero, 2014; Burke & Stephens, 2018). Nevertheless, the environmental footprint of RETs remains smaller compared to conventional sources. Consequently, the adoption of renewable energies signifies a stride towards environmental protection and sustainable development. The integration of policies and agreements that account for the external costs of electricity generation could exert a positive influence on the prevalence of clean energy within the global energy mix (Hekmatnia et al., 2020).

The energy sector should adhere to the 3A strategies, encompassing Accessibility, Acceptability, and Availability. Accessibility denotes the equitable provision of cost-effective clean energy to all segments of society, Availability signifies source reliability and security, and Acceptability encapsulates positive public reception aligned with prevailing social and cultural contexts (Qurashi & Hussain, 2015). Addressing environmental challenges necessitates a low-carbon transition within the global energy system, involving the replacement of carbon-intensive sources with progressively low-carbon alternatives.

Given the dire consequences of unchecked climate change and burgeoning populations, it is imperative that governments and policymakers channel their resources into mitigating the adverse impacts of global shifts, including environmental degradation, air, water, and soil pollution, as well as desertification. International initiatives such as the Sharm el-Sheikh Climate Change Conference (COP 27) and the Paris Agreement (COP21), along with national frameworks like Iran's 6th Development Plan, advocate for an increased share of renewable energies. This is aimed at curbing greenhouse gas emissions, adapting to climate change effects, and alleviating resulting damages and losses. By offering a comprehensive review of the environmental and social costs linked with fossil fuels and renewable energies, this study presents an unparalleled panoramic perspective. This compilation serves as a one-stop reference for policymakers, facilitating well-informed decision-making processes.

2. Methodology

This work constitutes a literature review conducted in two comprehensive phases. Initially, we delve into the ramifications of diverse electricity sources on the environment and human well-being. Subsequently, we present a comparative analysis of the externalities associated with electricity generation. The authors embarked on this endeavor by commencing with a conceptual exploration of the term "energy sources," drawing insights from both non-academic and academic literature that explicitly employ the term. This inclusive approach encompassed a range of peer-reviewed studies, constituting a burgeoning repository of scholarly contributions. To achieve this, extensive online searches were executed utilizing diverse publicly accessible search engines. These searches entailed keywords such as "renewable energies," "non-renewable energy sources," and "environmental impacts of energy technologies," yielding an assortment of reports, articles, websites, and books.

To broaden the search horizon, the terminology was expanded to include phrases like "social costs of renewable energies" and "non-renewable energies." Information procurement was executed through platforms such as Web of Science, Scopus, academic libraries, and widely-used search engines. This meticulous process facilitated the curation of peer-reviewed English-language academic literature pertaining to these subjects.

The goal of the research is to identify the environmental impacts of electricity generation using a variety of sources (i.e., fossil fuels, renewables, and nuclear power) during their life cycles. The scope of the research is the environmental impact of various energy technologies during their entire lifecycle from material extraction to processing, transportation, construction, utilization and decommissioning (Figure 2).

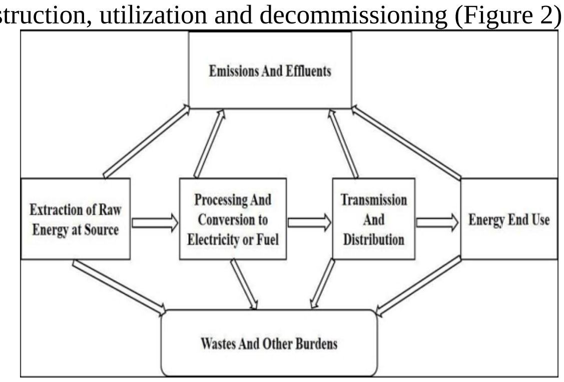

Figure 2. Schematic diagram of the life cycle of different energy systems

3. Results and discussion

Carbon dioxide emissions due to electricity generation were evaluated on a per kWh basis (Table 1). The environmental and social costs of air pollution and climate-relevant emissions were calculated based on the literature review (Table 2). Generally, the social cost of energy technologies covers their impacts on human and environmental health including their effects on morbidity and premature mortality, crops, biodiversity, buildings, and materials. The damage incurred by pollutants, particularly CO2, was derived for each technology based on the summarized research.

Table 1. CO_2 emissions (g/kWh) for various forms of electricity generation.

Energy source	gCO_2/kWh range	Reference
Coal	932-1132	(EIAa, 2018)
Oil	700-800	(Shahsavari & Akbari, 2018)
Gas	449-662	(EIAa, 2018)
Nuclear	2-15	(Vallero, 2014)
Photovoltaic	50-73	(McFarlan, 2018)
Wind	< 29.5	(Hekmatnia et al., 2020)
Hydroelectricity	< 7	(EIAa, 2018)
Biomass	10-1021	(Rosillo-Calle et al., 2015)

3. 1. Environmental impacts of energy production systems

3.1. 1. Coal

Coal represents an affordable energy source and is expected to retain its significance in the foreseeable future due to its wide availability. For instance, coal remains the most cost-effective energy source in the US, contributing to 30% of the country's energy supply through coal-fired power plants (EIAa, 2018). Nevertheless, coal is widely acknowledged as a highly polluting energy source, causing a plethora of environmental challenges throughout its lifecycle, including mining, processing, usage, and disposal. These challenges encompass land disruption, mine subsidence, and contamination of air, soil, and water resources.

Coal is notably associated with greenhouse gases (GHGs) like methane and carbon dioxide. In terms of the balance between energy production and CO_2 emissions, coal stands as the least efficient among fossil fuels. Table 1 illustrates the CO_2 emissions for various electricity sources. Coal-fired power plants exhibit the highest median CO_2 emissions (1025 gCO_2/kWh), encompassing an interquartile range of 932-1142 gCO_2/kWh (IAEA, 2016). In the US, an average coal-fired power plant releases 1000 tons of carbon dioxide, 8 tons of sulfur dioxide, 3 tons of nitrogen oxides, and 0.4 tons of particulate matter into the atmosphere per GWh of electricity generated (Fthenakis & Kim, 2011). The significant emission of GHGs is a primary drawback of coal utilization for power generation. Owing to its elevated carbon content, coal-fired power plants emit higher CO2 per unit of energy compared to other fossil fuels like crude oil (Demirel, 2016). Annually, burning coal contributes to the release of 9,000 million tons of CO2 into the atmosphere, with approximately 70% of this occurring during power generation (Mamurekli, 2010).

Moreover, coal inherently contains impurities, chiefly in the form of nitrogen and sulfur compounds, with coal displaying the highest sulfur content compared to other fossil fuels (Fouquet et al., 2001; Miller, 2005). The sulfur content in coal varies extensively based on the coal rank, ranging from lignite to anthracite. High-sulfur bituminous coal yields SO_2 emissions of 3180 ppm or 110 mg/g of dry coal, while low-sulfur sub-bituminous coal produces 188 ppm or 7.2 mg/g of dry coal

(Rokni, 2018). An estimated 60% of global SO_2 emissions linked to combustion are attributed to coal usage (IEA, 2016). Notably, China, with its substantial coal-fired power plants, emerges as the foremost SO2 producer in Asia, contributing to over half of the total emissions in the region (Qurashi & Hussain, 2015).

SO_2 and NO_x compounds precipitate as acid rain, infiltrating water and soil environments, consequently leading to acidification and damage to flora and fauna. Acid rain primarily affects aquatic ecosystems by altering pH levels and causing eutrophication. For instance, acidification in northern Fennoscandia's lakes led to the proliferation of acidobiontic and acidophilic species, coupled with diminished phytoplankton abundance and richness. The structural and functional makeup of phytoplankton communities changes as water pH shifts from 6 to 5 (Moiseenko, 2005). Sulfur compounds also inflict harm on materials, with SO_2 proving particularly detrimental to metal corrosion. Sulfur oxides react with water in the atmosphere or on metal surfaces to form sulfuric acid, accelerating the process of corrosion. Building materials such as limestone, marble, roofing slate, and mortar can be adversely affected by sulfuric and sulfurous acids (Miller, 2005). The acidification potential of hard coal largely stems from high SO_2 (86%) and NO_x (12%) emissions originating from coal combustion in power plants.

Eutrophication or hypertrophication, a consequence of nutrient imbalances in aquatic ecosystems, can render water toxic or unfit for both humans and animals, resulting in oxygen depletion. Increased phosphorus content significantly contributes to eutrophication, with approximately 73% of the phosphate (PO_4) responsible for eutrophication released during anthracite mining. Using anthracite for power generation releases around 2.3 g PO_4/kWh into the environment (Atilgan & Azapagic, 2015). A notable example of eutrophication occurred in 1998 in Hong Kong, where economic losses of approximately 40 million US dollars were incurred due to a 90% decline in fish stocks at local farms (IAEA, 2016).

Coal combustion gives rise to ash as a byproduct of energy generation (Demirel, 2016). During this process, substantial quantities of fly ash and coal dust are released into the atmosphere, contributing to particulate matter (PM) pollution and posing risks to human health. Coal ash may also contain heavy metals such as mercury (Hg), cadmium (Cd), arsenic (As), and nickel (Ni) (Treyer et al., 2014; Miller, 2005). A coal-fired power plant emits approximately 5 g of mercury per GWh generated. In the US, around 65% of mercury deposition into lakes and reservoirs can be traced back to fossil fuel combustion (Turney & Fthenakis, 2011). Persistent toxic elements like mercury accumulate within the food chain, subjecting top predators and humans to pollutant levels surpassing those present in the environment. Heavy metals such as cadmium can be directly absorbed through inhalation, causing disorders and fatal diseases, including cancer. India witnessed an estimated 80,000 to 115,000 deaths in 2010 and 2011 due to ambient $PM_{2.5}$ pollution stemming from coal-fired power plants. During the same period, $PM_{2.5}$ pollution resulted in 20.9 million asthma attacks, 900,000 emergency room visits, and 160 million restricted activity days (Guttikunda & Jawahar, 2014). If not properly managed, heavy metals from coal can contaminate surface water and groundwater, jeopardizing drinking water quality. Particularly in areas with extensive coal consumption, such as industrial regions, fly ash pollution can inflict substantial harm on terrestrial environments (Munawer, 2018). While the lowest-quality coal commercially used in the US yields approximately 28% ash, other parts of the world commonly employ coal with ash content of up to 40% (National Energy Strategy, 1991).

Furthermore, the extraction and aftermath of coal mining lead to the release of methane from the surrounding strata, both in underground and surface mines. Between 2006 and 2015, methane emissions from abandoned mines surged from 5.4 to nearly 13.3 billion cubic feet (Bcf), contributing to 1-13% of total methane emissions from coal mines in the US (EIAb, 2018; Nippgen et al., 2017). Abandoned coal mines in the UK release 1.4 million tons of CO_2 equivalent methane annually, with projections suggesting this trend will persist until 2050 (Department for Environment, Food, Rural Affairs, 2006).

Surface mining for coal fundamentally transforms the landscape surrounding the mine, impacting different land uses and giving way to pits, quarries, and mine tailing piles. In 2016, almost 65% of coal used in the United States was extracted from surface mines (EIAb, 2018). Coal mining yields substantial waste, amounting to tens of millions of tons annually, and the sites where this waste is deposited suffer irreversible repercussions, detrimental to the visual aesthetics of the surrounding environment (Mamurekli, 2010). Acid mine drainage, particularly prevalent in coal seams containing pyrite, emerges as an outcome of coal mining, as pyrite reacts with air and water to generate sulfuric acid.

Underground mining generates waste that is disposed of on the surface, leading to runoff, landscape alteration, and changes in local stream paths. Precipitation causes soluble minerals from the waste to dissolve into the runoff, elevating the total dissolved solids in nearby bodies of water (Nippgen et al., 2017). The resultant acidic runoff directly impacts the environment and can dissolve other metals such as zinc and nickel, thereby posing a threat to organisms downstream. These pollutants render water unsuitable for drinking, and can even render water unfit for agricultural and industrial uses.

Subsurface mining can also incite coal fires. These coal fires are accountable for a minimum of 3% of global carbon emissions. For instance, Chinese coal fires release nearly 1×10^9 tons of CO_2 into the atmosphere annually, with India's estimate standing at around 50×10^6 tons of carbon dioxide (Vallero, 2014). Underground excavation weakens the soil and rock structure, resulting in land subsidence — a significant concern associated with underground coal mining. Over time, pillars of coal and rock deteriorate, potentially leading to the collapse of upper layers and triggering land subsidence. This poses a threat to miners, local inhabitants, and nearby structures.

3. 1. 2. Oil

Currently, oil derivatives stand as the dominant fuel for the transportation sector. However, the global energy landscape is anticipated to witness a decrease in the share of oil, driven by advancements in fuel efficiency of combustion engines, the growing popularity of biofuels and natural gas, and the increased adoption of electric and hybrid vehicles (Independent, 2018). The exploration for oil and gas contributes to air, water, and soil pollution, releasing substantial volumes of pollutants during the processes of processing and refining.

CO2 stands as the major greenhouse gas (GHG) released by oil thermal power plants, yet other pollutants such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) are also emitted into the atmosphere. On average, an oil thermal power plant emits between 700 to 800 g CO_2/kWh (Shahsavari et al., 2019; Weisser, 2007). The extent of pollution generated during these stages is largely influenced by the final product;

for instance, refining crude oil into petroleum produces SO_x (0.2-0.6 kg/t of crude), NO_x (0.06-0.5 kg/t of crude), PM (0.1-3 kg/t of crude), and volatile organic compounds (VOCs), such as 2.5 g of benzene, toluene, and xylene per ton of crude. VOCs not only pose health risks but also contribute to the formation of smog (Vallero, 2014).

Significant water quantities are utilized in the refining process, resulting in the production of up to 5 m^3 of wastewater for refining every ton of crude oil (Vallero, 2014). Moreover, the oil industry contributes to methane emissions through practices like direct venting and inefficient flaring (Esmoil, 1995). Additionally, heavy metals such as cadmium (Cd), chromium (Cr), and nickel (Ni) are released during oil combustion (Ramirez, 2010).

The process of drilling for oil can lead to contamination of both surface water and groundwater. Groundwater contamination arises when oil and associated contaminants leak from casings and rock fractures into aquifers. Another form of oil-induced environmental pollution arises from oil spills. Notable examples include the oil spill in the Bay of Campeche, Mexico, during 1979 and 1980, the Gulf War oil spill in the Persian Gulf in 1991, and the Deepwater Horizon oil spill in 2010. The Deepwater Horizon spill, which endured for three months in the Gulf of Mexico, had detrimental effects on regional flora and fauna. It resulted in a doubling of whale and dolphin mortality, inflicted harm on wetlands, and impacted fishing activities (Vallero, 2014). This event underscored the environmental risks associated with deep-water drilling.

Similarly, oil leaks from tankers transporting oil present significant environmental hazards, with potentially devastating consequences for both terrestrial and aquatic ecosystems. For instance, in 2018, an Iranian tanker carrying 136,000 tons of condensed oil collided with a Hong Kong-flagged cargo ship. This incident led to the tanker's sinking in the East China Sea, causing extensive damage to the marine environment. The resulting pollution affected crucial fishing waters in China. The challenge was aggravated by the colorless and partially water-soluble nature of condensed oil, complicating its detection and separation (Kassotis et al., 2016). The costs of an oil tanker spill can reach millions of US dollars. Reducing the reliance on oil in the global energy supply not only safeguards the environment but also curtails cleanup expenses, reduces associated health problems, and mitigates economic losses (McFarlan, 2018).

Furthermore, oil has the potential to contaminate soil through the introduction of hydrocarbons, heavy metals, salts, and radioactive elements. These pollutants are released into the soil during drilling, hydraulic fracturing, or transportation, often due to casing, pipeline, or equipment failures (Pichtel, 2016).

The construction of access roads for well development leads to landscape fragmentation and habitat loss. Estimates suggest that the creation of a single well can impact an area ranging from 5.7 to 32.4 hectares (McDonald et al., 2009). Wildlife mortality linked to oil and gas fields is most pronounced around evaporation ponds and reserve pits (Esmoil, 1995). A study from 1989 documented 282 bird fatalities at 35 oil pits in just one week. A similar study in 1990 identified 334 dead birds at 53 pits (Ramirez, 2010).

Oil and gas industries exhibit significantly higher water consumption compared to renewable energies. Considering the global significance of water scarcity and pollution, these concerns should be factored into cost-benefit analyses during energy development. The water consumption during oil and natural gas extraction can widely fluctuate based on well characteristics and extraction methods. Current estimates indicate that oil extraction necessitates approximately 62 gallons of water per million British thermal units (MMBtu). Additionally, hydraulic fracturing, a water-intensive process used in over 90% of oil and gas wells since the 1970s, consumes nearly 1.6 million gallons of water per well or 80,000 gallons annually over the typical well lifespan of 20 years (Erickson et al., 2005).

3. 1. 3. Natural gas

As depicted in Fig 2, natural gas has ascended to the position of the third most prevalent fuel used for electricity generation, replacing oil and coal. This shift stems from the fact that the combustion of natural gas yields fewer pollutants compared to coal and oil (as outlined in Table 2). In contrast to coal-fired power plants, natural gas facilities emit 50% less carbon dioxide (CO_2), 70% less nitrogen oxides (NO_x), and a striking 99% less sulfur oxides (SO_2); furthermore, natural gas possesses negligible amounts of mercury, a distinct contrast to coal (Ramirez, 2010). The transition from coal to natural gas for energy generation yielded a 14% reduction (861 million metric tons) in CO2 emissions from coal combustion in the US between 2005 and 2017. In the same period, emissions from natural gas combustion increased by 24% (285 million metric tons) (EIAa, 2018).

Nonetheless, the combustion of natural gas, alongside oil and coal, stands as one of the most substantial sources of greenhouse gases (GHGs) per unit of electric power. On average, the emission of CO2 for each kWh of electricity generated using natural gas amounts to 492 g (with a range of 449-662 g CO_2/kWh) (IAEA, 2016). The majority of GHGs (74%) are released during combustion, followed by distribution (17%, often in the form of leakage from long-distance pipelines) (Atilgan & Azapagic, 2015). In addition to CO_2, natural gas contributes to methane emissions. Methane constitutes over 80% of natural gas and yields short-term climate impacts (Poinssot et al., 2014). In terms of trapping solar radiation, methane's potency surpasses that of CO2 by a factor of 28-36 (EPA, 2018). Methane can escape into the environment during drilling, extraction, and transportation of natural gas (Perera, 2018; Nippgen et al., 2017). Both venting and accidental leaks released approximately 155 million metric tons of CH_4 into the atmosphere in 2012. During the same year, a comparable quantity of methane was emitted by the natural gas industry due to processes like compression, flaring, and the removal of non-hydrocarbon gases at power stations (Bradbury, 2015). Notably, pipelines contribute significantly to fugitive methane emissions, with estimates indicating an annual entry of 62.6 kilotons of methane into the atmosphere from pipelines across the UK (Boothroyd, 2018).

In average terms, natural gas-fired power plants exhibit an acidification potential of 0.8 g SO_2/kWh, a value several times lower than that of coal. The majority of environmental impacts associated with natural gas occur during extraction (57%), combustion for electricity generation (26%), and distribution (17%). Additionally, natural gas poses a minimal eutrophication potential, around 0.1 g PO_4/kWh (Atilgan & Azapagic, 2015).

Drilling operations serve as a source of volatile organic compounds (VOCs). Venting, flaring, and dehydration processes release substantial quantities of VOCs. Furthermore, hydrogen sulfide (H_2S), a toxic pollutant naturally found in association with natural gas, is released during drilling operations (Vallero, 2014). Among the countries engaged in natural gas production, the US and Canada extensively employ hydraulic fracturing. While this process expands the availability of supplies, its substantial water demand and the chemicals employed have the potential to adversely impact water resource quality and quantity (Erickson et al., 2005).

3. 1. 4. Nuclear

Nuclear energy has emerged as a potential solution to two key challenges posed by fossil fuels: dwindling reserves and adverse environmental impacts. Comparable to other low-emission sources such as wind and solar power, nuclear power plants release negligible quantities of CO_2 into the atmosphere (below 15 grams CO_2-equivalent per kWh) when considering the complete life cycle of a plant. Over the period from 1970 to 2013, nuclear power plants played a pivotal role in preventing the emission of 66 gigatons of CO_2.

Uranium, the primary fuel utilized in nuclear reactors, boasts a substantially higher energy density compared to fossil fuels. Just one kilogram of natural uranium can yield 44,000 to 50,000 kWh of electric power (IAEA, 2016; Nieuwlaar, 2013; World Nuclear Organization, 2021). By contrast, a kilogram of coal and oil only generates a mere 3 kWh and 4 kWh, respectively (IAEA, 2016). While nuclear fission itself does not generate GHGs or air pollutants, the extraction and enrichment of uranium often rely on fossil fuels. Consequently, the greenhouse gas emissions tied to nuclear energy predominantly stem from the consumption of fossil fuels during uranium extraction, processing, waste disposal, reactor construction, and decommissioning (Shahsavari et al., 2019; NEI, 2017). Nearly half of GHG emissions and around 90% of air pollution linked to nuclear energy arise during the processes of uranium extraction, conversion, and enrichment (Poinssot et al., 2014). Notably, nuclear plants exhibit a minimal sulfur dioxide (SO2) production of 0.096 g SO_2/kWh, far below that of fossil fuels; nuclear power plants emit just a tenth of the SO_2 emissions produced by combined-cycle gas turbine-geothermal power plants and merely a seventieth of those from coal-fired plants (Vallero, 2014).

However, the advantageous low-carbon nature of nuclear energy is counterbalanced by its limited popularity due to safety concerns and the challenges associated with decommissioning. Consequently, the share of nuclear energy within the global electricity mix has been in decline since 1993 (Moriarty & Honnery, 2012). Nuclear plants generate higher-level radioactive waste (HLW), which remains hazardous for thousands of years, posing potential challenges for future generations. While the most common uranium isotope (U-238) is not intensely radioactive, U-235 emits alpha and gamma radiation, posing health risks during extraction and processing. The toxicity of alpha radiation is on par with that of heavy metals like lead (Elliott, 2007). The complexities surrounding HLW disposal present a substantial impediment to the widespread adoption of nuclear energy globally (Elliott, 2007; Fanchi, 2005). Effectively managing radioactive and hazardous waste stands as one of the most formidable challenges associated with nuclear energy. Public concern and independent critiques since the 1970s have unveiled instances of mismanagement of radioactive waste. It is important to note that the toxicity of nuclear waste diminishes over time, and a significant portion of the radioactive waste generated in the fuel cycle can be recycled.

The processing of uranium ore results in the generation of mill tailings containing heavy metals and radioactive substances. The sludge produced during this process retains over 85% of the radioactivity of the original ore, and it has the potential to contaminate groundwater and soil. Poorly constructed tailings dams are susceptible to natural hazards like earthquakes, endangering public health, particularly that of the local population (Stevens, 2019). Furthermore, nuclear plant failures can have disastrous consequences. The Chernobyl disaster, for instance, led to severe health effects among plant personnel and emergency workers, with 134 cases of acute radiation poisoning reported among the latter, resulting in 28 fatalities. Other cases experienced negative health outcomes including skin lesions and cataracts. The incident also exposed recovery operation workers and the local population to substantial doses of radiation, significantly elevating cancer rates among them. In 2005, Belarus and Ukraine reported 6,000 cases of thyroid cancer (15 leading to fatalities) in connection to the event (Boothroyd et al., 2018).

Estimates indicate that for every terawatt hour (TWh) of electricity produced using nuclear energy, there are 0.96 permanent disabilities, 0.02 deaths among workers in the nuclear industry, and 296 lost working days. Occupational hazards tied to nuclear energy primarily occur during the construction and decommissioning of nuclear plants. While the transportation of nuclear waste poses risks to the public, these risks remain minimal. For instance, estimates for French nuclear plants suggest 0.0003 deaths and 0.0017 injuries per TWh of electricity (approximately 0.1 death and 0.7 injuries annually) when radiological health impacts are not factored in. Uncontrolled releases of radioactive materials due to human error or events such as floods and fires can amplify the health consequences of nuclear energy (NRC, 2010).

Per every kWh of energy produced by a nuclear power plant, approximately 0.55 µg of chlorofluorocarbons (CFC-11) are emitted, with most of this release occurring during the mining, processing, and enrichment of uranium (Harvey, 2010). Notably, CFC-11 is an ozone-depleting greenhouse gas. Over a 100-year span, CFCs exhibit a global warming potential (GWP) 4,600 to 10,600 times greater than that of carbon dioxide (IPCC, 2001).

Similar to any energy source, nuclear energy demands land. For every gigawatt-hour (GWh), nuclear energy necessitates 211 m^2 of land for nuclear fuel disposal; corresponding figures for mining and reactor construction are 144.1 m^2/GWh and 45.1 m^2/GWh, respectively (Poinssot et al., 2014). Approximately 400 gallons of water are consumed per megawatt-hour (MWh) of electricity generated using nuclear energy in the US. In 2015, nuclear plants in the US collectively consumed a total of 320 billion gallons of water (Styles, 2018).

3. 1. 5. Solar

Renewable energy sources encompass non-fossil energy options like solar, wind, geothermal, hydropower, and energy derived from biomass. Earth receives an astonishing 11,000 times the global energy demand through solar radiation. Solar energy can be actively harnessed for electricity generation and heat, or utilized passively for lighting, heating, and ventilation (Harvey, 2010). Developing nations hold greater potential for leveraging solar energy, as energy-intensive activities expand, and solar power can play a role in emission reduction (Shahsavari & Akbari, 2018). The primary methods for converting solar radiation into heat and electricity are photovoltaic (PV) panels and concentrated solar power (CSP). PV panels directly transform sunlight into electricity, whereas CSP employs sunlight to generate heat, subsequently converted into electricity. PV cell variants encompass monocrystalline, polycrystalline, and amorphous silicon solar cells. Notably, PV energy technologies offer the advantage of curbing GHGs; for every gigawatt-hour (GWh) of electricity produced, PV systems avert the emission of up to 1000 tons of CO_2, 10 tons of SO_2, 4 tons of NO_x, and 0.7 tons of particulate matter (Aly & Hussein, 2014).

The environmental implications of solar technologies exhibit variability contingent on the type and generation of technology. On average, monocrystalline panels exhibit lower GHG emissions compared to other technologies (43-62 g CO_2/kWh vs 50-73 g CO_2/kWh) (Weisser, 2007). However, GHG emissions also display regional variations based on the deployment location of solar panels (IAEA, 2016). The National Renewable Energy Laboratory (NREL) reports that thin-film solar cells generate lower CO_2 emissions than alternative technologies (NREL, 2015). The utilization of solar energy via PV technology spans various stages, from resource extraction to disposal and site restoration (Burke & Stephens, 2018). Approximately 60% of CO_2 emissions linked to this technology stem from the extraction and purification of silicon. At present, solar power bears a significant carbon footprint. Yet, advancements in PV technology are poised to diminish silicon usage and subsequently reduce the carbon footprint associated with solar technology (Parliamentary of Office Science and Technology, 2006; Hondo, 2005).

Solar plants require substantial land areas for energy production. To fulfill the energy needs of the United States, approximately 32,000 km^2 of land (roughly the size of Maryland) would need to be covered with PV panels operating at 10% efficiency (Wilshire et al., 2008; Lovich & Ennen, 2011). Direct land requirements for PV installations range from 2.2 to 12.2 acres per megawatt (MW) depending on operational scale, with a capacity-weighted average of 6.9 acres/MW. Single-axis tracking systems entail a smaller land demand, spanning from 4.2 to 10.6 acres/MW, and boasting a capacity-weighted average of 6.3 acres/MW. Comparable figures for CSP facilities stand at 2.0 to 13.9 acres/MW, with a capacity-weighted average of 7.7 acres/MW (Hekmatnia et al., 2020). Land requirements prove more substantial in small countries characterized by high population densities and regions where land holds a premium. The land demand of PV systems can result in land-use shifts, habitat loss, and habitat fragmentation. Sizeable solar installations can also negatively impact the aesthetic qualities of landscapes. The continued maturation of solar technologies and the widespread adoption of panels on residential and industrial rooftops will significantly diminish the land footprint of solar energy. Incorporating solar panels on these structures can cut land and transmission costs by 20% (Pimentel, 2008). Rooftop PV systems capitalize on the potential of residential and industrial areas while minimizing development in surrounding landscapes. Solar energy initiatives demand more resources and materials compared to fossil fuel plants per unit of energy (Abbasi & Abbasi, 2000). However, by optimizing the efficiency of solar cells, streamlining manufacturing processes, and implementing robust recycling practices, the material demands, energy consumption, and greenhouse gas (GHG) emissions associated with solar energy production can be effectively mitigated (Panwar et al., 2011).

Small quantities of heavy metals (such as cadmium, lead, and nickel), corrosive substances, and explosive gases are employed in the production of solar cells. Cadmium serves as a semiconductor in cadmium telluride thin-film solar cells (World Energy Council, 2016; Shahsavari et al., 2019). The direct emission of cadmium during the extraction and processing of raw materials totals 0.015 g/GWh overall and 0.004 g/GWh during module manufacturing. A cadmium telluride solar module contains 90-300 times less cadmium than what is released during the generation of 1 kWh of electricity using coal (Fthenakis et al., 2008). Modules featuring indium selenide comprise the toxic element selenium. Additionally, several manufacturers incorporate lead in silicon wafer-based panels (Letcher, 2008; Smith et al., 2013). These toxic materials pose health hazards to workers within solar cell manufacturing facilities. The production process of silicon thin-film cells necessitates nitrogen trifluoride (NF3), a compound with a global warming potential surpassing that of CO_2 by a factor of 17,000. Consequently, stringent control over emissions of hazardous materials utilized in solar cell manufacturing proves crucial (Shahsavari et al., 2019).

The expansion of solar energy can lead to habitat loss, habitat fragmentation, and direct harm to wildlife through vegetation removal and landscape alteration. Solar energy projects often entail earthworks and vegetation removal, potentially generating dust (Munson et al., 2011). In arid environments, dust already presents a challenge, with potential impacts on ecological processes across various scales. The focused sunlight within central-tower CSP facilities has the potential to harm insects and birds that come into contact with light reflected from mirror arrays. Furthermore, solar installations can influence local climate; a CSP facility can elevate the surface albedo of arid environments by 30% to 56%, thereby affecting air temperature, precipitation patterns, wind speed, and evapotranspiration (Wilshire et al., 2008; Lovich & Ennen, 2011).

CSP technologies (e.g., parabolic trough, solar tower, and Fresnel technology) rely on water for cooling, placing their water consumption on par with that of fossil fuel and nuclear plants. Given that water scarcity can be a concern in arid regions, certain solar energy projects, presently under construction in the Mojave Desert in the United States and semi-arid areas of Shaanxi province in China, are designed to employ dry cooling. However, dry cooling can lead to decreased efficiency and increased energy costs. In hotter climates, dry cooling can lead to a 7% reduction in annual electricity output and a 10% rise in costs. On the other hand, solar tower technology demonstrates greater efficiency and is less affected by dry cooling (Wiser et al., 2016; IEA, 2012).

As the prevalence of solar panels rises, the disposal of old and unwanted cells becomes an issue due to the presence of various toxic chemicals (e.g., cadmium, lead, chromium, and brominated flame-retardants) within PV cells. Adequate waste management measures are imperative for the controlled handling and disposal of PV cells (Smith et al., 2013; Hohmeyer & Ottinger, 1999).

3. 1. 6. Wind

Wind turbines function by harnessing the energy of moving air to generate electricity. The utilization of wind-generated electricity contributes to stabilizing energy costs, enhancing energy security, and mitigating environmental pollution and climate change. Globally, the entire surface of the earth receives an annual wind energy potential of 100 billion watts (Qurashi & Hussain, 2015).

During the construction of wind power plants, approximately 29.5 g CO_2/kWh is released, representing the largest portion of CO_2 emissions associated with wind energy, accounting for over 70% of total emissions (Hondo, 2005). A breakdown of CO_2 emissions from wind power plants is provided in Table 2. The wind energy sector stands as a well-established competitive industry with relatively low or even zero carbon emissions. However, akin to other energy sources, wind energy does have the potential to generate environmental impacts. While wind turbines themselves do not emit greenhouse gases during operation, it's essential to acknowledge that emissions are generated throughout the manufacturing, installation, maintenance, and decommissioning processes tied to wind turbines (Shahsavari & Akbari, 2018).

Avian wildlife faces particular challenges due to wind turbines and associated infrastructure. Turbine blades and meteorological towers present distinct obstacles for flying creatures. Estimates suggest that approximately 9,200 bird deaths beyond California can be attributed to wind power plants. In habitats like grassland-steppe and shrub-land regions of Wyoming, where there are 69 wind turbines and 5 meteorological towers, an estimated 143 bird fatalities occur annually. During the initial three years of operation, 122 instances of collision-related fatalities were recorded. In Vansycle Ridge, Oregon, the installation of 38 turbines in an agricultural landscape led to 12 bird deaths resulting from collisions with turbine blades in the first year of operation. Overall, field observations estimate an annual mortality of around 24 birds per year, or 0.63 birds per turbine, linked to wind energy (Erickson et al., 2005). Given the risks posed by wind turbines, it's recommended that they be situated at least 300 meters away from nature reserves. Enhancing the visibility of wind turbines and employing deterrent technologies such as strobe lights can contribute to reducing bird fatalities.

Noise pollution is another concern associated with wind turbines. Noise arises through two mechanisms: the interaction of turbine blades with the air (aerodynamic noise) and the interaction of turbine components with each other (mechanical noise) (Pimentel & Biofuels, 2008; Letcher, 2008; Quaschning, 2005). Noise pollution and shadow flicker primarily impact individuals living in proximity to wind turbines. Beyond a distance of 2.1 km, turbines are virtually inaudible, even when located downwind from the largest turbines. At 400 meters, the noise generated by a wind turbine is comparable to that of a home air conditioning unit (60 decibels) (Pimentel & Biofuels, 2008). Wind turbines come in various sizes; offshore turbines, being larger and more productive, result in less significant noise pollution due to their distance from human settlements. This also minimizes their impact on the landscape. Modern wind turbines exhibit notably reduced noise levels compared to older technologies. For example, an 850 kW wind turbine at Dundalk Institute of Technology in Ireland, installed 250 meters away from the nearest residence, generates almost imperceptible noise beyond the campus, and residents have not reported noise-related complaints (Letcher, 2008).

The installation and maintenance of wind power facilities do impact natural ecosystems through activities such as vegetation clearing and soil disruption. Nevertheless, these impacts are comparatively minor when juxtaposed with the effects of coal mining and coal-fired power stations (Owen & Hanley, 2004). Wind farms and their associated facilities do influence the visual characteristics of the surrounding landscapes. Visual impacts often represent significant considerations during the permitting process for wind farms. Under conditions of good visibility, wind turbines can be observed from distances as great as 25 to 30 kilometers (Abromas, 2014). To yield substantial energy through wind power, several large turbines must be installed. The larger turbines can be positioned closer to each other, resulting in reduced land requirements and fewer turbines needed for electricity generation. This approach mitigates the visual impact of wind farms compared to scenarios where a larger quantity of smaller turbines are employed. Notably, wind power boasts the smallest external cost among all electricity sources. On average, a 50-kW turbine necessitates 1.3 hectares of land to ensure adequate spacing for maximum power generation, with the turbine itself occupying just 2% of this area (Pimentel & Biofuels, 2008). The remaining land can be repurposed for activities such as grazing or farming.

3. 1. 7. Hydroelectricity

Hydroelectricity stands as one of the power generation technologies with the lowest greenhouse gas (GHG) emissions, measuring around 7 g CO_2-eq/kWh (IAEA, 2016). It holds considerable potential for GHG emissions reduction. An illustrative example is the Three Gorges Dam (TGD) in China, which prevented the emission of approximately 406.7 million tons (Mt) of CO_2 from 2003 to 2010. This figure amounts to roughly 0.84% of China's total emissions in 2010 (Wu et al., 2011). On a global scale, hydroelectricity leads the way as a renewable energy source and was the sole low/zero-emission energy source until the 1960s. Nonetheless, the worldwide expansion of hydropower has encountered impediments due to its adverse environmental and social effects (Sumathi et al., 2015). Dam construction contributes to issues such as dust emissions, soil erosion, landslides, debris creation, as well as noise and air pollution. During dam construction, dust emissions and landslides emerge as primary drivers of both health risks and environmental damage. When dams are operational, various factors must be effectively managed to mitigate environmental impacts, encompassing water release timing and volume, sediment movement, aquatic animal migration, and the implications of access roads and transmission lines.

Large dams have drawn mounting social opposition due to their upstream (e.g., land submersion, sedimentation) and downstream (e.g., altered or unnatural streamflow) impacts. Furthermore, hydroelectric dams can shape land use, contingent upon the project's magnitude and local topography (EPA, 2018; Evrendilek & Ertekin, 2003). Reservoirs formed by dams result in the submersion of substantial land areas. To provide a comparison, the 250-MW Balbina hydroelectric power plant in Brazil is situated on a large flat expanse, covering 2,000 acres per MWh, whereas a small run-of-the-river plant in mountainous terrain might encompass as little as 0.25 acres per MWh. TGD led to the reduction of croplands, woodlands, and grasslands between 1977 and 2005, while the areas covered by water and constructed spaces increased by 2.79% and 4.45% respectively between 2000 and 2005 (Zhang et al., 2009).

The most intricate challenge posed by large-scale hydroelectric projects involves the displacement of local communities (IPCC, 2001; Gujba et al., 2010). Over recent decades, an estimated 40-80 million individuals have been compelled to relocate as a consequence of dam construction (Chen et al., 2008). The social and environmental costs of TGD have been subject to extensive investigation (Tian et al., 2007; Yang et al., 2007; Chen et al., 2008; Tranvik & Downing, 2009; Lopez-Pujol & Ren, 2009; Fu et al., 2010; Xu et al., 2013). Around 190,000 people residing in close proximity to the reservoir, with some living as near as 175 meters from the reservoir, needed to be resettled (Xu et al., 2013). Similarly, the Sardar Sarovar dam in

India resulted in the displacement of 320,000 people (Berger, 1994; Nilsen, 2010).

Moreover, large dams capture sediment, leading to a decline in sediment downstream. TGD, for instance, trapped two-thirds of its 200-million-ton sediment input between 2003 and 2006 (Chen et al., 2008). The accumulation of sediment within reservoirs diminishes their capacity and lifespan over time, deprives downstream streams of the necessary sediment levels for maintaining natural channel form, and adversely affects aquatic environments downstream (Kondolf et al., 2014). Downstream sediment decline stemming from TGD triggered channel erosion, exerting significant pressure on the coastal areas of the Yangtze River and the East China Sea (Fu et al., 2010). This sediment decrease has ushered in changes in the riverbed due to modifications in the erosion-deposition dynamics, particularly in proximity to the dam (Lopez-Pujol & Ren, 2009). The dam's construction has also exacerbated soil erosion; between 2002 and 2011, the Hubei province saw an average soil erosion rate of about 108.8 million cubic meters per year (Xu et al., 2013). As rivers deposit sediment into a dam's reservoir, water gains some capacity for sediment transportation. Upon release, the water, now carrying fewer sediments, erodes the streambed, adversely impacting aquatic organisms in the process. The augmented erosive force of the stream can result in riverbank collapse, as witnessed with the Yangtze River (Fu et al., 2010). .

Modified stream flows, changes in sediment and nutrient composition, as well as the reservoir's barrier effect, induce habitat alterations in riparian, riverine, and coastal ecosystems. The region surrounding TGD is recognized as a biodiversity hotspot in China, hosting three endangered endemic fish species. The Gorges region is home to approximately 6,000 plant species, 500 terrestrial vertebrates, and nearly 160 fish species. The operation of TGD could potentially influence biodiversity through its impact on species composition. As the reservoir of TGD was filled, 22 vegetation types, four woody communities, nine shrub communities, and nine grass communities faced endangerment (Tian et al., 2007).

Reservoirs formed by large dams exert an influence on temperature both upstream and downstream. For instance, between 2003 and 2009, the annual mean temperature upstream of TGD was 0.2-1.0 °C warmer compared to the period of 1996-2002 (MEPPRC, 2012). As a reservoir transitions from river-like thermodynamic conditions to conditions resembling a lake, organisms both upstream and downstream experience significant impacts. Temperature-sensitive organisms are compelled to adapt or relocate in response to these changes. Failure to do so threatens their survival. Additionally, inadequate water retention during river diversion can adversely impact aquatic life.

Lastly, hydroelectric dams in tropical regions can serve as sources of GHG emissions. When water rich in methane undergoes pressure reduction within a turbine due to lower hydrostatic pressure, a substantial portion of the dissolved methane is released into the atmosphere (Tranvik et al., 2009). Global estimates place the average methane emission from a hydroelectric station at approximately 5.7 g CH_4/kWh (Li & Zhang, 2014).

3. 1. 8. Biomass

The expansion of biomass as an energy source encounters various challenges, encompassing issues like food security, water usage, livelihood impact, greenhouse gas (GHG) emissions, and changes in land use (Rosillo-Calle et al., 2015; Georgakellos, 2012). Notably, biomass exhibits the widest range of GHG emissions among renewable energy technologies (RETs), with emissions spanning from 10 to 101 g CO2/kWh (WNA, 2011). The utilization of biomass contributes to GHG emissions, with particular emphasis on gases such as N_2O, CH_4, and CO_2. These emissions result from activities encompassing the consumption of agricultural inputs, management practices, and modifications in land use (Georgakellos, 2012). GHG emissions encompass both direct and indirect emissions. Direct emissions pertain to the release of gases due to actions like vegetation clearance, cultivation, use of inputs such as fertilizers, and the implementation of management practices. Indirect emissions are those originating from changes in land use, as natural ecosystems are replaced by cultivated areas to compensate for the land allocated to energy production.

Biomass stands as one of the world's oldest energy sources, derived from organic matter such as herbaceous materials, forestry residues, or organic municipal waste. It can be classified into traditional and modern fuel categories. Interestingly, as of 2015, nearly half of global bioenergy was utilized in wood stoves within developing countries, with only 12% allocated to power generation systems (IEA, 2016). The use of traditional biomass fuels in household settings results in significant GHG emissions compared to other renewable sources (IAEA, 2016). For instance, the CO_2 emissions of Ethiopia surged from 5.1 million tons in 2005 to around 6.5 million tons in 2010 (Li & Zhang, 2014). Biomass constitutes a substantial 91% of total energy consumption in Ethiopia (IEA, 2006). The use of traditional biomass fuels also triggers substantial emissions of air pollutants, including PMs, polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), nitrous oxides (NO_x), and methane (CH_4) (Panwar et al., 2011).

The detrimental effects of air pollution stemming from biomass fuels are particularly pronounced among women and children, leading to health issues like cancer, chronic sinusitis, allergies, and asthma. In fact, annual deaths due to indoor air pollution caused by burning biomass reach 1.3 million, disproportionately affecting women and children. China alone bears an estimated annual death toll of around 420,000 (IEA, 2006; Apte & Salvi, 2016). Among these fatalities, a significant number result from inhaled PMs causing pneumonia in children under the age of 5 (Cherian, 2015). PMs released during biomass combustion are often larger and more elongated than those emitted when burning coal, with PM size averaging 90-150 μm for biomass compared to 75-90 μm for coal (IEA, 2016) In addition, the combustion of biomass tends to produce more volatile compounds in comparison to coal (Riaza et al., 2017). However, biomass emits significantly lower amounts of sulfur dioxide (SO2) than coal. Low-temperature pyrolysis, or torrefaction, can release some sulfur into the atmosphere, resulting in lower SO_2 emissions from torrefied biomass fuels compared to raw biomass. Nitrogen oxides (NO_x) emissions are also common from biomass combustion, occurring during de-volatilization and char oxidation. Biomass typically contains higher nitrogen content than coal, and torrefaction further increases the nitrogen content in fuels. Consequently, torrefied fuels tend to have higher nitrogen content. For instance, torrefied corn straw emits 288 ppm of NO_x, whereas raw corn straw emits 144 ppm of NO_x.

Biomass combustion generates hydrogen chloride (HCl) and particulate chlorine, similar to SO2 and NOx. HCl, akin to SO_2 and NO_x, can corrode boilers and lead to acid precipitation. Storing biomass under anaerobic conditions can result in the production of ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organic acids, among other chemicals (Ren et al., 2017). The combustion of both coal and biomass yields chloromethane, which can have severe neurological effects in cases of acute exposure and harm the liver, spleen, kidneys, and central nervous system with chronic exposure (Chandrappa & Kulshrestha, 2016).

The large-scale cultivation of energy crops for biofuel production gives rise to environmental and social challenges. The competition between food and fuel production can elevate food prices and trigger social issues when land is repurposed for energy crop cultivation. Biomass requires expansive land areas for energy production, approximately 380,000 m^2 year/GWh, signifying the highest land requirement within the spectrum of energy sources (Shahsavari & Akbari, 2018; NEAb, 2018).

Deforestation rates have been notably high since 1990, particularly in regions like Latin America, the Caribbean, East Asia, the Pacific, and sub-Saharan Africa. Notably, Cameroon faces substantial deforestation, with roughly 100,000 hectares of its 21 million hectares of forests cleared annually, partially for oil palm cultivation for biodiesel production (Mboumboue & Njomo, 2016; Wirba et al., 2015). Presently, Cameroon has 108,000 hectares of land dedicated to oil palm cultivation. During the years 2001 to 2006, 30,000 hectares of forest in Cameroon were cleared for energy crop cultivation, particularly oil palm (Mboumboue & Njomo, 2016). The cultivation of oil palm for biodiesel also impacts the tropical forests of Southeast Asia, as deforestation disrupts rainfall patterns, rendering drier forests susceptible to fires, and consequently exacerbating the decrease in rainfall (Ruan et al., 2016). A significant portion of the world's impoverished communities depend on forests for their livelihoods, with 80% of sub-Saharan Africa's population relying on biomass for energy. Deforestation endangers these livelihoods and poses a threat to biodiversity (Ruan et al., 2016). Land-use changes from natural ecosystems to farmland and commercial forests have posed a major threat to biodiversity (Christie et al., 2004).

The use of nitrogen fertilizer in cornfields negates the potential benefits of ethanol in terms of lower CO_2 emissions (Ruan et al., 2016). While nitrogen fertilizer application can boost yields, the GHG emissions associated with its production, transportation, and distribution offset the advantages of ethanol usage. Fertilizer application can also contribute to the production of nitrous oxide (N_2O) by soil microbes (Poinssot et al., 2014). The global warming potential of N_2O is estimated to be 265-298 times greater than CO_2. Moreover, if nitrogen enters water sources, it can degrade water quality and indirectly trigger N_2O emissions downstream.

Furthermore, as more land is cultivated for energy, erosion rates are likely to increase. Energy farms can contaminate their surroundings when pesticides and agricultural chemicals enter the air and water (Marten, 2018). Additionally, biomass farms and plantations are considerably less capable of sequestering soil carbon compared to natural ecosystems. For example, forests store nearly fifteen times more carbon in biomass per unit area than agricultural lands (Jones & Pejchar, 2013). Byproducts of biofuels made from soy and corn can be utilized as animal feed, reducing the need for cultivating animal feed crops and thus mitigating the competition between biofuel crops and feed crops. Biofuels produced from agricultural residues or waste exhibit significantly lower impacts on land use. Simultaneously, utilizing biomass for energy can aid in managing waste generated by feedlots, sawmills, sugarcane plantations, and municipal sewage treatment plants. The utilization of methane produced from sewage and landfills can further curb methane emissions.

5.Externalities of energy systems

Production and utilization of energy will incur social and environmental costs regardless of the source (Shahsavari et al., 2019; Wilshire et al., 2008; Burke & Stephens, 2018). In this study, externalities are defined as long-run marginal costs. Yet, due to transboundary effects, evaluation of the social and environmental impacts of externalities is challenging. Currently, coal has a greater energy return on investment in comparison with the alternatives; however, using coal incurs significant environmental costs through pollution and global warming. The social cost of coal is estimated between 4.0 and 9.5 US cents/kWh (Table 2).

Table 2. External cost estimates for various sources of power (US cent/kWh) (Shahsavari & Akbari, 2018; El-Guindy et al., 2019)

US c/kWh	Coal	Oil	Gas	Nuclear	Hydro	Wind	Solar
Max	9.5	9	3	1.5	1	0.25	0.6
Min	4	3	0.49	0.2	0.03	0.001	0.25

The impacts of energy production, encompassing greenhouse gas (GHG) emissions and pollution, can impose substantial social and environmental costs by affecting public health and biodiversity, and by diminishing the quality of air, water, and soil. As indicated in Table 2, the external costs linked with Renewable Energy Technologies (RETs) and nuclear energy are notably lower than those associated with fossil fuels. Table 2 also illustrates the detrimental effects of fossil fuels on natural ecosystems and man-made structures (Owen & Hanley, 2004; Streimikiene & Alisauskaite-Seskiene, 2014; El-Guindy et al., 2019; NEAa, 2018). The social costs attributed to fossil fuels far outweigh those of RETs. Within the realm of RETs, biomass is marked by the most substantial negative impacts (Fouquet et al., 2001). The social costs of fossil fuels are heavily influenced by the technology employed for energy generation; as shown in Table 2, the utilization of natural gas for electricity production exhibits the lowest social costs. The external costs of fossil fuel power plants primarily revolve around climate change, stemming from CO_2 emissions and air pollution generated during plant operation (Georgakellos, 2012).

Energy production and consumption exert varying impacts on different countries, contingent on the technology and the number of affected individuals (Zvingilaite, 2011). For example, Greece and Poland bear the highest costs of electricity generation due to their heavy reliance on coal. Conversely, Norway, Sweden, and Switzerland encounter the lowest external costs, owing to the substantial share of RETs and nuclear energy in their energy mix. In Norway, a striking 98% of electricity demand is met through hydropower, while hydroelectric and nuclear energy significantly contribute to Sweden's and Switzerland's energy composition (Weinzettela et al., 2012). While social costs in Western European nations might be modest, the external costs arising from emissions are elevated, given the large population impacted (EEA, 2007; WHOb, 2018).

Climate change precipitates diverse environmental transformations on various scales, leading to social, political, and economic repercussions such as food and water price hikes, unemployment, displacement, migration, and tensions regarding water, land, and food resources (IPCC, 2001). For instance, extreme weather events in the United States between

1980 and 2017 incurred individual costs exceeding 1 billion dollars and a cumulative sum exceeding 1.1 trillion dollars. Such incidents are increasing globally (NOAA, 2019). Climate change directly affects public health through heat-related illnesses and fatalities. A heatwave in 2003 caused over 70,000 deaths across Europe, while a similar event in 2006 led to an estimated 655 fatalities in California. Predictions suggest that by 2030, climate change-related costs arising from deaths and diseases like diarrhea, malnutrition, malaria, and thermal stress will surpass 2-4 billion dollars annually (WHOb, 2018). The expenses of climate change mitigation measures are significantly lower than the costs incurred by the negative impacts of climate change (Owen & Hanley, 2004).

Air pollution stemming from carbon-emitting energy sources imposes substantial social and economic burdens. In the United States, pollutants emitted during electricity generation from fossil fuels lead to yearly economic losses reaching hundreds of billions of dollars. These losses emanate from reduced life expectancy, health complications, decreased productivity due to workdays lost, and direct healthcare system expenses. For carbon-emitting sources like coal and oil, these costs exceed the retail price of electricity, underscoring the magnitude of associated social costs (Machol & Rizk, 2013). Annually, coal combustion-related air pollution costs the United States around 187 billion dollars (Perera, 2018). Estimates demonstrate that air pollution causes over 3.5 trillion dollars in social welfare damage each year in the Organization for Economic Co-operation and Development (OECD) member states, India, and China (Millstein et al., 2017). In the United States, $PM_{2.5}$ (particulate matter with a diameter of 2.5 micrometers or smaller) was responsible for 15,000 premature births in 2010, amounting to approximately 5 billion dollars in medical expenses, special education, and lost economic activity (Perera, 2018). $PM_{2.5}$ pollution in China often leads to haze and visibility reduction to less than 1 km, prompting school and airport closures. In India, the health impact of $PM_{2.5}$ pollution from coal-fired plants is estimated at 3.3-4.6 billion dollars annually (Guttikunda & Jawahar, 2014).

While the causative role of SO_2 and NO_x in acid precipitation is well-established, assessing their impacts is compounded by transboundary effects. In Germany, annual material damage due to air pollutants is estimated at approximately 2 billion euros (Quaschning, 2005). The damage inflicted by SO_2, NO_x, and PM pollution varies based on technology and the population density of affected regions; estimates for EU countries in 2003 indicated power plant emissions causing damage ranging from 1,027-1,486 euros per ton (Finland) to 11,388-12,141 euros per ton (Belgium) (Owen & Hanley, 2004).

As previously discussed, the sustainability of nuclear facilities raises concerns. Moreover, nuclear accidents introduce an element of uncertainty to impact evaluations of nuclear energy. The repercussions of highly radioactive-hazardous substances on the environment and human health are also alarming. On average, the social costs linked with nuclear plants are estimated between 0.2 and 1.5 cents per kWh. However, these figures warrant scrutiny. While the operational social cost of nuclear plants remains low, assessing the risks of major accidents and the expenses of long-term nuclear waste storage is challenging (Streimikiene & Alisauskaite-Seskiene, 2014; EEA, 2007; Timmons & Harris, 2014). Given nuclear energy's low GHG and pollutant emissions, it can be a competitive energy source in comparison to coal, provided CO_2 is priced at 10 dollars per ton (Letcher, 2008).

Concerning social costs, RETs demonstrate a favorable standing compared to conventional sources. Wind energy presents the lowest social costs, while natural gas and biomass exhibit closer proximity concerning atmospheric emissions. RETs also deviate from conventional sources in terms of the nature of associated social costs, particularly when factoring in air pollutants and CO_2 releases from fossil fuels (Fouquet et al., 2001). RETs are generally deemed emission-free during operation, with external costs originating primarily from construction and manufacturing.

Emissions stemming from hydroelectric plants result from construction material production, as hydroelectricity's direct contribution to air pollution is minimal. The external costs of hydropower plants stem from their adverse effects on biodiversity and landscape aesthetics. Similarly, wind energy demonstrates low to zero emissions. Nevertheless, the transportation expenses associated with wind farm installation can be substantial, especially for offshore installations (NRC, 2010). The external costs of wind energy are mainly tied to ecological impacts and noise pollution.

Regarding biomass, external costs related to climate change arise from GHGs emitted during production, transport, and combustion. The most significant external cost attributed to biomass emerges from the impact of land-use change on natural ecosystems. While numerous other electricity sources also necessitate extensive land areas when evaluating the complete fuel cycle, biomass's land requirement remains substantial (NEAb, 2018). Whether biomass is a preferable energy source depends on net emissions per energy unit compared to fossil fuels. For instance, transitioning from coal to biomass yields more considerable benefits than shifting from natural gas to biomass (EEA, 2007).

The social costs linked with solar energy largely derive from solar panel manufacturing, yet these costs remain lower than those of fossil fuels. While solar energy exhibits significantly lower emission rates, they still surpass those of nuclear, wind, and hydroelectric power. Mining and processing raw materials for PV cells can release toxic substances into the environment (EEA, 2007; NEAb, 2018). As solar cell technology advances, social costs tied to solar energy are projected to decrease. Overall, uncertainties tied to RETs are unlikely to elevate social costs, as these costs principally arise from technology impacts on human health. Although quantifying these impacts might be complex, they are not more substantial than those associated with conventional fuels. Research focusing on the external and direct costs of low-carbon and carbon-intensive energy sources has contributed to an enhanced understanding of how various sources fare within an economic context.

The potential of clean energies to mitigate GHG and pollutant emissions hinges on the degree to which renewables displace carbon-intensive energy sources in electricity generation. The lower pollutant emissions and reduced global warming impact of renewables can yield significant health co-benefits. On a global scale, up to 230 billion dollars in annual savings could be realized if RETs constitute 36% of the global energy mix by 2030 (Watts et al., 2015).

Nations relying extensively on RETs to fulfill their energy needs stand to achieve substantial monetary savings. For instance, the United States saved 29.7-112.8 billion dollars between 2007 and 2015 (largely from averting 3,000-12,700 premature deaths) due to a 25% reduction in SO_2 and NO_x emissions facilitated by wind energy adoption. The climate benefits of wind energy during the same period amounted to 5.3-106.8 US dollars. From 2007 to 2015, solar energy enhanced air quality and public health, resulting in savings of 1.3-4.9 billion dollars, along with climate benefits reaching 0.4-8.3 billion dollars in the United States (Millstein et al., 2017). Predictions suggest that solar energy could curtail GHG emissions and air pollution by roughly 10% from 2010 to 2050, equating to an approximate value of 250 billion dollars. By 2010, Egypt and Morocco respectively saved approximately 720 and 685 million dollars through renewable energy utilization. The imperative of transitioning to renewable energies is underpinned by diverse factors, including financial savings, heightened energy security, expanded job opportunities, improved environmental conditions, and reduced reliance on fossil fuels (El-Guindy et al., 2019).

Even in countries boasting extensive coal reserves, such as Australia, renewable power generation proves more cost-effective than fossil fuels. In Australia, the cost of onshore wind-generated electricity was 8% lower than natural gas and 14% lower than coal in 2013. In Egypt, onshore wind costs 0.04 dollars per kWh, in contrast to 0.07-0.19 dollars per kWh for fossil fuels (Utilities Middle East, 2019). When factoring in the impact of fossil fuels on human health and the environment, the cost of fossil fuel-generated electricity increases by 0.01-0.13 dollars per kWh, contingent on technology and nation (IRENA, 2014). However, electricity prices often exclude the social and environmental costs of energy production (Shahsavari et al., 2019; Millstein et al., 2017; Kashtabeh et al., 2023). For instance, air pollution stemming from natural gas-based electricity generation incurs costs of around 0.74 billion dollars for EU nations; excluding these costs, the average electricity cost was 0.04 dollars per kWh in 2005. If external costs were accounted for, the cost of electricity generated from coal and natural gas would surge by 100% and 30%, respectively (WNA, 2019; EPA, 2023).

5.1. Transmission and distribution impacts

Centralized electricity production necessitates land for constructing and operating transmission lines. A substantial portion of the primary energy derived from fossil fuels is lost during production and transportation to end users. The power transmission lines and distribution infrastructure responsible for conveying electricity from power plants to consumers also impart environmental effects. These activities can influence native plant and wildlife populations. Most transmission lines employ large towers and aboveground cables, altering the visual landscape, particularly in undeveloped regions. Vegetation in proximity to power lines may undergo disturbance and require continuous management to prevent encroachment onto the lines (EPA, 2023). Furthermore, power lines can exert a notable adverse impact on airborne creatures; for instance, they can elevate bird mortality rates due to collisions.

Opportunities abound to augment the energy efficiency of power plants while concurrently exploring the feasibility of siting power generation facilities in proximity to end users. This approach holds the potential to curtail distribution expenses and mitigate losses sustained during electricity transmission. Rapidly advancing renewable energy technologies like onsite solar panels and small wind turbines are gaining prominence. These innovations empower electricity generation at or near the consumption point, thereby reducing losses inherent in conveying and distributing electricity via conventional power grids (Nieuwlaar, 2013).

6. CONCLUSION

As demonstrated in this study, renewable energies exhibit significantly lower environmental impacts and social costs when juxtaposed with non-renewable energies. Within the category of fossil fuels, coal and oil bear the greatest burden of social and environmental harm, while natural gas exhibits comparatively milder effects. In terms of implications for human health, nuclear energy and most renewables (excluding direct biomass combustion) present fewer health risks than fossil fuels. Coal- and heavy oil-fired steam power stations yield an average of 800-1000 g CO2/kWh, whereas wind turbines and PV cells release approximately 0.05 times the CO_2 emissions of fossil fuel plants. In the realm of environmental impacts, negative repercussions primarily stem from land requirements and raw material extraction for RETs. The social costs tied to RETs predominantly emanate from equipment production, facility construction, and infrastructure development.

Largely, energy prices fail to accurately encompass genuine social and environmental costs. However, addressing climate change necessitates accounting for the expense of curbing harmful atmospheric emissions. The body of research in this field underscores the significance of reducing the portion of conventional fuels, especially coal, in the global energy mix. Such reduction not only mitigates the energy sector's impacts but also yields economic advantages.

With improvements in RETs and escalating concerns about climate change and pollution worldwide, an incremental shift toward renewable energies is anticipated. Concurrently, a more precise assessment of the external costs linked to fossil fuels will contribute to advancing renewables. The external costs associated with conventional sources are substantial enough to prompt policymakers to internalize these expenses, rendering clean energies competitive alternatives. By factoring in environmental costs into energy pricing, electricity generated from coal becomes costlier and less efficient compared to RETs. While RETs may not entirely supplant carbon-intensive energy sources in the immediate future, the growing affordability of wind turbines and PV cells will restrain emissions and expand the share of pollution-free energy.

Achieving a global energy mix with a 36% contribution from renewable technologies by 2030 could lead to annual savings totaling $230 billion. The trend toward phasing out fossil fuel subsidies and the decreasing cost of RETs will encourage countries to transition toward renewables. In Iran, Article 50 of the 6th Development Plan mandates the government to elevate the share of renewable power plants to at least 5% of the country's total capacity by the program's conclusion. Consequently, it becomes imperative to comprehensively integrate renewable energies into Iran's development agendas in alignment with existing legal provisions. Embracing renewable energy sources as viable substitutes for fossil fuels offers the potential to mitigate deforestation and vegetation clearance, thereby curbing and preventing desertification.

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