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AIR EMISSIONS AND ENVIRONMENTAL CHALLENGES IN THE ENERGY INDUSTRY: A REVIEW

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ABSTRACT

The global energy sector, owing to the high complexity of its installations, technological processes, and the waste streams it generates, has a profound and multifaceted impact on the environment. Electric power generation influences ecosystems, alters local microclimatic conditions, and poses risks to human health. Conventional thermal energy production based on fossil fuels remains the most polluting source, whereas renewable energy technologies and nuclear power generally exhibit lower environmental footprints, though they may still involve indirect or long-term ecological effects. Pollutants originating from the energy sector contribute to the degradation of air, soil, and water quality, as well as to climate change and broader ecological imbalances. Patterns of energy production and consumption differ significantly among countries, reflecting disparities in resource availability, geographic characteristics, and policy frameworks. Despite the accelerating deployment of renewable energy, fossil fuels continue to dominate the energy mix in many regions of the world.

KEYWORDS: energy industry, pollution, climate change, fossil fuels, combustion

1. Introduction

In recent decades, environmental issues have become increasingly severe and urgent. Pollution, climate change, soil degradation, and biodiversity loss are among the most pressing challenges facing our planet today [1]. Nevertheless, there is hope in technological innovations that can contribute to environmental remediation and the mitigation of these adverse effects [2].

One of the most critical environmental challenges is air pollution. Industrial emissions, transportation activities, and the combustion of fossil fuels constitute some of the major sources of atmospheric contaminants. To address this issue, a wide range of innovative technologies has been developed, including air filtration systems, air purifiers, and air quality monitoring networks [3]. These technologies facilitate the removal of particulate pollutants from the atmosphere and enable the measurement and tracking of pollution levels to identify the primary sources of emissions.

Addressing environmental challenges is a shared responsibility. Nevertheless, technological innovation can play a pivotal role in accelerating environmental remediation and reducing pollutant emissions. It is therefore essential to continue developing and implementing advanced environmental technologies in order to protect natural ecosystems and ensure a sustainable future for future generations [4].

Anthropogenic sources of pollution are more numerous and emit more concentrated pollutants than natural sources, while also undergoing continuous development - thus representing a significant ecological threat that must not be overlooked [5]. Unfortunately, there are still many polluting industrial plants operating with obsolete technologies, often situated in areas lacking favourable meteorological or topographical conditions that would support natural self-purification [6]. Figure 1 schematically presents various technological systems characterized by different levels of environmental impact, classified as follows [7]:

- Polluting plants with outdated technology, which fall under the Passive type of ecological approach, where pollution is largely ignored;
- Plants that take into account atmospheric protection through measures such as land-use

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planning, meteorological and topographical studies, and the dilution–dispersion principle, generally categorized as Reactive type systems.

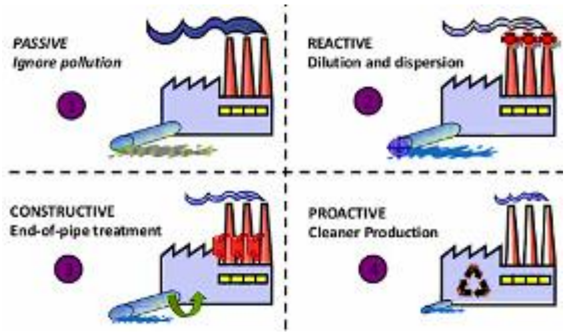

***Fig. 1.** Technologies with different types of environmental impact* [7]

Product design under the motto "cleaner production" can be approached in two main ways from the perspective of material selection based on ecological criteria [8], namely:

- The "reactive" approach, which applies end-of-pipe technologies and provides solutions for transforming pollutants generated during the production process into less harmful forms. This type of approach does not actually reduce the number of pollutants but rather converts or even increases it in certain cases.

- The "preventive" approach, which involves modifying the production process itself so that pollution is minimized from the very beginning. The preventive strategy seeks to eliminate the causes of pollution at the source through practical measures such as product redesign or technological modifications.

2. Energy Sources and Impact

Regarding air pollution originating from industrial activities, the categories of materials that can act as pollutants include [9]:

- Raw materials (e.g., coal, minerals, etc.);

- Impurities in raw materials (e.g., sulphur, arsenic, lead, mercury, fluorine, etc.);

- Intermediate substances, generated at specific stages of the technological process (e.g., SO_2 in the sulfuric acid industry, carbon disulfide (CS_2), hydrocarbons in the petrochemical industry, etc.);

- Final products (e.g., cement, carbon black, chlorine, nitric acid (HNO_3), sulfuric acid (H_2SO_4), etc.).

At the global level, the energy sector, due to the complexity of its installations and technological processes, the characteristics of the raw materials involved, and the waste generated, as well as the number and extent of land areas occupied, is one of the most significant industrial sectors, with a major environmental impact [10, 11]. Electric power generation is not a technologically efficient process [11], particularly when environmental impact considerations are taken into account. Consequently, any method of electricity production involves a varying degree of environmental burden.

Hydropower developments, during their operational phase, cause localized modifications of the microclimate, affecting both flora and fauna [12]. However, a major disruption of ecosystems occurs primarily during the construction phase of hydropower projects [13]. Deforestation, large-scale excavations, and dam construction produce substantial environmental impacts that affect all environmental components [12, 13]. Nevertheless, modern hydropower turbines can convert up to 90% of the available energy into electricity, whereas even the most efficient fossil fuel-based installations achieve an efficiency of only 50% [14].

At nuclear power plants, radioactive pollution is minimal, typically not exceeding the natural background radiation [11]. Nevertheless, this type of facility carries the risk of major radioactive contamination, as the devastating effects of potential accidents can affect large areas [15]. Therefore, all possible measures must be implemented to ensure the safe operation of nuclear reactors. Another perspective on nuclear energy, in terms of its potential pollution, concerns the entire technological chain, from nuclear fuel extraction to radioactive waste disposal [16]. Even under these conditions, nuclear energy remains far less polluting and safer than conventional thermal power generation [17].

Electricity generation from wind or solar installations is considered clean technologies. However, changes in airflow distribution and evaporation volumes, with subsequent effects on the local microclimate, cannot be neglected [11]. Additionally, it may be of interest to analyse the pollution associated with the production of electricity required for the construction of unconventional installations, particularly since almost all materials used are energy-intensive.

The exploitation of geothermal resources (dry and hot rocks) remains prohibitively expensive at present. Biomass incineration (municipal and industrial solid waste) emits harmful substances, as many of these residues are toxic [18]. Due to the high moisture content and low calorific value of biomass, combustion typically requires a support fuel, which can also be used for ignition [19].

The last category refers to conventional thermal power generation, based on the combustion of fossil fuels, which has a major impact on all environmental components. The environmental burden arises not only from the combustion process itself but also from all associated processes, including extraction and waste storage. It is also noteworthy that this highly polluting process accounts for a substantial share of the total energy produced globally. Consequently, fossil fuel combustion processes worldwide generate the following pollutants, with quantities expressed as a percentage of the total anthropogenic emissions within each pollutant category [11]: Sulphur oxides (SOx): 90%, Carbon monoxide (CO): 30–50%, Suspended particulate matter: 40%, Volatile organic compounds (VOCs): 55%, Methane (CH_4): 15-40%, Carbon dioxide (CO_2): 55–80%. In addition, other pollutants are released in varying proportions [11], including nitrogen oxides (NOx), hydrogen sulphide (H_2S), arsenic (As), fluorides (F_2), phenols, hydrocarbons, aldehydes, ketones, inorganic and organic acids, among others.

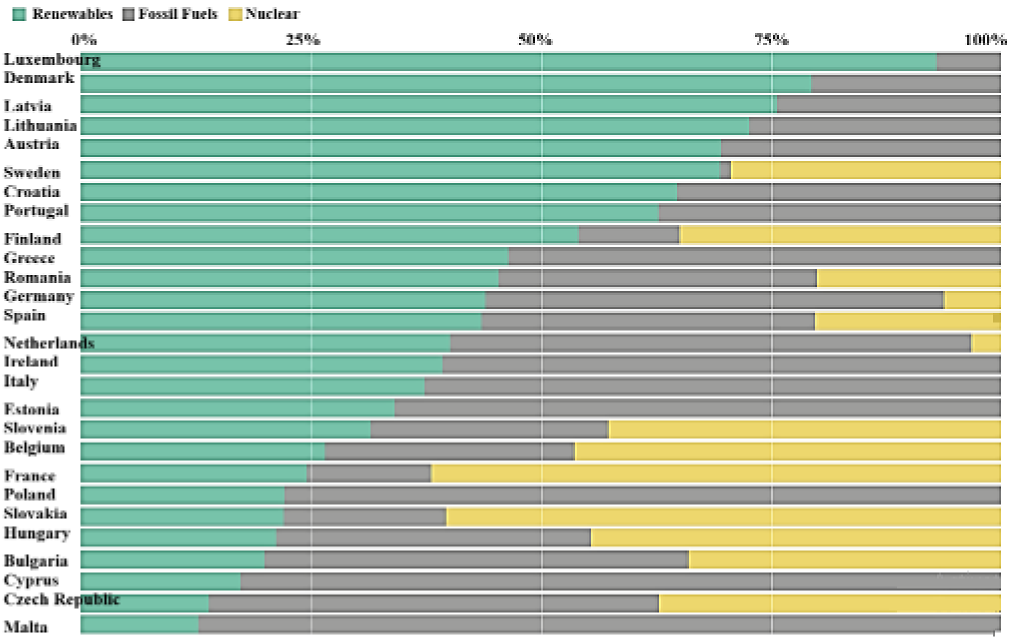

***Fig. 2.** Electricity production in European countries (2022)* [21]

3. Proportion of Thermal Energy in Romania and Globally

The share of electricity consumption in each country varies depending on [20]: geographical conditions, availability of natural resources (coal or gas deposits), economic structure and political decisions (such as whether to develop nuclear power generation capacity). In 2022, the European Union (EU) produced 2,641 TWh of electricity, distributed as follows [21] (Figure 2):

- Approximately 40% - renewable energy sources;
- Fossil fuels accounted for 38.6%;
- Nuclear power contributed more than 20%.

Among fossil fuels, natural gas was the primary source for electricity generation (19.6%), followed by coal (15.8%) [21]. Figure 3 shows the net electricity production in the EU by fuel type in 2022. Data over the past 20 years indicate that the share of renewables in electricity production has increased from 20% to over 45% (Figure 4). Consequently, in the last 2–3 years, within Europe, several countries such as Poland, Estonia, Italy, and Greece still lack nuclear power generation capacity, and renewable energy sources do not yet represent a significant share. In these countries, fossil fuel combustion remains the predominant method of electricity generation.

***Fig. 3.** Net electricity production in the EU by fuel type (2022)* [21]

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In Romania, renewable energy sources have experienced significant growth; however, the thermal power industry still accounts for approximately half of electricity production in winter (Figure 5) and about one-third in autumn (Figure 6).

Electricity production and consumption in Romania over a single day in January 2025 [22] show that, out of a total production exceeding 6,600 MW, more than 3,000 MW are generated by hydrocarbons (yellow line) and coal (black middle line) — i.e., fossil fuels. Nuclear power contributes approximately 1,400 MW, and hydropower provides over 1,500 MW. Other sources, including wind, solar, and biomass, account for approximately 600 MW.

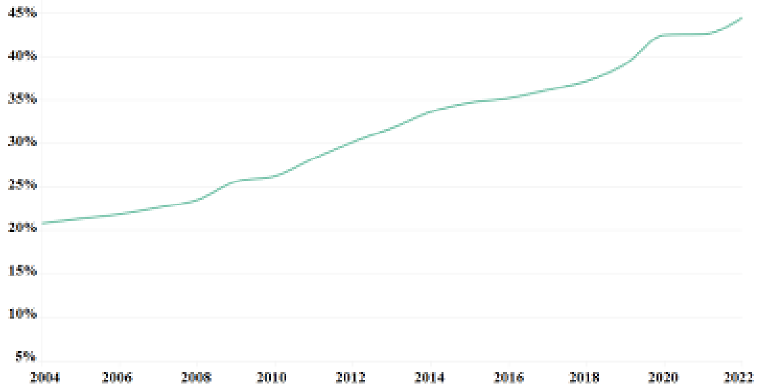

Fig. 4. *Share of renewable energy in electricity production in the EU (2004–2022)* [21]

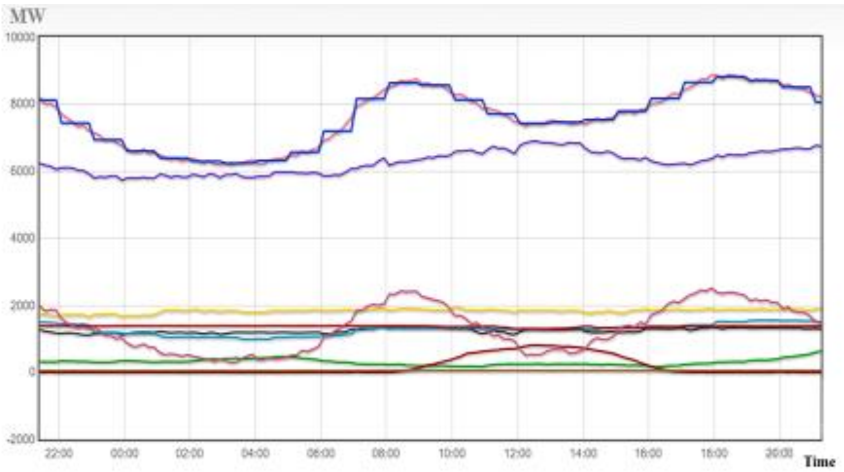

Fig. 5. *Electricity production and consumption in Romania in January 2025* [22]*: ■ Consumption: 8342 MW ■ Hourly average consumption: 8504 MW ■ Production: 6668 MW ■ Coil: 1297 MW ■ Hydrocarbons: 1855 MW ■ Hydropower: 1534 MW ■ Nuclear: 1380 MW ■ Wind: 545 MW ■ Solar: -2 MW ■ Biomass: 56 MW ■ Sold: 1674 MW*

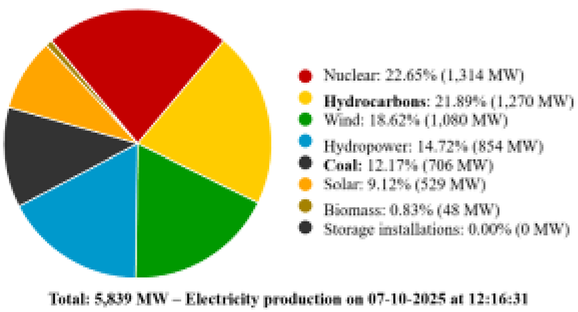

Fig. 6. *Electricity production and consumption in Romania in October 2025* [22]

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Thermal power plants therefore produce approximately 80% of the global electricity demand, relying on fossil fuels (solid, liquid, or gaseous) [9].

4. Key Gaseous Emissions in Thermal Power Generation

The pollution resulting from combustion is closely linked to the composition of the fuel [23]. In the case of complete combustion, the resulting particulate pollutants consist primarily of ash.

In high-rank coals, ash content ranges from 5-10%, whereas in low-rank coals it reaches 40-50%, representing one of the quantitative criteria for assessing coal quality; the higher the ash content, the lower the calorific value, and the greater the amount of coal required to achieve the same energy output [23]. This not only contributes to atmospheric pollution but also interrupts the carbon cycle by halting the natural carbonization process [9]. In the case of incomplete coal combustion, the emitted gases are rich in ash, soot, and unburned coal particles [24]. The largest quantity of soot is released during the initial ignition phase, when not all the fuel has reached the combustion temperature (~750 °C) [9]. Therefore, interruptions in operation and temperature fluctuations during combustion are undesirable, both from an environmental and economic perspective [23, 24]. Accordingly, it is recommended that fast-igniting fuels (e.g., natural gas or petroleum products) be used at boiler start-up, as they burn without producing soot, so that once the system reaches normal operating temperature, coal can be introduced [9].

4.1. Carbon-Based Compounds

Carbon oxides (CO and CO_2) are produced during the combustion of carbon, from any type of fuel. Incomplete combustion of carbon (in the presence of insufficient air), which produces CO, has the following disadvantages: it releases approximately 3.5 times less heat than complete combustion and generates a toxic gas [25]. The higher the CO_2/CO ratio, the better the combustion efficiency [26]. In modern installations, the CO_2/CO ratio is continuously monitored, and by adjusting the fuel-to-air ratio, the CO concentration is reduced to near zero. In cities with developed industry, CO_2 concentrations, expressed as a volume percentage, range between 0.03–0.05% [27]. While this level is not significant from a toxicological perspective, it is important in terms of indoor air quality deterioration and intensifying the greenhouse effect on a global scale [27].

Table 1 compares the various amounts of major pollutants released into the atmosphere by different technological sources with those produced naturally within their respective cycles. It has been observed that for carbon, sulphur, and nitrogen derivatives, human activity is significantly altering their circulation rates in the biosphere. In fact, the magnitude of anthropogenic H_2S, SO_2, and sulphate (aerosol) emissions is comparable to that released naturally through biogeochemical processes (113×10^6 t/year versus 130×10^6 t/year). A similar situation is observed for carbon, due to excessive fossil fuel consumption.

Table 1. *Comparison between the amounts of gaseous substances produced by humans and those released into the atmosphere through natural biogeochemical processes* [9]

Compound	Quantities Produced (x 10^6 tonnes/year)	
	of natural origin	of industrial origin
O_2	$1.8 \cdot 10^3$	small
CO_2	$7.2 \cdot 10^4$	$1.95 \cdot 10^4$
CO	>70	$>3 \cdot 10^2$
H_2O	$4.5 \cdot 10^8$	$1.5 \cdot 10^3$
Sulfur Compounds	130	113
Nitrogen Compounds	1400	<93

The carbon cycle (Figure 7) is one of the most efficient biogeochemical cycles, due to the rapid rate at which carbon circulates among inorganic reservoirs and within the living community, through trophic chains. The carbon cycle operates on a timescale of approximately 300 years, and human activity has disrupted this cycle, primarily through the increasing consumption of fossil fuels [28], which enriches the atmosphere with CO_2 (Figure 7). It has been calculated that fossil fuels are consumed thousands of

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times faster than the rate at which carbon naturally fossilizes [30].

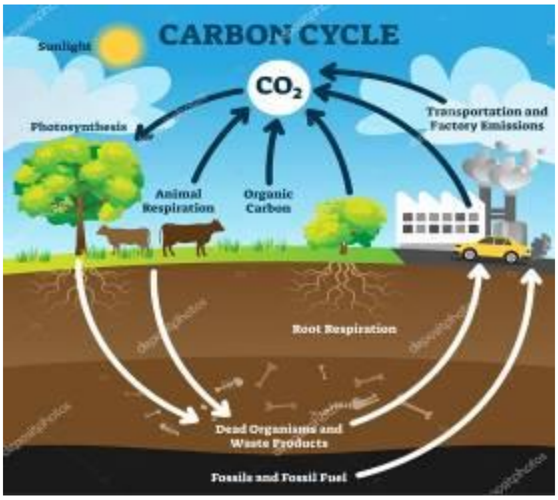

Fig. 7. *The Carbon Cycle* [29]

Data from Table 2 present a comparison of the quantities of CO_2 circulating in the biosphere from different sources. Analysis of these data shows that CO_2 consumed through photosynthesis is lower than the quantities released into the atmosphere through respiration, fermentation, combustion, and deforestation, resulting in a continuous increase in atmospheric CO_2 levels. Vegetal biomass also acts as a balancing factor, consuming a significant portion of CO_2 via photosynthesis. Human-driven deforestation of tropical areas results in increased atmospheric CO_2, which is no longer absorbed through photosynthesis, while a considerable amount of dead organic matter is introduced into the soil. The oceanic reservoir plays a crucial role in regulating the cycle by dissolving CO_2 from the air and transferring it to the ocean floor as sediments in deep layers. Experiments indicate that only 49% of the CO_2 produced through combustion since 1950 has been deposited in the deep ocean layers [28]. Therefore, as fossil fuel use and accelerated exploitation of forest ecosystems continue, the atmospheric concentration of CO_2 is steadily increasing, which in turn enhances the greenhouse effect [30].

The global distribution of CO_2 emissions from industrial sources shows a concentration in the heavily industrialized Northern Hemisphere, with major contributors including China and the USA, followed by Russia, India, and Europe (Figure 8).

Table 2. *CO_2 circulation in the biosphere* [9]

The process	Quantity (t/year)	Recovery time (years)
Atmospheric Content	$2.6 \cdot 10^{12}$	-
Photosynthesis	$2.2 \cdot 10^{11}$	<12
Respiration and Fermentation	$2.3 \cdot 10^{11}$	-
Combustion	$1.95 \cdot 10^{10}$	143
Deforestation	$1.2 \cdot 10^{10}$	219
Fossilization	10^7	$2.8 \cdot 10^5$

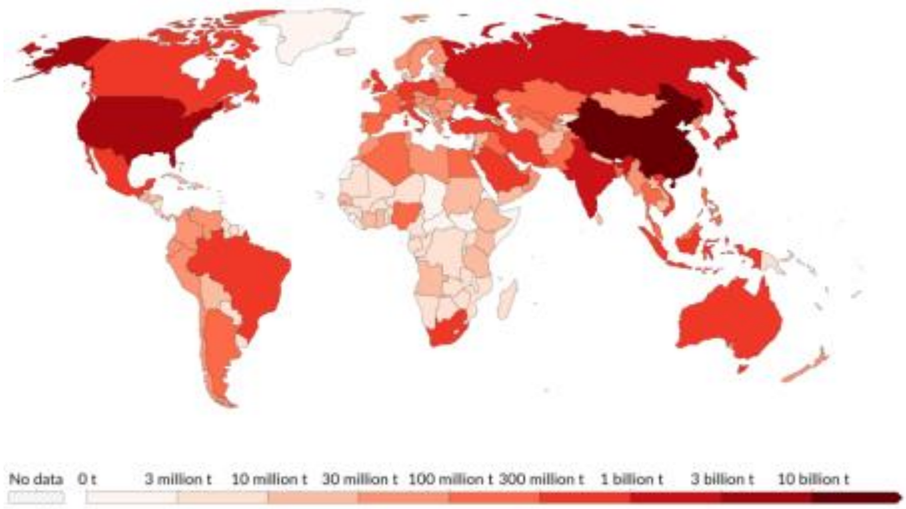

Fig. 8. *The global distribution of CO_2 emissions from industrial sources* [31]

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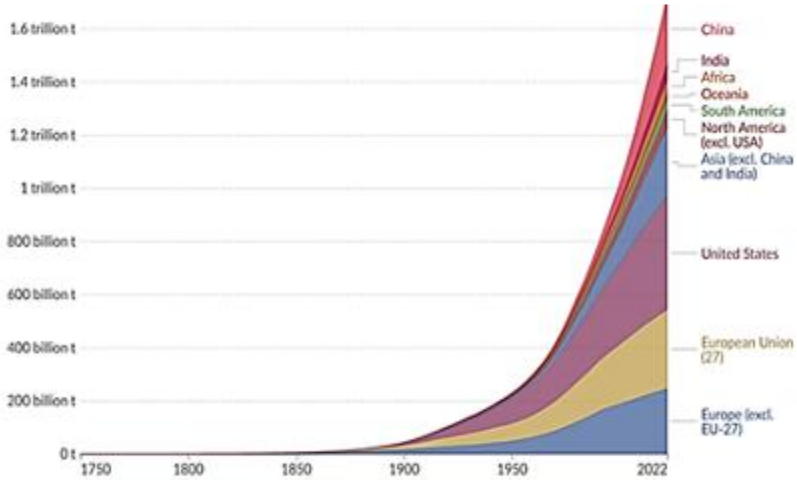

***Fig. 9.** The global CO_2 emissions from fossil fuel combustion, solely from industrial sources, 1750–2022* [31]

Quantitatively, the same global distribution of annual CO_2 emissions highlights that China alone, as the leading emitter, releases 1,600 million tons of CO_2 annually. Compared to previous centuries, beginning in the 20th century, CO_2 emissions have been on a continuous upward trend (Figure 9).

Hydrocarbons are present in combustion gases, either due to their formation and release from fuels during combustion (through processes such as cracking, dehydrogenation, polymerization, decarboxylation, and dealkylation) or as a result of incomplete combustion due to insufficient air supply [28]. Emissions are higher for liquid fuels, where hydrocarbons are already present prior to combustion.

4.2. Sulphur-Based Compounds

Coal contains sulphur in proportions of 0.6–6%, crude oil 0.1-4%, while natural gas contains negligible amounts [32]. In Romania, lower-rank lignite contains on average 1% sulphur, and bitumen around 2%. Consequently, bitumen-fired thermal power plants emit more SO_2 into the atmosphere than lignite-fired plants [9]. In coal, sulphur occurs in both organic and inorganic forms (sulphides and sulphates). Sulphur in sulphates remains in the ash, while organic sulphur and sulphides are converted into SO_2 and SO_3 [32]. Approximately 80–90% of atmospheric SO_2 originates from the combustion of fuels [33].

To date, the problem of atmospheric sulphur acid pollution has been only partially addressed, primarily through coal washing and/or increasing chimney heights to 200 m [34]. These measures are insufficient, as SO_2 pollution can be detected up to 8–10 km around a thermal power plant equipped with outdated technology. When released into the atmosphere, SO_2 reacts with oxygen at a rate of approximately 1–2‰ per hour under ultraviolet radiation, forming SO_3 [34]. This gas subsequently reacts with water vapor to form sulfuric acid. During foggy or highly humid conditions, the conversion rate can reach up to 15.7%.

SO_2 is a colourless gas with a pungent, suffocating odour. Its environmental and health impacts include the exacerbation of chronic respiratory diseases. At low concentrations, it causes spasms and constriction of the upper respiratory muscles, whereas at high concentrations, it can cause burns of the respiratory and conjunctival mucosa, breathing difficulties, and a sensation of suffocation. The presence of sulphur oxides in the environment affects plants directly and also alters the composition of water and soil. High concentrations of SO_2 destroy chlorophyll, an effect that is amplified synergistically with NO_2 [35]. Sulphur oxides, and the resulting sulphurous and sulfuric acids produced through hydration, cause corrosion, material discoloration, and reductions in the strength and elasticity of organic compounds [36].

The odour of SO_2 can be detected at 2–5 mg/m³, depending on individual sensitivity. Respiratory irritation begins at 6-13 mg/m³, poisoning occurs around 50 mg/m³, and concentrations of 1 g/m³ or higher can be fatal [37].

4.3. Nitrogen-Based Compounds

Nitrogen oxides (NOx) are formed from the reaction between oxygen and nitrogen in the air at combustion temperatures, with the reaction rate increasing at higher temperatures. It is estimated that

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the thermoelectric industry is responsible for approximately 50% of atmospheric NOx, with the remainder originating from transportation sources [38]. Numerous industries emit NOx. Figure 10 presents the sources of NOx emissions in the USA, measured in 2017. "Mobile sources" - including road vehicles, boats, aircraft, and agricultural machinery - are the largest contributors. In both the USA and Europe, road vehicles are the primary type of mobile NOx source. In areas where vehicles dominate NOx emissions, higher concentrations of NO_2 are often observed during peak traffic hours.

The global distribution of nitrogen oxides emissions indicates that the largest contributors to global N_2 compound emissions are East Asia, South Asia, Africa, and South America. Emissions from synthetic fertilizers dominate in China, India, and the USA, whereas emissions resulting from the application of manure-based fertilizers dominate in Africa and South America. The highest growth rates occur in emerging economies, particularly in Brazil, China, and India, where both crop production and livestock numbers have increased (Figure 11).

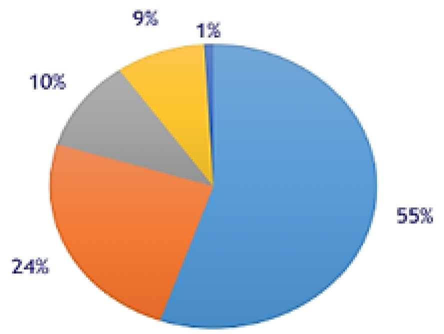

Fig. 10. *Sources that emit NO_2 into the atmosphere* [39]*:* ● *Mobile sources* ● *Other sources* ● *Industrial processes* ● *Fossil Fuels combustion* ● *Natural sources*

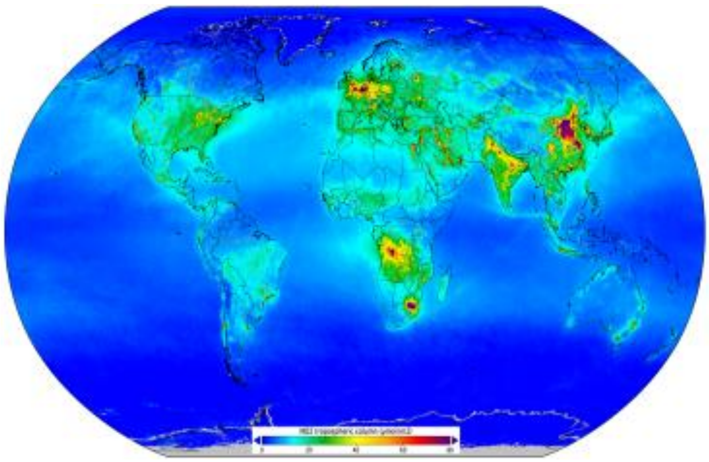

Fig. 11. *The global distribution of NOx emissions* [39]

Due to their aggressiveness and toxicity, nitrogen oxides and nitric acid are extremely hazardous to humans [40]. They attack mucous membranes and respiratory tracts and convert oxyhemoglobin into methemoglobin, which can lead to paralysis. Prolonged exposure to nitrogen oxides, even at very low concentrations (0.5 ppm), weakens the human body, increasing susceptibility to bacterial infections - a risk especially pronounced in children. Additionally, the toxicity of nitrogen oxides is amplified synergistically by the presence of other toxic substances.

Nitric acid, formed by the reaction of NO_2 with H_2O, causes various types of corrosion, severely affecting metal structures. HNO_3 reacts with different atmospheric cations to form nitrates, which are corrosive to copper, brass, aluminium, nickel, and may also damage electrical and telecommunications networks [38]. These processes can occur even at very low NOx concentrations in the atmosphere (0.08 ppm).

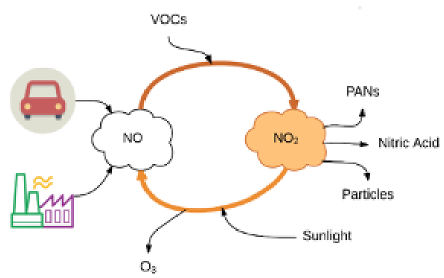

Fig. 12. *NO_2 life cycle* [39]

As shown in Figure 12, at the emission point (i.e., the exhaust pipe), NOx consists of approximately 90% NO and 10% NO_2. After several hours in the atmosphere, and in the presence of volatile organic compounds (VOCs), NO is converted into NO_2. This reaction may occur over timescales ranging from seconds to several hours.

NO_2 further reacts with other atmospheric substances to form nitric acid, particulate matter, and peroxyacyl nitrates (PANs). Additionally, under sunlight, NO_2 can revert to NO and produce ozone (O_3) as a secondary pollutant. Due to the potential to form these secondary pollutants, its monitoring and regulation are essential.

Primary and secondary measures for reducing nitrogen oxide emissions are always accompanied by the formation of secondary emissions of CO, N_2O, and NH_3. This may result it to an increase of up to 10% in annual N_2O concentrations in the troposphere.

The harmful effects of N_2O are twofold [40]: first, it contributes to the enhancement of the greenhouse effect; second, and more importantly, N_2O destroys the protective ozone layer. While inert in the troposphere, N_2O is harmful in the stratosphere due to its catalytic role in photochemical reactions, generating active radicals that deplete ozone. This phenomenon is intensified by N_2O's long atmospheric lifetime, which can reach up to 180 years [40].

Atmospheric pollution arguably has the most severe impact on the environment, not only due to the quantity and diversity of pollutants but also because of its effects on vast geographic areas. For this reason, atmospheric pollution is no longer a local problem but has acquired a global character. Based on both its effects and their spatial and temporal extent, atmospheric pollution can be classified into the following categories:

- Proximity (local) pollution: occurring on a time scale of hours, where the main atmospheric pollutants (SO_2, NOx, CO, O_3, Pb, particulate matter) have immediate effects on human health and ecosystems.
- Distributed (regional) pollution: occurring on a time scale of days, with primary effects including acidification, eutrophication, and photochemical pollution.
- Global pollution: occurring on a time scale of years, leading to outcomes such as intensification of the greenhouse effect and destruction of the stratospheric ozone layer.

5. Conclusions

Thermal power plants, which rely predominantly on fossil fuels, remain the largest contributors to global electricity production, providing approximately 80% of the world's energy demand. The combustion of solid, liquid, and gaseous fuels generates significant emissions of pollutants, including particulate matter, sulphur oxides (SO_2, SO_3), nitrogen oxides (NOx), carbon oxides (CO, CO_2), and volatile organic compounds, with both direct and indirect effects on air quality, human health, and the environment.

The generation and release of pollutants depend on fuel composition, combustion efficiency, and technological processes. Incomplete combustion increases the emission of soot, unburned hydrocarbons, and CO, while modern plants monitor CO_2/CO ratios and apply combustion control to minimize harmful emissions. Sulphur content in fuels leads to SO_2 and SO_3 emissions, which cause acid rain, corrosion, and respiratory problems, whereas nitrogen oxides contribute to smog formation, ozone generation, and nitric acid deposition, with severe toxicological effects even at low concentrations.

Renewable energy sources (solar, wind, hydro) and nuclear power exhibit lower direct pollution compared to conventional fossil fuel-based thermoelectric plants. Nuclear energy, while low in routine emissions, poses potential risks from radioactive contamination if accidents occur. Renewable energy technologies, although cleaner, can still affect local microclimates and require energy-intensive production of equipment, highlighting the need for life-cycle assessments of all energy sources.

Air pollution has evolved from a local to a global problem, affecting human health, ecosystems, and climate systems across large geographic areas. Atmospheric pollution can be classified as local (proximity), regional (distributed), or global, depending on spatial extent and temporal scale. The continued increase in greenhouse gases, particularly CO_2 and N_2O, due to fossil fuel consumption and deforestation, contributes to climate change and ozone depletion.

Mitigating the environmental impacts of energy production requires innovative technologies, including cleaner combustion, emissions-scrubbing technologies, and renewable energy deployment, combined with policy measures that promote sustainable energy production and efficient resource use. Preventive approaches, which modify production processes and fuel selection to reduce pollution at the source, are generally more effective than end-of-pipe solutions, which transform rather than eliminate pollutants.

The data reviewed indicate that global energy systems must transition toward low-emission, high-efficiency technologies to protect the environment, ensure public health, and secure a sustainable energy future. While progress has been made in renewable energy adoption and emission control, the dominance of fossil fuels, particularly in certain regions,

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continues to pose significant ecological and climatic challenges.

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