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Nuclear energy in the context of climate change

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Abstract: Human society faces the great challenge of drastically reducing greenhouse gas emissions while providing increased amounts of energy. Although the share of renewable energy sources has increased in recent years, fossil fuels are still widely used and burning them makes large amounts of carbon dioxide enter the atmosphere. However, renewable energy sources may not be able to supply in time enough energy to replace fossil fuels. Under the circumstances, the question arises as to whether nuclear energy could play a significant role in mitigating climate change. Although there is still confidence and support for nuclear energy, it is unlikely that this energy source will make a greater contribution to combating climate change in the coming decades. This study analyzes the current state of nuclear energy, as well as the development prospects in the context of climate change and risks to the environment and human health.

Key words: fossil fuels, climate change, renewable energy, nuclear energy, nuclear reactors

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1. INTRODUCTION

The burning of fossil fuels generates greenhouse gases that cause global warming. The concentration of CO_2 in the atmosphere reached 410.5 ± 0.2 ppm in 2019, a considerable increase compared to the level of the mid-18th century (pre-industrial period), estimated at 278 ppm [1,2]. According to the Paris Agreement, in order to avoid the serious effects of climate change on the environment, the increase in global temperature must be kept well below 2°C compared to the pre-industrial period [3]. Thus, low-carbon energy sources, especially the renewable ones, need to replace fossil fuels, which continue to predominate in the final energy consumption, as soon as possible, although their share has gradually declined in recent decades, from 74% in 1980 to 67% in 2019 [4]. This conversion will be a major challenge because by 2050 an increase in global energy consumption of about 50% and final electricity consumption of 80% is expected [5].

Although renewable energy sources have increased at an average annual rate of 2% since 1990, in 2018, of the total energy supplied worldwide, only 13.5% came from these energy sources (biofuels, hydropower, municipal waste renewable energy, wind, solar, geothermal or tidal energy). If we refer only to power production, the share of renewable energy sources was over 25%, occupying the second position after coal [6]. Under the circumstances, the share of renewable energy in total energy consumption will have to increase significantly by 2050, reaching about two thirds [7]. However, this growth is not certain. According to U.S. Energy Information Administration (2019), although renewable energy sources will increase by more than 3% per year between 2018 and 2050, their share in global energy consumption will not exceed 28%.

At present, nuclear energy supplies about 10% of the world's power and is an important component of all low-carbon power production. According to the International Energy Agency (2019), the use of nuclear energy has prevented over 60 gigatons of CO_2 emissions in the last 50 years from entering the atmosphere. However, the March 2011 nuclear accident in Fukushima (Japan) called into question the safe operation of nuclear power plants, with some countries such as Germany and Switzerland announcing the early closure of the existing nuclear facilities [8].

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Thus, in the context of increasing global energy consumption and climate change concerns, the widespread use of low-emission energy sources is a must. The big challenge will be to produce enough energy from renewable sources to replace fossil fuels used in the production of electricity and heat or in transport, in the context of population growth, economic development, urbanization or the expansion of electric mobility.

2. LITERATURE REVIEW

The role of nuclear energy in the global energy system has been intensively analyzed over time, including in relation to climate change. Many studies have shown that nuclear fission technology is capable of providing large amounts of energy, safely and with low carbon emissions, which is essential for meeting the climate goals and the Paris Agreement. Consequently, nuclear energy must play a major role in the global energy system [9–14]. In this category, some authors believe that there are no insurmountable technical barriers to nuclear expansion, but this expansion must be carried out in accordance with very high safety standards [9]. Other argue that, in the long run, nuclear fission technology is the only source of energy capable of providing the large amounts of energy that modern industrial societies will need in a safe and sustainable way, both in terms of ecological view and in terms of the available resource base [10]. On the other hand, it is considered that the most serious problem facing humanity is that we only have a few decades to implement effective measures to stop global warming. In the long run, thorium and molten salt reactors could compete with uranium-based reactors. Nuclear expansion should be accompanied by effective international safety assurances, including a mandate to stop the construction of unsafe nuclear power plants [11].

There are still many uncertainties about the future evolution of nuclear energy, due to the fears about the potential risks to human health from possible nuclear accidents or radioactive waste [15–18]. There are authors who question the fact that nuclear energy is a low-carbon technology and therefore they advocate strictly for a non-nuclear future [19]. Other believe that the contribution of nuclear energy to climate change mitigation is and will be very limited. In addition, a substantial expansion of nuclear energy will not be possible due to technical barriers and limited resources [20].

3. METHODS AND DATA

The statistical data used were taken from the databases of the International Atomic Energy Agency, the International Energy Agency, U.S. Energy Information Administration, International Renewable Energy Agency or Our World in Data, which periodically collect and publish energy information. These data were represented graphically in order to track the dynamics over time of some indicators: global nuclear power production, the share of power from nuclear sources, reactors newly connected to the grid and reactors permanently shut down. The future evolution of nuclear energy is based on data published in 2020 by the International Atomic Energy Agency. The arguments for or against the role of nuclear energy in the global effort to combat climate change are based on a series of scientific articles published in various journals and other sources.

4. RESULTS

4.1. The current state of nuclear energy

At the beginning of 2020, 443 nuclear reactors were operational, with a total installed capacity of 393 GWe. In addition, 54 reactors, with a total capacity of 54.5 GWe, were under construction [21] (Table 1). Nuclear power plants generated 2,657 TWh of power, representing 10.4% of the global power production [22] (Figure 1). Although in 2019 there was an increase by 3.7% compared to 2018, the production of nuclear power was below the maximum value recorded previously, that is 2,791 TWh, reached in 2006 [23] (Figure 2). The United States, France, China, Russia and South Korea together generated 70% of the total nuclear energy in 2019; US and France accounted for 45% of the total [4].

After the first nuclear reactor was connected to the network (Obninsk, located about 100 km southwest of Moscow), in June 1954, followed a period of development that recorded two peak values: 26 network connections in 1974 and 33 connections to the network in 1984 (Figure 3). After the Chernobyl nuclear accident, a period of decline followed, and in 1989, for the first time in recent history, the number of permanently closed reactors exceeded that of the new reactors connected to the network. From 2012 (after the Fukushima nuclear accident) to the beginning of 2020, 55 new reactors were connected to the network, of which 34 in China alone [21, 24].

Table 1. Nuclear Power Reactors in the World.

Country	Operational (2020)		Under Construction (2020)		Nuclear Electricity Production in 2019	
	Number of units	Net capacity MWe	Number of units	Net capacity MWe	TWh	% of total
World	**443**	**393,068**	**52**	**54,515**	**2,657.2**	**10.4**
Argentina	3	1,641	1	25	7.9	5.9
Armenia	1	423	-	-	2.0	27.8
Bangladesh	-	-	2	2,160	-	-
Belarus	1	1,110	1	1,110	-	-
Belgium	7	5,930	-	-	41.3	47.6
Brazil	2	1,884	1	1,340	16.1	2.7
Bulgaria	2	2,006	-	-	16.5	37.5
Canada	19	13,554	-	-	95.4	14.9
China	50	47,518	14	13,175	348.3	4.9
Czechia	6	3,932	-	-	28.6	35.2
Finland	4	2,794	1	1,600	22.9	34.7
France	56	61,370	1	1,630	379.5	70.6
Germany	6	8,113	-	-	71.1	12.2
Hungary	4	1,902	-	-	15.4	49.2
India	23	6,885	6	4,194	40.7	3.2
Iran	1	915	1	974	5.9	1.8
Japan	33	31,679	2	2,653	65.6	7.5
Korea	24	23,150	4	5,360	138.6	26.2
Mexico	2	1,552	-	-	10.8	4.5
Netherlands	1	482	-	-	3.7	3.1
Pakistan	6	2,332	1	1,014	9.0	6.6
Romania	2	1,300	-	-	10.3	18.5
Russia	38	28,578	3	3,459	208.8	19.7
Slovakia	4	1,837	2	880	15.3	53.9
Slovenia	1	688	-	-	5.5	37.0
South Africa	2	1,860	-	-	13.6	6.7
Spain	7	7,121	-	-	55.8	21.4
Sweden	6	6,859	-	-	55.8	34.0
Switzerland	4	2,960	-	-	16.5	23.9
Turkey	-	-	3	3,342	-	-
Taiwan	4	3,844	-	-	31.1	13.4
Ukraine	15	13,107	2	2,070	83.0	53.9
United Arab Emirates	1	1,345	3	4,035	-	-
United Kingdom	15	8,923	2	3,260	51.0	15.6
United States of America	93	95,523	2	2,234	809.4	19.7

Source: IAEA/PRIS, 2021 [21]

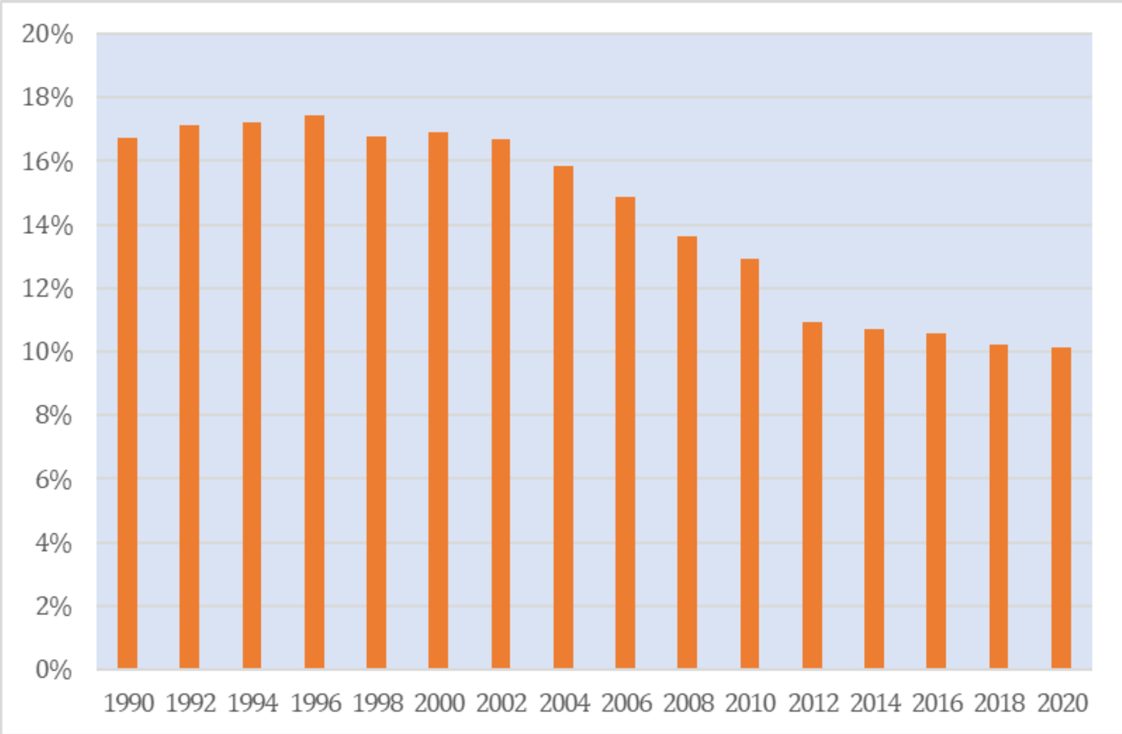

Figure 1. Share of nuclear power production.
Source: Our World in Data, 2021 [22]

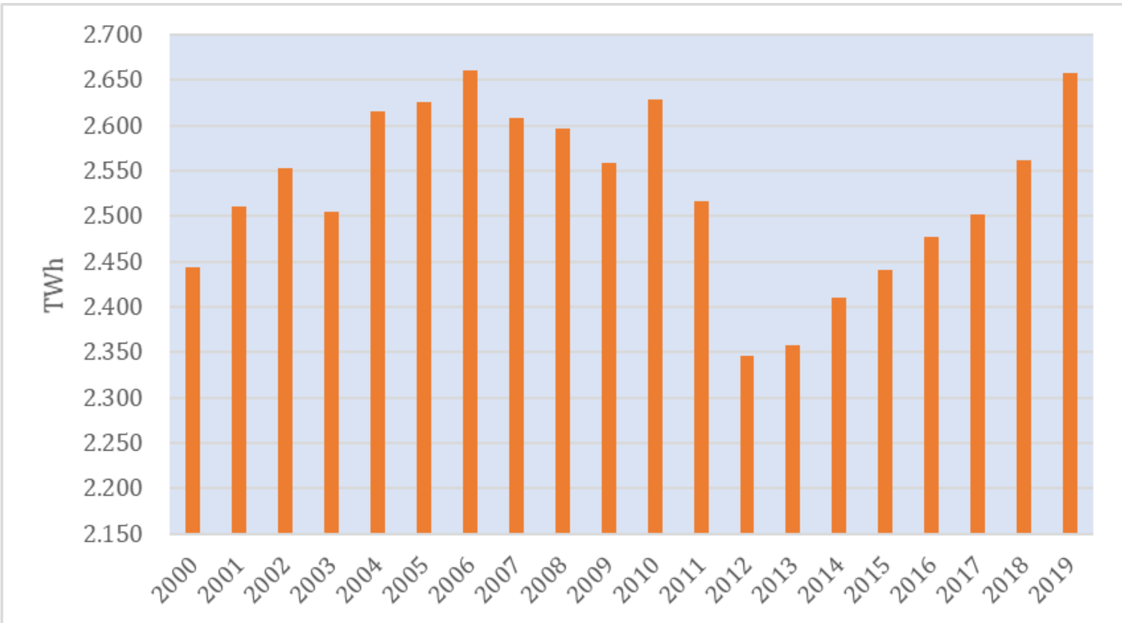

Figure 2. World nuclear power supplied.
Source: IAEA/PRIS, 2021 [23]

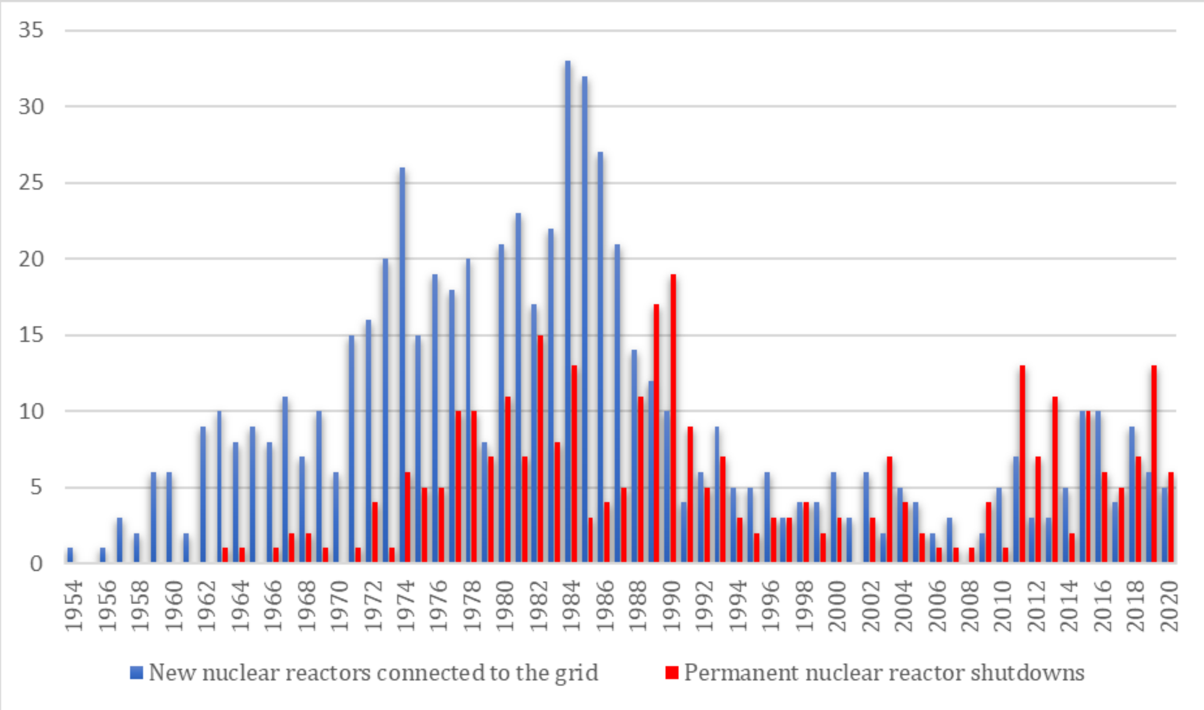

Figure 3. Comparison between reactors newly connected to the network and reactors permanently shut down.
Source: IAEA/PRIS, 2021 [23]

In the absence of major construction programs, the average age of nuclear reactors operating in the world continued to rise, reaching 30.7 years by mid-2020. A total of 270 reactors, two-thirds of the world's total reactors in operation, have been in operation for more than 30 years, including 81 reactors (20% of the total) that have been in operation for more than 40 years [24].

4.2. Prospective evolution of nuclear energy

Currently, 52 nuclear reactors are under construction, of which 14 in China, with a net capacity of 54,515 MWe. Especially due to the high costs, many of these reactors have construction delays, in some cases the delays being very long. For instance, the construction on the Bushehr-2 reactor in Iran began in 1976, that is 45 years ago. Construction was suspended for about four decades and resumed in 2019 [24].

According to IAEA projections (2020), by 2050 the nuclear power generation capacity will be about 7% lower for the low variant and about 80% higher for the high variant (Table 2). In both cases, the share of nuclear energy in the total power generation capacity is expected to decrease. Regarding the power production of nuclear power plants, an increase between 10% (in the case of the low variant) and 100% (in the case of the high variant) is estimated by 2050.

Table 2. Perspective evolution of nuclear power generation and production capacity.

	2019	2030		2040		2050	
		Low	High	Low	High	Low	High
Nuclear Electrical Generating Capacity (GWe)	392	369	475	349	622	363	715
Nuclear as % of Electrical Capacity	5.3%	3.4%	4.4%	2.6%	4.7%	2.3%	4.5%
Nuclear Electrical Production (TWh)	2,657	2,872	3,682	2,774	4,933	2,929	5,762
Nuclear as % of Electricity Production	10.4%	8.2%	10.5%	6.4%	11.4%	5.7%	11.2%

Source: International Atomic Energy Agency, 2020 [4]

5. DISCUSSIONS

Discussions on nuclear energy must balance, on the one hand, its contribution to mitigating climate change and air pollution and, on the other hand, the risks to the environment and human health associated with nuclear accidents or radioactive waste. A first argument in favor of nuclear energy is its contribution to the decarbonisation of the atmosphere. However, as with the main renewable energy sources (wind, solar), nuclear energy produces emissions indirectly. Taking into account the entire life cycle, from uranium mining and fuel fabrication to the construction of the nuclear power plant and the storage of spent fuel, nuclear energy releases certain amounts of greenhouse gases into the atmosphere, which vary, depending on various factors, between 2 tonnes of CO_2/GWh equivalent and 130 tonnes of CO_2/GWh equivalent [25]. Thus, the greenhouse gas emissions of nuclear power plants are among the lowest when it comes to power production (Table 3). Many other studies [26-28] confirmed that greenhouse gas emissions associated with nuclear energy are low.

Table 3. Lifecycle GHG emissions for the different power generation methods (tonnes CO_2e/GWh).

Electricity generation methods	Mean	Low	High
Lignite	1,054	790	1,372
Coal	888	756	1,310
Oil	733	547	935
Natural Gas	499	362	891
Solar PV	85	13	731
Biomass	45	10	101
Nuclear	29	2	130
Hydroelectric	26	2	237
Wind	26	6	124

Source: World Nuclear Association, 2011 [25]

At present, however, the contribution of nuclear energy to climate change mitigation is quite limited, reducing by only 2-3% the total global GHG emissions annually. According to the announced plans for new nuclear construction and lifetime extensions, this value would decline further in the coming decades [20].

Secondly, nuclear power plants can operate without interruption. Compared to some renewable energy sources (wind, solar or even hydropower), which provide electricity intermittently, depending on wind speed, cloudiness or water flow, nuclear power plants can operate uninterrupted for a long time. This feature makes nuclear energy a viable alternative to replacing coal-fired power plants or other fossil fuels. Another advantage over wind or solar power plants is the small space occupied. According to U.S. Department of Energy (quoted by EnergySage, 2021) [29], a typical nuclear facility that produces 1,000 MW of electricity occupies about 1km^2 of land while a solar farm that produces the same amount of energy requires an area 75 times larger, and a wind farm 360 times larger. This is a very important aspect, especially for agriculture, if the land is fertile.

On the other hand, the construction of nuclear power plants is extremely expensive, and costs have been rising in recent years. There are also high costs with waste management. The most recent estimates of overnight construction costs of nuclear reactors are between 3,000 and 6,000 USD/kW, being slightly lower in non-OECD countries [8]. Due to the very high costs, the construction of many reactors has been suspended or much delayed. Thus, the prospects for the expansion of nuclear energy remain low in many parts of the world.

The most worrying aspect of nuclear power plants is the risk of a nuclear accident, such as those at Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011). Despite the safety measures applied to these nuclear power plants, various factors have led to nuclear accidents with a major impact on the population (deaths and mass evacuations), the economy and the natural environment. In the case of the Chernobyl nuclear accident, although the number of deaths directly attributed to radiation exposure was 31 people, those who lost their lives as a result of the long-term effects of radiation in the region could exceed 4,000 [30]. Also, the contaminated land area was estimated at about 150 thousand km^2, and the number of evacuees exceeded 200 thousand [31].

Another negative effect of nuclear energy is the radioactive waste it produces, which is hazardous to human health and the environment, and for which a long-term safe storage solution has not yet been identified. The waste is sealed in concrete containers and stored in the ground. The radioactivity of waste will decrease, but this process can take a long time. According to Corkhill and Hyatt [32], because nuclear fission generates a lot of energy from a very small amount of fuel, the volume of waste produced so far globally is relatively small. Radioactive waste, which is of several types depending on the degree of radioactivity (very low-level waste/VLLW, low-level/LLW, intermediate-level/ILV, high-level/HLW), includes both radioactive materials and contaminated ones (Table 4). The most radioactive waste (HLW), and consequently the most hazardous, represents less than 2% of the volume, but 95% of the total radioactivity of the waste [33].

Table 4. Nuclear waste inventory.

	Radioactive waste in storage (m³)		Total (m³)	Radioactive waste in disposal (m³)		Total (m³)
	Solid	Liquid		Solid	Liquid	
VLLW	2,356,000	-	2,356,000	7,906,000	-	7,906,000
LLW	3,479,000	53,332,000	56,811,000	20,451,000	39,584,000	60,035,000
ILW	460,000	6,253,000	6,713,000	107,000	8,628,000	8,735,000
HLW	22,000	2,786,000	2,808,000	0	68,000	68,000
Total (m³)	6,317,000	62,371,000	68,688,000	28,464,000	48,280,000	76,744,000

Source: International Atomic Energy Agency, 2018 [33]

As far as the uranium is concerned, in the last decade, uranium production was over 53,000 tonnes per year (Figure 4), with a maximum of 62,379 tonnes in 2016, with the largest producers being Kazakhstan, Canada, Australia and Namibia. Kazakhstan is the largest producer, supplying over 41% of global uranium production in 2019 [34].

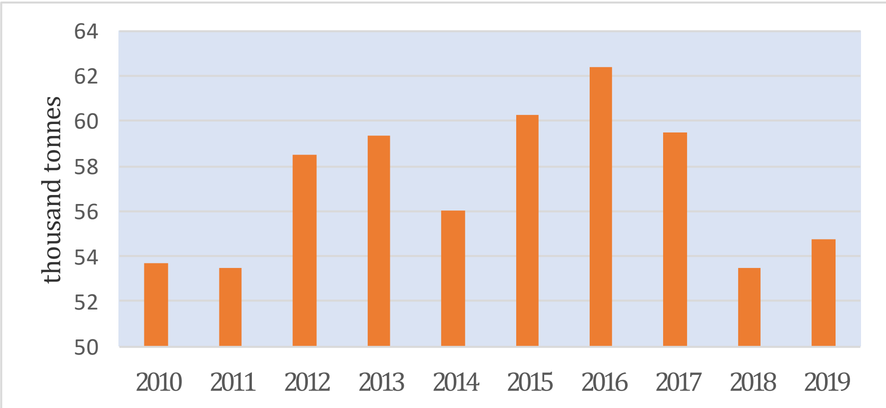

Figure 4. World uranium production in the period 2010-2019.
Source: World Nuclear Association (2020) [34]

Taking into account the estimates of uranium deposits (about 8 million tonnes), at current consumption, they would be available for more than 80 years. Any increase in installed nuclear capacity also means an increase in uranium ore mining to ensure the supply of fuel for nuclear power plants. In 2019, uranium production accounted for 81% of world demand [34].

In some cases, uranium mining may drag on due to public opposition. One such example is Greenland, where the government has announced that it is preparing a law that will ban uranium mining and stop the development of the Kvanefjeld mine, one of the largest rare earth deposits in the world [35].

6. CONCLUSIONS

The prospect of severe effects of climate change on the environment requires an urgent shift to a low-emission greenhouse gas economy. This goal can be achieved by replacing fossil fuels in energy production with other sources that do not have CO_2 emissions or which have reduced emissions. Because fossil fuels are a major component of energy systems in most countries of the world, such an approach could significantly affect electricity supply. Although the share of renewable energy has increased significantly in recent decades, the possibility of these energy sources, such as hydropower, wind or solar energy, replacing fossil fuels is not at all certain, especially in the context of increasing global electricity consumption, including by expanding electromobility.

As for the contribution of nuclear energy to climate change mitigation, at least in the short and medium term, it will not be significant. Current estimates show that in the next two decades, nuclear energy will not contribute more than 3% per year of total global greenhouse gas emissions. The long-term development of nuclear energy also depends on the supply of uranium deposits, which are a depletable resource, or the development of technologies based on another radioactive fuel. Thorium and molten salt reactors or other technologies are not viable solutions in the short term. Current nuclear reactors, no matter how safe, present a certain risk for serious accidents, with considerable emissions of radioactive materials. This is the case of the Fukushima nuclear accident.

Other restrictive factors in the development of nuclear energy are the very high costs of nuclear power plants, which the developing countries cannot bear, as well as the risks associated with radioactive waste. In fact, from the earliest stages of development, nuclear energy has been viewed with concern by public opinion, and nuclear accidents have intensified these concerns. This is also the reason why in some countries such as Germany or Switzerland several nuclear power plants have been shut down.

As the risks to humanity due to climate change are very high, all energy sources with low greenhouse gas emissions should be considered. We must not exclude nuclear energy from this equation. In the long run, this source of energy could become very important if, as a result of research efforts, safe solutions are found for the production of energy (safe reactors) and the storage of radioactive waste.

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