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Challenges in Energy Transition from Fossil Fuel to Clean Energy

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Abstract

The use of fossil fuels has led to global warming and air pollution, the transition from fossil fuel to clean energy is necessary for human society to achieve sustainable development. But there are challenges in the transition from fossil fuels to clean energy: 1) Fossil fuels remain the primary energy for most countries, more than 80% of primary energy consumption come from the use of fossil fuels; 2) Upfront cost and intermittence are shortcomings that influence the large-scale application of renewable energy, hydrogen is not yet fully mature in terms of technology and economy; 3) Continuous deforestation reduces the capability of the environment to turn CO_2 into wood and leads to the rise of atmospheric concentration of greenhouse gases; and 4) Overpopulation and continuous growth of human population in developing countries cause the continuous increase of fossil fuel use and deforestation. If people do not take effective policies to get out of this predicament, global warming and air pollution will continue and become worse.

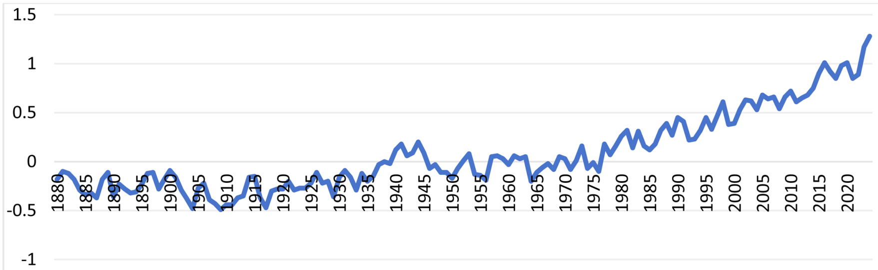
Keywords

Fossil Fuels, Renewable Energy, Deforestation, Overpopulation

1. Introduction

Since the Industrial Revolution in the 18th century, human induced atmospheric CO_2 concentration has increased by 50%, the carbon dioxide in the atmosphere is 1.5 times that of 1750. Global mean surface temperature (GMST) has been rising faster since the Industrial Revolution, observed events showed that human activities are the main cause that has driven the rise of GMST. The GMST in 2024 was 1.17˚C, the warmest year on record since 1880. It is warmer than that in 1880 by 1.46˚C [1]. **Figure 1** is GMST from 1880 to 2024 [1]. We can see that the trend of GMST is rising slowly, it fluctuates gradually upward.

Heat waves, wildfires and hurricanes are becoming common, extreme weathers lead to annual loss of billions of dollars in the United States. There have been 400 weather and climate disasters since 1980 in the United States, these events led to 16,768 deaths. The loss of each event exceeds $1 billion, the total loss of the 400 events exceeds $2.785 trillion [2]. The global total loss from extreme weather was $2.86 trillion from 2000 to 2019, about $143 billion per year [3]. Driven by global warming and El Niño weather pattern, GMST will be higher than 1.5˚C in the next few years, but lower than 2˚C [4].



Sources: GISS surface temperature analysis (GISTEMP v4).

Figure 1. Global mean surface temperature in degrees celsius 1880-2024.

Air pollution has become the second risk factor for death after high blood pressure due to the continuous increase in fossil fuel use. In 2021, air pollution contributed to 8.1 million deaths, accounting for more than one eighth of the death toll worldwide. Of which, 58% deaths are from ambient PM2.5, 38% deaths from household air pollution, 6% deaths from ozone [5]. The number of estimated annual global death was 8.34 million due to fine particulate matter and ozone air pollution, 5.13 million people died each year from ambient air pollution from fossil fuel use, which can be avoided by phasing out fossil fuels [6]. The use of fossil fuels is responsible for 20% premature deaths across the world, fossil fuel pollution has brought about premature birth, impaired fetal growth, asthma, respiratory and cardiovascular disease. Fossil fuel pollution will lead to the extinction of one-third of wildlife in the coming 50 years. The by-products of fossil fuels pose a threat to children's health, climate change leads to a decline in children's adaptability, causing global inequality and environmental injustice [7].

2. Challenges in Energy Transition from Fossil Fuels to Clean Energy

2.1. Fossil Fuels Remain the Primary Energy for Most Countries

Transition from fossil fuel to clean energy is the key to addressing global warming and air pollution, however, the transition has been progressing slowly. Fossil fuels accounted for more than 80% of primary energy consumption in China, the United States and India in 2023, and this is also the case in most developing countries. Global fossil fuel consumption in 2023 accounted for 81.29% of total primary energy consumption, the consumption of hydroelectric and other renewable energy accounted for only 14.68%, nuclear power accounted for 4.03% [8]. In 2019, the burning of fossil fuels accounted for 74% of greenhouse emissions in the United States [9]. Obviously, in China, the proportion of fossil fuel emissions is higher.

Energy consumption by fuel in 2023 in the United States, China, India, and OECD countries are presented in **Table 1**, the shares and growth rates of energy consumption are presented in **Table 2** [8]. We can see that the sum of primary energy consumption in China, India, and OECD countries in 2023 was 439.66 Exajoules, accounting for 71% of the world total.

Table 1. Primary energy consumption by fuel in the Unites States, China, India, and OECD countries in 2023 (Units: Exajoules).

country	oil	gas	coal	nuclear energy	Hydro electricity	other renewable energy	Total
Unites States	35.86	31.91	8.20	7.32	2.21	8.78	94.28
China	32.73	14.57	91.94	3.90	11.46	16.13	170.74
India	10.57	2.25	21.98	0.43	1.39	2.38	39.02
OECD countries	87.15	63.25	25.15	16.44	12.96	24.96	229.90

The consumption of fossil fuels in OECD countries was 175.55 Exajoules in 2023, it is 180.87 Exajoules in 2022, dropped by 2.94%. The consumption of fossil fuels in the non-OECD countries in 2023 was 329.28 Exajoules, it is 316.59 Exajoules in 2022, increased by 4.01%. Growth rate of primary energy consumption in OECD countries in 2023 was −1.56%, but it was 4.26% in the non-OECD countries [8].

Table 2. Growth rate and share of primary energy consumption in the Unites States, China, India, and OECD countries in 2023 (Units: %).

country	consumption in 2023 (Units: Exajoules)	growth rate in 2023 (%)	annual growth rate during 2013-2023 (%)	share in the world in 2023 (%)
Unites States	94.28	−1.2	0.2	15.2
China	170.74	6.5	3.4	27.6
India	39.02	7.3	4.2	6.3
OECD countries	229.90	−1.6	−0.2	37.1

CO_2 is an important heat-trapping gas, atmospheric CO_2 concentration has been rising since the industrial revolution in the 18th century. The atmospheric CO_2 concentration in March 1958 was 315.71 ppm, and 425.38 ppm in March 2024. Thus, it has increased by 109.67 ppm, an increase of 34.74% [10]. Human-induced increase of atmospheric carbon dioxide is greater than that from the natural environment, 50% increase of carbon dioxide concentration in the air is brought about by humans since 1750 [10]. Power industry was the biggest contributor to global CO_2 emissions in 2023, it accounted for 38.24% of the world total. The second contributor was transportation industry, accounting for 21.11% of the world total [11].

The top three countries of primary energy consumption in 2023 were China, the United States and India, they accounted for 27.6%, 15.2%, and 6.3% of the world total respectively. Their growth rate of energy consumption in 2023 was 6.5%, −1.2%, and 7.3% respectively. The consumption of fossil fuels accounted for 81.55% of primary energy in China, 80.58% in the United State, and 89.19% in India. The consumption of renewable energy accounted for 16.16% of primary energy in China, 10.6% in the United States, and 9.66% in India [8]. Thus, fossil fuels remain the major energy in most countries, it's just that renewable energy grows rapidly.

2.2. Shortcomings of Renewable Energy

The cost of generating electricity from renewable sources is not high, but it is expensive preparing the infrastructures for the use of renewable sources. It takes time and financial resources to get everything up and running, the initial cost of putting the infrastructure in place is high. Thus, there are high upfront costs in the transition from fossil fuels to renewable energy. A wind turbine in wind farms can generate 2 - 3 MW of electricity at a cost of $2.5 million - $4 million. The largest wind turbine in wind farms can generate 12 MW of electricity, and it costs tens of millions of dollars [12]. The average cost of a 5 kW solar panel system in the United States is $14,210 in 2024, a typical household needs 10kW to power their home, which is $28,241. The cost can drop to $19,873 considering the federal solar tax credit [13].

The cost of hydro power ranges from $1500 - $5500 per kilowatt, which depends on project scale, site conditions, regional construction expenses. The cost of hydro power from small plants ranges from $1000 - $2000 per kilowatt [14]. There is substantial initial investment in building a hydro power plant including cost for dams, reservoirs, turbines, transmission lines. The initial investment of a large hydro power plant ranges from $2 billion - $10 billion, and the cost ranges from $2000 - $5000 per kilowatt [14].

Wind turbines cannot generate electricity if there is no wind, thus, wind farms should be located in open places where there are strong winds of moderate to high intensity. Solar cells generate little electricity if it is cloudy, thus, solar power farms should be located in places where the sun shines most of the year. Hydro power is susceptible to droughts, thus, hydro power plants should be located in places where there are rivers and flowing water. Thus, renewable energy generation is environment-dependant or weather-dependent. Due to the influence of weather and geography, renewable energy is intermittent and unreliable, we need some measures to solve intermittence of renewable energy.

One way to solve the problem is to have batteries that can store electricity on a large scale. Batteries store electricity during peak generation periods, and release electricity to power customers when renewable energy sources stop working. An-other approach is to produce hydrogen by renewable energy generation, use hydrogen as a fuel to drive machines, replacing fossil fuels with hydrogen. Hydrogen and oxygen undergo a chemical reaction, burning and generating water. Hydrogen is a clean energy, there is no pollution. Thus, we need batteries or hydrogen to make up for the shortcomings of renewable energy.

Table 3 is renewable energy generation by source in the Unites States, China, India, and OECD countries in 2023. The sum of renewable energy generation in the United States, China, and India was 4249.8 terawatt-hours in 2023, accounting for 47.28% of the world total. Table 4 is renewable energy consumption in the Unites States, China, India, and OECD countries in 2023. The sum of renewable energy consumption in the Unites States, China, and India was 42.37 Exajoules in 2023, accounting for 47% of the world total. In 2023, the consumption of renewable energy was 37.91 Exajoules in the OECD countries, 52.32 Exajoules in the non-OECD countries, and their annual growth rate was 3.72% and 6.3% respectively [8].

Table 3. Renewable energy generation by source in the Unites States, China, India, and OECD countries in 2023 (Units: Terawatt-hours).

country	wind power	solar power	hydro power	other renewable energy	total	growth rate in 2023 (%)	share of the world (%)
Unites States	429.5	240.5	236.3	67.3	973.7	0.5	10.83
China	885.9	584.2	1226.0	198.1	2894.1	8.4	32.2
India	82.1	113.4	149.2	37.3	382.0	0.9	4.25
OECD countries	1149.4	755.3	1385.5	385.9	3676.0	3.7	40.9

Sources: Statistical review of world energy, energy institute 2024.

Table 4. Renewable energy consumption in the Unites States, China, India, and OECD countries in 2023 (Units: Exajoules).

country	consumption in 2023 (Units: Exajoules)	growth rate in 2023 (%)	annual growth rate during 2013-2023 (%)	share of the world (%)
Unites States	10.99	2.0	5.2	12.2
China	27.60	8.0	9.7	30.6
India	3.78	1.0	7.1	4.2
OECD countries	37.91	3.7	4.1	42.0

Sources: Statistical review of world energy, energy institute 2024.

Hydrogen is extremely flammable, safety technology and measures are necessary for the entire industry from production and transportation to use. The lack of unified technical standards and certification procedures has brought difficulties to manufacturers, developers, and users. The cost of hydrogen is more expensive than natural gas, the performance of technical equipment used to produce hydrogen need to be improved, the efficiency of catalysts and manufacturing processes needs to be increased, and the cost of electrolytic cell technology needs to be reduced. In addition, hydrogen infrastructure needs to be integrated with existing energy systems. These problems should be solved in terms of technology and management.

The widespread of hydrogen energy faces difficulties: (1) the manufacture of hydrogen vehicles requires complex technology and expensive materials, such as platinum catalysts in fuel cells, (2) the production, storage and transportation costs of hydrogen are relatively high, and (3) the lack of infrastructure and supply chain services is an obstacle to the widespread application of hydrogen energy. For example, there were two kinds of hydrogen-powered cars in the United States in 2024, the Toyota Mirai and the Hyundai Nexo. The 2024 Toyota Mirai was $50,190, and the 2023 Hyundai Nexo was $60,135 [15]. The cost of the fuel for a hydrogen vehicle is 3 times higher per mile than a gasoline hybrid vehicle, and 2 times higher than a gasoline vehicle [16]. The average cost of a new car was $48,759 in 2023, but the highest price that people would like to pay for a new car was $22,090 [17]. Thus, the sales of hydrogen-fueled vehicles have been hampered by high costs and inadequate infrastructure, but electric vehicles have been boosted by rapid decline in the cost of production and government support [15].

2.3. Continuous Deforestation

Trees absorb CO_2 through photosynthesis and releasing oxygen, reducing the amount of atmospheric CO_2. Trees also absorb harmful pollutants, such as sulfur dioxide, nitrogen oxide, improving air quality and reducing respiratory disease. Trees and forests provide shelter and nesting places for wildlife, and they are the sources of food for wildlife. Forests account for 20% of the global absorption of greenhouse gases, providing 21% of global oxygen supply [18], they are second only to phytoplankton of the oceans as sources of oxygen. Trees and forests are the foundation of biodiversity and healthy ecosystems, playing a vital role in combating global warming and air pollution. Thus, it is crucial for oxygen production and environmental protection to preserve and protect trees and forests.

Continuous deforestation is one of the causes that lead to the rise of atmospheric concentration of greenhouse gases and global warming. When trees are cut down, part of the carbon were emitted into the air, 10% - 20% of carbon are lost due to logging, 10% - 30% of carbon are lost due to fire [19]. The tropical deforestation was responsible for 2.6 billion tonnes of CO_2 emissions per year from 2010 to 2014, it accounted for 6.5% of global CO_2 emissions. 23% of CO_2 emission are driven by export in Latin America, 44% in Indonesia and Malaysia, and 9% in Africa [20]. International trade was responsible for 29% of CO_2 emissions and accelerated global deforestation, crop planting accounted for 71% of global deforestation [19].

Tropical forests are the natural state for storing carbon and huge carbon warehouses [21], they are the richest and most diverse ecosystems, over half of the species of the world are in tropical forests [22]. When people cut down rainforest, they are destroying the habitats of the unique species in the tropical forests, leading to the loss of biodiversity [23].

Since the last ice age about 10,000 years ago, humans have cut down a third of the world's forests to grow crops and feed livestock, or to use them as fuel wood [20]. Half of global forest loss occurred from 8000 BCE to 1900 CE, the other half was lost in the 20th century. The rate of forest loss accelerated rapidly in the last few centuries. Most temperate forest across Europe and North America were cut down during 1700-1850, it's about 2,850 million hectares of forests [20]. 47% of France was covered by forests 1000 years ago, and now it's 31.4%. 46% of the United States was cover by forests in 1630, and now it's 34% [20]. 154 million hectares of tropical forests was cut down across the world in the decade of 1980s, the net loss was 102 million hectares with the regrowth of trees. The net loss of forests in 1990s was 78 million hectares, and it was 47 million hectares in 2010s [24]. 14% of forests in Africa were lost from 2009 to 2020, the annual global forest loss from 2010 to 2020 was 3.9 million hectares [25].

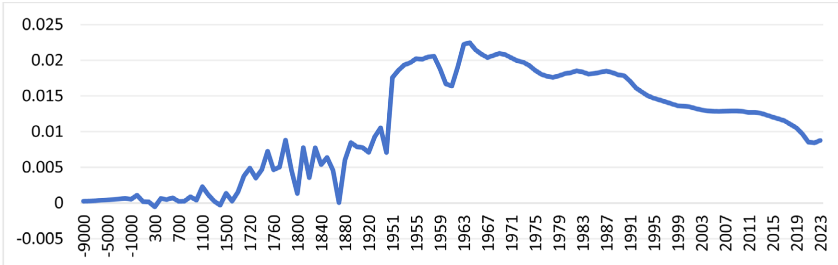
The rate of deforestation has halved in Asia and South America, although the pace has declined in recent ten-year periods, it is still a challenge for the world to halt deforestation. Global forests continue to shrink, 27% of global forest loss are driven by commodity and trade, urbanization accounts for 0.6% of forest loss. 90% of global deforestation take place in the tropics, of which, deforestation in both Brazil and Indonesia account for almost half. Agricultural expansion is responsible for 60% - 80% of tropical deforestation, which was driven by overpopulation and the need to sustain livelihoods [20].

2.4. Overpopulation and Environmental Degradation

Human population has grown faster since the Industrial Revolution, fossil fuel consumption continued to increase and forests continued to decrease. Over population has brought about global warming, air pollution and environmental degradation. Human population was 4.5 million in the year 10,000 BCE, it was 595.46 million in 1700, and 8091.74 million in 2023. The average annual growth rate of human population was 0.06% from 10,000 BCE to 1700, it was 1.36% from 1700 to 2023. Human population grew slowly from 10,000 BCE to 1700, but it became much faster from 1700 to 2023. The fastest period was from 1951 to 2019, with a growth rate of 1.76% [26]. The growth rate has slowed down since 2019. **Figure 2** is the average annual growth rate of global human population from 10,000 BCE to 2023 [26].

According to the researches of Berger and Loutre [27], there was a cooling trend in climate that began about 6000 years ago, it will continue for the next 23,000 years. However, human-induced increase of the concentration of greenhouse gases in the atmosphere has brought about a warmer climate, and this situation of warming climate will continue for many millennia [28]. Thus, the rise in global temperatures is abnormal and unnatural, caused mainly by the impact of overpopulation, fossil fuel use and deforestation. Their relationship is as follows:

$$\text{Overpopulation} \Rightarrow \begin{cases} \text{fossil fuel use} \\ \text{deforestation} \end{cases} \Rightarrow \begin{cases} \text{air pollution} \\ \text{global warming} \end{cases}$$



Data sources: Our world in data (2024a): population, 10,000 BCE to 2023.

Figure 2. Average annual growth rate of global human population from 10,000 BCE to 2023.

According to environmental ecology, the number of people living in a given area is limited, there is a maximum population size for a given environment. If the number of human population is more than the maximum value, the ecological balance will be disrupted, and there will be environmental degradation. Over the past few years, air quality in the United States declined, unhealthy air days increased by 38%. In 2024, people in the United States experienced the most very unhealthy and hazardous air days due to particle pollution [29]. Sub-Saharan Africa and South Asia have experienced the fastest population growth in recent decades, overpopulation exacerbated their poverty, the excessive exploitation of water and land has damaged the natural environment.

We conduct a regression between world human population (WHP) [26] and GMST [1], the output is presented in **Table 5**. We can see that there is a positive relationship between WHP and GMST, changes in WHP account for 89% of changes in GMST. t-Statistics are significant at the 0.05 confidence level, F-statistic is also significant.

Table 5. The regression output between WHP and GMST from 1880 to 2024.

Dependent variable: GMST		coefficient:	t-Statistic:	R-squared: 0.89
Independent variable:	constant (C)	−0.55	−26.31	F-statistic: 1163.91
	WHP	1.75E−10	34.12	D-W statistic: 0.81

Note: C is the intercept.

3. Discussion

Total solar irradiation is the primary force that shapes the Earth's climate, Earth's orbit and the Angle at which its axis tilts play a key role. Three types of Earth's orbital movements affect solar radiation entering the atmosphere, the cyclical orbital variations bring about changes of incoming solar radiation at the mid-latitudes by up to 25% [30]. The obliquity of Earth to the Sun ranges from 22.1 degree to 24.5 degree, it is currently 23.4 degrees, decreasing in a cycle that spans about 41,000 years. As the obliquity decreases, winters become warmer and summers become cooler. Over time, ice and snow at high latitudes will accumulate into large ice sheets. As the ice sheet grows, it reflects more and more solar energy back into space, promoting further cooling [30].

The average total solar irradiance reaching to Earth from the Sun was 1361.07 W/m^2 from 2000 to 2025, it changes little during an 11-year solar cycle. During the period of 2000-2025, the maximum value of total solar irradiance is 1362.95 W/m^2, and the minimum value is 1357.92 W/m^2 [31]. The averaged change in total solar irradiance between pre-industrial and 2019 is 0.06 W/m^2. The average total solar brightness varies by up to 1 W/m^2 during strong solar cycles, with an impact of 0.1˚C or less on global surface temperature, making a relative small contribution to global warming [32].

Atmospheric circulation and ocean current circulation are important factors that affect climate, they drive the change of global climate by redistributing heat and moisture. For example, there are more land masses in the Northern Hemisphere, and seasonal changes are distinctive in the middle and high latitudes. The majority of the Southern Hemisphere is covered by ocean, which makes seasonal temperature variation smaller. Driven by global anthropogenic forcing and rapid rising in sea surface temperature in tropical Indian Ocean, tropical Atlantic, North Atlantic, and subtropical North Pacific, GMST reaches a new high in 2023 [33].

The increase in global surface temperature from the rising concentration of greenhouse gases exceeds the level of a strong Grand Solar Minimum, and postpones the Milankovitch-driven ice age by tens of thousands of years [32]. There was a strong relationship between GMST and CO_2 in the air, which confirms that CO_2 is the dominant driver for current global warming [34]. Increasing consumption of fossil fuels, overpopulation, and deforestation are the main causes for the rising concentration of CO_2 in the air and air pollution.

Average CO_2 concentration in the air from 1750 to 1850 is 280 ppm [35], it is 315 ppm in 1958, and 427 ppm in February 2025 [36]. Overpopulation has brought about the rise of carbon dioxide concentration by 1.67 ppm per year since 1958. If atmospheric carbon dioxide levels remain above 300 ppm, the next ice age predicted by the theory of Milankovitch is unlikely to occur in 50,000 years. If CO_2 concentration exceeds 350 ppm, GMST is likely to exceed pre-industrial levels by 2˚C, which will bring about: 1) cooling of the Southern Ocean, 2) slowing down of the overturning circulation of the Southern Ocean, 3) slowdown and eventually shutdown of the Atlantic overturning circulation, 4) increasingly powerful storms, and 5) rising sea levels of several meters over 50 - 150 years [37].

We conduct Granger Causality test between GMST and global atmospheric carbon dioxide concentration (GACDC), the output is presented in **Table 6**. The data of GMST are from NASA [1], the data of GACDC are from NOAA [38] [39]. We can see that GACDC is the Granger cause for GAST, while GAST is not the

Granger cause for GACDC. We also conduct a regression analysis between GMST and GACDC, the output is presented in **Table 7**. We can see that changes in GACDC account for 92% of changes in GMST, t values and F value are all significant at 5% confidence level.

Table 6. Granger causality test between GMST and GACDC.

Null Hypothesis	Obs	F-Statistic	Prob.
GMST does not Granger Cause GACDC	118	0.48	0.62
GACDC does not Granger Cause GMST	118	18.45	1E−07

Table 7. Regression output between GMST and GACDC.

Dependent variable: GMST		coefficient:	t-Statistic:	R-square: 0.92
Independent variable:	constant (C)	−3.35	−35.75	F-statistic: 1398.14
	GACDC	0.01	37.39	D-W stat: 1.2

Note: C is the intercept.

4. Conclusions

The phasing out of fossil fuels is considered an effective way to improve health and save lives, if fossil fuels are replaced by clean energy, ambient air pollution will no longer be a major environmental health risk factor. Reducing emissions of greenhouse gases and air pollution could reduce deaths by up to 82% [6]. Fossil fuels are running out, we have 139 years in coal deposits at the current usage rate, 56 years in oil deposits, and 49 years in gas deposit [40].

Deforestation is serious across the world since the Industry Revolution, in 2021, more than 140 countries pledged to halt and reverse forest loss and environmental degradation by 2030. But in 2022, deforestation increased by 4% worldwide compared with 2021, and 66,000 square kilometers of forests were destroyed [41]. Global deforestation is exacerbated by crop cultivation, cattle grazing, and international trade.

Developing countries have been the major emitters of greenhouse gases in recent decades, their emissions of greenhouse gases have been increasing due to overpopulation. In Asian cities, the levels of particulate matter, sulfur dioxide, nitrogen dioxide, and ozone in the air are higher, posing greater health risks than in Europe and North America [42]. for example, primary energy consumption in Asia Pacific area accounted for 47.1% of the world total with a growth rate of 4.7% in 2023 (Energy Institute, 2024). At the same time, CO_2 emissions in middle- and upper-income countries have been doubled since 2000 [43].

Fossil fuels are reliable, but they emit greenhouse gases that pollute the environment. Nuclear power is reliable, but it produces dangerous waste that is hard to dispose, renewable energy is not as reliable as fossil fuel, and supply chain hurdles are hindering their installation. Researches found that large scale renewable energy installations require more land than coal- or gas-fired power plants. No one source of energy is superior in every way, it is more practical to establish a multi-level energy supply system in developing countries, in which each energy is used to its full advantage, and its shortcoming is compensated by other energy.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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