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Review of Environmental and Socio-Economic Implications of Renewable Energy Technologies and Their Hidden Ecological Impacts

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Abstract

Renewable energy technologies offer a clean and sustainable solution, minimizing environmental harm, waste production, and ensuring long-term economic and social viability. However, some of these renewable energies are associated with hazardous substances which substantially affect the environment. This present study explores the environmental and socio-economic implications of renewable energy technologies, highlighting that all energy sources have some environmental impact. The primary drawbacks of fossil fuel combustion and nuclear energy production are depletion of the ozone layer, global warming and greenhouse effect. Although considered environmentally friendly, renewable energy sources like wind, solar, biomass, hydro, geothermal, and tidal power still have some ecological effects. Impacts of solar, biomass, hydro, geothermal and tidal powers were described, their specific hazards and environment impacts identified. This review work shows that most of these renewable energies: solar, hydro, biomass and geothermal are associated with hazardous substances during production, usage and disposal such as emission of carcinogenic substances(Arsenic, Galium Arsenide etc.) and emission of toxic heavy metals and Sulphur dioxide which has a tremendous impact on our eco-system. Though renewable energy is thought to be harmless and intended to replace the fossil fuels, particularly petroleum, but based on this review work it has been discovered that materials used for renewable energy production and storage are mostly toxic in nature and affect eco-system. Therefore, caution should be observed in considering it as a viable energy alternative.

Keywords: Renewable energy, Environment, Impact, Energy Security, Photovoltaic cell

1. INTRODUCTION

Increase in air pollution in our cities due to vehicular emissions, growing worries about climate change and global warming, combined with rising oil costs, are moving interest toward research, development and commercialisation of renewable energies. Government initiatives, regulations, and investments supported the sector's growth, despite the global financial downturn. The International Energy Agency forecasted in 2014 that solar power could account for approximately 30% of global electricity generation by 2050, significantly decreasing environmentally harmful greenhouse gas emissions (Holechek et al., 2022). The proponents of renewable energy left no stone unturned in marketing their products but just like the usual characteristics of a marketer failed to look at the consequences of transiting from non-renewable to renewable energy sources. They emphasized more benefits such as the creation of new jobs, reduction in greenhouse gas emissions etc to justify their campaign for legislation and policy toward renewable energy development. Energy sources mostly used are fossil fuels: oil, coal, and natural gas which supply about 81 % of the world's commercially traded energy, while nuclear energy from uranium contributes about 5 %. These forms of sources of energy are known as non-renewable with a total contribution of 86 % of the global energy mix. Out of the 86 % non-renewable energy source supplies, coal accounts for 27 %, oil 32 %, and natural gas supplies about 22 %. The remaining is being supplied by renewable energy options like biofuels, sunlight, water power, geothermal, and tidal waves (IEA, 2017). The non-renewable energy challenges such as climate change and global warming concerns make renewable energy a better option, but recent studies indicated that even renewable energy has a lot of challenges concerning health, safety, and the environment. Renewable energy is dependent on the fossil fuel-based economy; hence increase in the production of equipment and devices for renewable energy will lead to a large increase in mining activities which are associated with the release of hazardous/toxic substances into the environment.

2. PRIMARY ENERGY MIX

In Nigeria, conventional biomass and agricultural waste meet approximately 74% of the country's primary energy needs (Ebisi, 2024). This energy demand is predominantly driven by heating and cooking requirements in rural regions, where utilisation of LPG cooking gas and electrical heating is not available. The IEA (2017) reports that as of 2017, 74 million people relies on biomass mostly firewood for their energy need. According to estimates, indoor air pollution resulting from biomass burning claimed the lives of approximately 64,586 individuals in 2016 alone (IHME 2017). Figure 1 illustrates Nigeria's primary energy composition.

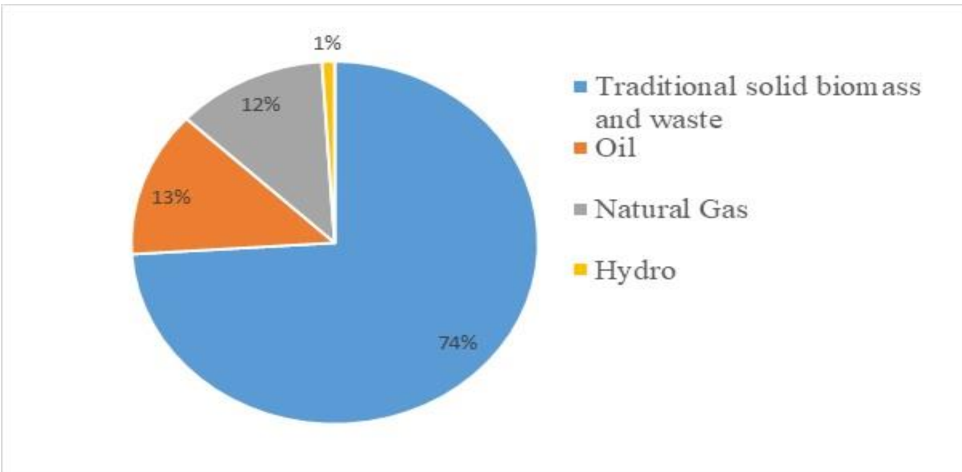

Figure 1: Primary Energy Mix of Nigeria Source: IEA (2017)

2.1 Solar Energy

Solar energy is the sun's radiant light and heat, which can be captured using a variety of advancing technologies: solar concentration process and photovoltaic cells (Ajarostaghi & Mousavi, 2022). Utilizing N-type and P-type semiconductor materials, photovoltaic (PV) cells convert sunlight directly into usable energy through the photovoltaic effect (Rathore et al., 2021). Solar panels can convert most visible light, and roughly half of ultraviolet and infrared light, into usable energy. Solar cell efficiency is limited by physics of semi-conductors which requires minimum energy required for a photon to free an electron from a crystal structure, also known as the bandgap energy. Silicon has a band-gap energy of 1.12 electron volts. Since sunlight contains a broad energy spectrum, some photons lack sufficient energy to release electrons in silicon photovoltaic cells (Dhobi, 2021). Moreover, excess energy from absorbed photons is converted into heat, rather than usable energy. Due to these limitations, the theoretical maximum efficiency of silicon solar cells is around 33%, with actual efficiencies typically below 20%.

2.1.1 Life-Cycle Global Warming Emissions from Solar Cell Manufacture

Silicon, derived from quartz, is the main material used for solar cell production. To make silicon usable, quartz is mined and heated in a furnace, releasing sulfur dioxide and carbon dioxide into the atmosphere. The following are the most common chemicals involved in commercial solar cell manufacture: Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), Ethylene Vinyl Acetate EVA, Potassium hydroxide, Nitric acid, Hydrofluoric acid (Chen, 2018; Jordan & Kurtz, 2018). The solar cell manufacturing process consists of several steps: silicon purification, single-crystal silicon formation, silicon wafer production, additional purification, polishing, doping, electrical contact placement, placing of thin strips, anti-reflective coating, and encapsulating the cell. Solar cells come in two forms: rigid crystalline structures (like Si and GaAs) and flexible thin-film cells (like Si, CdTe, and CIGS). Although solar energy itself produces no greenhouse gas emissions, other stages of the solar panel lifecycle do, including production, transportation, installation, maintenance, and end-of-life disposal and recycling. The solar panel manufacturing process often involves highly potent greenhouse gases, including Sulphur hexafluoride (SF6). With a global warming potential 22,800 times higher than carbon dioxide, SF6 is the most potent greenhouse gas known, making it a significant contributor to climate change. Nitrogen trifluoride NF_3 is another chemical used in the manufacture of solar panels and it is 17000 times more potent than carbon dioxide. Although manufacturers implement measures to contain these harmful gases in their production lines, any accidental release can have devastating environmental consequences. Table 1 highlights the global warming potential of various major greenhouse gases associated with solar panel manufacture. Recent studies in the US have indicated that the production of solar panels is a significant source of nitrogen trifluoride (NF_3) emissions, by 1,057 per cent over the last 25 years (Liu et al., 2024).

Table 1: Global warming potentials of major greenhouse gases from solar panels manufacture.

Species	Chemical formula	Global Warming Potential (100 years)
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
Carbon Tetrachloride	CCl_4	1730
Hexaflouroethane	C_2F_6	12200
Nitrogen Triflouride	NF_3	17200
Sulfur Hexaflouride	SF_6	22800

Besides emitting greenhouse gases, the production of solar panels also generates hazardous by-products that pollute the environment (especially water). For example; for each ton of polysilicon produced, four tons of silicon tetrachloride, a substance that can contaminate topsoil is produced. There are numerous other chemicals involved in solar panel manufacture that are hazardous as shown in Table 2.

Table 2: Hazardous chemicals in photovoltaic cell manufacturing (Ren et al., 2022).

Material	Source	Critical Effects
Acetone	Wafer cleaning	CNS, irritant
Antimony	Coating	Lung, heart, gastrointestinal
Arsenic	dopant	Carcinogen and mutagen.
Boron	dopant	CNS, irritant
Cadmium Chloride ($CdCl_2$)	$CdCl_2$ treatment	Teratogen
Cadmium Sulfide (CdS)	CdS deposition	Kidney, Pulmonary System
Cadmium Telluride (CdTe)	CdTe deposition	CNS, cancer, kidney, liver
Carbon Tetrachloride	Etchant	Liver, cancer, greenhouse gas
Chloro-Silanes	a-Si, x-Si deposition	Irritant
Copper Indium Galium Selenide (CIGS)	CIS deposition	Pulmonary, bone, GI
Diborane	a-Si dopant	Pulmonary, CNS
Galium Arsenide (GaAs)	GaAs Chemical Vapour Deposition	Cancer, lung, kidney
Germanium	a-Si dopant	Blood, CNS, Kidney
Hexaflouroethane	Etchant	Irritant, burns, dizziness
Hydrogen Sulfide	CIS Sputtering	Irritant, CNS, flammable
Lead	soldering	Toxic by ingestion or inhalation of dust or fumes.

*CNS - Central nervous system, *RS - respiratory system, *GI - Gastro intestinal.

2.2 Wind Energy

A wind turbine is a device that harnesses the kinetic energy of the wind and transforms it into rotational mechanical energy, which is then converted into electricity. Wind turbines are installed in large numbers in areas of favourable wind production forming what is known as wind farms. To generate substantial electricity for a large population, numerous wind turbines are interconnected. A typical wind turbine comprises three main components: the tower, the nacelle, and the rotor blades. A wind turbine requires consistent air with a speed greater than 15.5 miles per hour (25 kilometres per hour) and has an actual efficiency of about 30% (Samberg et al., 2020). Although wind turbines offer a renewable energy source, they also have environmental drawbacks. Concerns include their visual impact, particularly when large wind farms are built near untouched natural areas. Additionally, wind turbines can pose a threat to bird populations and generate significant noise pollution from their rotating blades. Other challenges include; intermittency and safety at sea if installed offshore (Nazir et al., 2022).

2.3 Geothermal energy

This is a type of energy that originates from the thermal energy from within the Earth due to the geothermal gradient. The geothermal gradient refers to the rate at which the Earth's temperature increases with depth. The Earth's internal heat is primarily generated by two sources: residual heat from the planet's formation (20%) and heat produced by radioactive decay (80%). The main isotopes responsible for this heat production are potassium-40, uranium-238, uranium-235, and thorium-232 (Anakoli, 2020). In dry steam power plants, steam produced underground is piped directly to the power plant, where it drives a turbine/generator unit. Flash steam power plants are the most common type and use geothermal reservoirs of water with temperatures greater than 360°F (182°C). The hot water flows up through wells under its pressure, boiling into steam as pressure decreases. The steam is then separated from the water and used to power a turbine/generator, with leftover water and condensed steam injected back into the reservoir (Mahmoud et al., 2024). These plants use the heat from the hot water to boil a working fluid, usually an organic compound with a low boiling point. The working fluid is vaporized in a heat exchanger and used to turn a turbine. The water is then injected back into the ground to be reheated, with little to no air emissions. While geothermal energy offers a renewable source of power, there are significant upfront costs associated with building geothermal power plants and heating/cooling systems. Geothermal power is considered renewable only if the reservoirs are managed sustainably, ensuring their long-term viability (Lennax, 2023). Geothermal power is associated with minor environmental issues, including the potential to trigger earthquakes in extreme cases, particularly during hydraulic fracturing in Enhanced Geothermal Systems (EGS).

2.4 Hydroelectric energy

Hydroelectric power harnesses the gravitational potential of elevated water, which is lifted from oceans by sunlight. However, its renewability is limited, as reservoirs eventually fill up and require costly excavation to be restored. Moreover, in the developed world, the most suitable locations for hydroelectric dams are already being utilized.

2.5 Biomass

Biomass energy refers to energy derived from plants. While it is a widely used energy source globally, the most common method of utilizing biomass energy - burning trees for cooking and warmth - releases significant amounts of carbon dioxide and contributes to poor air quality. More modern and efficient forms of biomass energy include biogas production and the manufacture of alcohol for use as automotive fuel and power electric plants. Another significant contribution of biomass to energy production is in biodiesel production from vegetable oils to replace diesel from crude oil. Biomass and biofuels derived from biomass offer alternative energy sources to fossil fuels. Although burning biomass releases carbon dioxide (CO_2), a greenhouse gas, the plants used to produce biomass absorb a similar amount of CO_2 through photosynthesis during their growth, making biomass a potentially carbon-neutral energy source. Replacing fossil fuels with wood, wood pellets, and charcoal for heating and cooking can lead to lower overall CO_2 emissions. However, wood smoke contains harmful pollutants like carbon monoxide and particulate matter, which can be mitigated by using modern wood-burning stoves that reduce particulate emissions. In developing countries, wood and charcoal are primary fuels for cooking and heating, but unsustainable harvesting practices can lead to deforestation. Furthermore, burning municipal solid waste can produce ash containing high levels of toxic metals, such as lead and cadmium, which originate from waste materials like textile dyes, printing inks, and ceramics (Dilthey, 2018). Biofuels have the potential to be carbon-neutral, as the plants used to produce them, such as corn, sugarcane, soybeans, and oil palm trees, absorb CO_2 during their growth, which can offset the emissions released during biofuel production and combustion. However, the cultivation of biofuel crops is a contentious issue, as it competes with food production for land, fertilizers, and energy. Furthermore, widespread deforestation and clearance of natural vegetation have occurred in some regions to make way for biofuel crops, such as sugarcane, soybeans, and oil palm trees (Tudge et al., 2021).

Bioethanol produced from starch-rich crops like maize and wheat, as well as sugar crops like sugarcane and sugar beets, is the dominant contributor to global biofuel production. As a result, bioethanol represents the largest renewable energy source in the transportation sector. The cost of biofuels is still high compared to petroleum products. Ethanol and ethanol-gasoline blends offer cleaner combustion and higher-octane ratings compared to pure gasoline. However, they also result in higher evaporative emissions from fuel tanks and equipment, contributing to ground-level ozone and smog formation. To mitigate this, gasoline must undergo additional processing before being blended with ethanol. On the other hand, biodiesel combustion has several environmental benefits, including reduced emissions of sulphur oxides, particulate matter, carbon monoxide, and unburned hydrocarbons. Nevertheless, biodiesel does produce more nitrogen oxide emissions than conventional petroleum diesel. Biomass, a renewable energy source derived from plant matter, can still cause significant environmental harm despite its renewable nature.

2.5.1 Hydrogen and Fuel Cells

Hydrogen gotten from biogas is used as fuel and in fuel cells. Hydrogen has the potential to be a clean-burning fuel, producing only water as a combustion byproduct when burned in a vehicle or used in fuel cells to power an electric motor. This could significantly reduce urban pollution. However, large-scale hydrogen production requires substantial amounts of energy, which can lead to the relocation of pollution from cities to power plants, rather than a complete elimination of pollution (Woźniak et al., 2021).

2.6 Tidal power

Tidal waves is a source of renewable energy related to local geological conditions; the use of tidal sources is limited by geographic location.

2.7 Energy security

The International Energy Agency IEA defines energy security as “the uninterrupted availability of energy sources at an affordable price”. Energy security encompasses multiple dimensions, including long-term energy security, which involves timely investments to meet future energy demands while addressing economic and environmental sustainability, and short-term energy security, which focuses on the energy system's ability to respond promptly to sudden supply-demand imbalances. Ultimately, the core of energy security is providing a reliable supply of sustainable and resilient energy at a reasonable price, and predictable stable demand that will guarantee economy stability of both the consuming and the producing nations. In light of this, energy security to consuming industrialized nations could even mean energy insecurity for producing less developing nations like Nigeria. While many developed nations embarked on renewable energy programs with stated objective to safeguard the environment, the real motive could be to increase energy security. Most governments’ strategies on energy security focus on mitigating risks to energy supply (Axon & Darton, 2021) such as:

i. Market fluctuations
ii. Infrastructure disruptions and equipment failures
iii. Physical security threats encompassing a range of potential disruptions, including conflicts, terrorism, extreme weather events, and infrastructure overload. Additionally, centralized power generation, transmission, and distribution systems, as well as gas pipelines, are vulnerable to intentional attacks. Global oil supply restrictions resulting from political actions also pose a significant threat to energy security.

A lot of opinions by renewable energy proponents, energy experts, economists and environmental scientists point to the fact that transition from fossil-based energy sources to renewable sources could lead to increase in energy security (Kabeyi & Olanrewaju, 2022). However, Hache (2018) predicted a more complicated relationship among nations having abundance raw material for renewable energy and those without. The new challenges induced by energy transition policies could paradoxically turn out being as complex as today's geopolitics of energy”.

3. CAN RENEWABLE ENERGY SOURCES REPLACE FOSSIL FUELS?

These phenomena call for urgent action to stop the release of greenhouse gases which results in global warming. Part of the measures taken by the world's leading industrialised nations is to embark on programs and policies leading to the replacement of fossil fuels with renewable sources of energy (Kumar et al., 2023). A lot of predictions have been made about the possibility of replacing fossil fuels with renewable energy; most of them are based on the successes recorded in increasing efficiencies and lowering the cost of renewable technologies in the last ten years. Most developed countries set a target of 2050 to either completely replace fossil fuels or reduce it to a very small percentage of their total energy need. Transitioning to renewable energy is more complex than it's often portrayed by companies' chief executives and politicians; it is indeed quite the opposite. While it's widely assumed that switching from fossil fuels to renewable energy sources can solve greenhouse gas and energy issues, the limitations and constraints of renewable energy are often overlooked. Proponents of renewable energy technologies tend to focus on the potential benefits, making optimistic claims about their capabilities, while downplaying the difficulties and hurdles associated with a large-scale transition. Apart from technological limitations, the intermittency of some renewable sources such as wind and solar posed a serious challenge. Wind turbines are idle on calm days, while solar panels generate no electricity at night, necessitating the continued operation of conventional power plants as a backup to ensure a stable energy supply. Adopting biomass sources would threaten food security because of the enormous land required and may also cause serious damage to the ecosystem (Hache, 2018). Projections indicate that global energy demand will surge by approximately 30% by 2035. Furthermore, it's crucial to acknowledge the substantial energy access gap, with over 1.2 billion people worldwide still lacking electricity. As the global population is expected to swell to nine billion over the next five decades, energy demands will inevitably rise in tandem, placing unprecedented pressure on the world's energy systems. This may counter the growth of renewable energy and make such replacement a mirage. The world's total annual energy demand stands at approximately 400 quadrillion BTUs, with fossil fuels - oil, coal, and natural gas - accounting for around 81% (325 quadrillion BTUs) of this demand. Oil is the largest contributor, providing 32% of the world's total energy, followed by coal at 27%, and natural gas at 22%. Looking ahead, global energy consumption is projected to rise by 50% by 2020, adding 200 quadrillion BTUs to the demand (IEA, 2017). Renewable energy sources are unlikely to be able to meet this increasing demand.

4. APPLICATION OF GREEN CHEMISTRY IN FOSSIL FUEL PROCESSING AND UTILIZATION AS ALTERNATIVE TO RENEWABLE ENERGY

Green chemistry, also known as sustainable chemistry, is an approach that aims to design chemical products and processes that reduce or eliminate the use and generation of hazardous substances. It encompasses the entire lifecycle of a chemical product, from design and manufacture to use and disposal. To achieve this, 12 key principles have been established, including: preventing waste, maximising atom economy, designing less hazardous chemical syntheses, designing safer chemicals and products, using safer solvents and reaction conditions, increasing energy efficiency, using renewable feedstocks, avoiding chemical derivatives, use catalysts instead of stoichiometric reagents, design chemicals and products to degrade after use, analyze in real-time to prevent pollution, and minimize the potential for accidents. Sustainable and green chemistry is essentially a mindset shift in how chemistry and chemical engineering can be harnessed to protect the planet. It's about adopting innovative approaches to design, develop, and implement chemical products and processes that prioritize the well-being of people, the economy, and the environment. By embracing these principles, scientists and engineers can creatively reduce waste, conserve energy, and replace hazardous substances, ultimately benefiting both humanity and the planet.

5. CONCLUSION

The potential of renewable energy as a substitute to fossil fuels have been identified and the technological and cost limitations were enumerated together with the environmental effects associated with transiting from non-renewable to renewable energy sources. Most of the renewable energies: solar, hydro, biomass and geothermal are associated with hazardous substances during production, usage and disposal which has a tremendous impact on our eco-system. Though, there is a substantial benefit of using renewable energy sources in terms of greenhouse gases emission, this may not provide the needed energy security for countries like Nigeria. There is need to clearly distinguish the objective of embarking on renewable energy programs; either for energy security or for the purpose of protecting our planet. This present study identified the need for a country endowed with vast hydrocarbon resources to focus on the use of green chemistry while exploiting them. Formulation of an optimum energy mix for Nigeria would provide energy security and safeguard the environment.

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