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An Economy Aspect of Different Nuclear Energy Development

Dinka Lale, Dubravko Pevec, Mario Matijević

Summary — Humanity must face the reality that it cannot depend indefinitely on combustion of coal, gas and oil for most of its energy needs. In the long term, nuclear energy seems to be the only one capable of replacing fossil fuel energy in the production of electricity in the world. The specific greenhouses gases (GHG) emissions of nuclear power plants are among the lowest of any electricity generation method. Nuclear power is cost-competitive with other forms of electricity generation, except where there is direct access to low-cost fossil fuels.

Global primary energy needs rise more slowly than in the past, but still an increase of 19% between today and 2050 is expected according to World Energy Outlook 2022. Electrical energy needs will rise faster than primary energy needs and the electrical energy production has to be with low GHG emissions due to global warming mitigation. We assume in our scenarios that nuclear energy will be global electricity production leader with a percentage of 36.7 % in the year 2050. In addition, we assume that all thermal power plants will be replaced by uranium or thorium fuel cycle nuclear power plants by the year 2057.

This paper describes a comparison of different long term nuclear energy development scenarios according to costs. The calculated saving of GHG emissions in case of significant use of nuclear energy in the future in the world is emphasized.

Keywords — **Climate change, Economy aspect, Nuclear energy, GHG emissions**

I. Introduction

Global warming is a big problem that humanity is facing, so we have to find a solution soon. Energy needs are increased by the economic development and the constant increase in earth population. On the other side, the production and use of primary and electrical energy cause the release of carbon dioxide into the atmosphere. Green House Gas (GHG) emissions are the main cause for climate change, which is increasingly affecting planet Earth [1] [2]. Global GHG emissions increased by 1.2 per cent from 2021 to 2022 to reach a new record of 57.4 gigatons of CO_2 equivalent ($GtCO_2e$) [3]. Global energy-related CO_2 emissions grew by 0.9% or 321 Mt in 2022, reaching a new high of over 36.8 Gt [4]. Humanity is in constant search for new energy sources to meet its own energy needs.

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The global population growth projection are from 7.8 billion people in 2021 to 8.5 billion in 2030 and 9.7 billion in 2050. The energy, mineral, and carbon prices projections are given by the IEA (International Energy Agency) and presented in 3 different scenarios. NZE (Net Zero Emissions by 2050 Scenario) sets out a pathway to the stabilisation of global average temperatures at 1.5 °C above pre–industrial levels. Announced Pledges Scenario (APS) assumes that governments will meet, in full and on time, all of the climate–related commitments that they have announced, including longer term net zero emissions targets. Stated Policies Scenario (STEPS) looks not at what governments say they will achieve, but at what they are actually doing to reach the targets and objectives that they have set out [2].

Global electricity demand climbed to 24700 TWh in 2021 – an increase of 6% from the previous year and the biggest annual increase since 2010 – reflecting a rebound in many economies following the pandemic. The largest electricity consumers are China, United States and Europe. Together, they account for over 60% of global electricity demand [2].

Renewable energy technologies currently provide close to 30% of electricity generation and are set for rapid growth in all scenarios, led by solar photovoltaics (PV) and wind. In the NZE Scenario (WEO 2022) the share of renewables in electricity generation rises from 28% in 2021 to over 60% in 2030, and nearly 90% in 2050 (shown in Figure 1) [2].

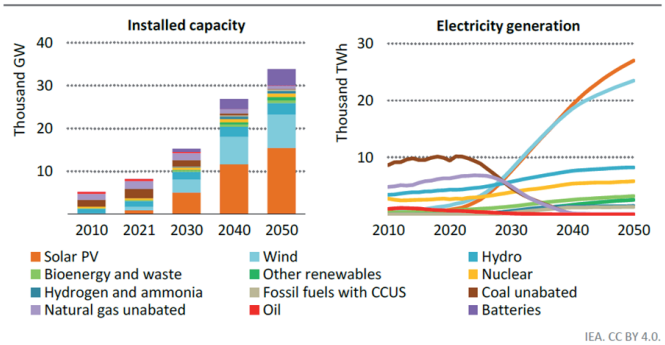

Fig. 1. "Total installed capacity and electricity generation by source in the NZE Scenario, 2010-2050"

In general, the predictions in WEO 2022 related to renewable energy sources are that renewables, notably solar PV and wind, gain the most ground of any energy source this decade, accounting for 43% of electricity generation worldwide in 2030, up from 28% today.

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It is important to take into account both finances and environmental impact when planning investments in the electric power system. Nuclear energy has proven to be one of the most profitable [5] [6] [7] [8]. Figure 2 [5] shows the effect of discount rate on levelized cost of electricity (LCOE) for different technologies (source: OECD Nuclear Energy Agency).

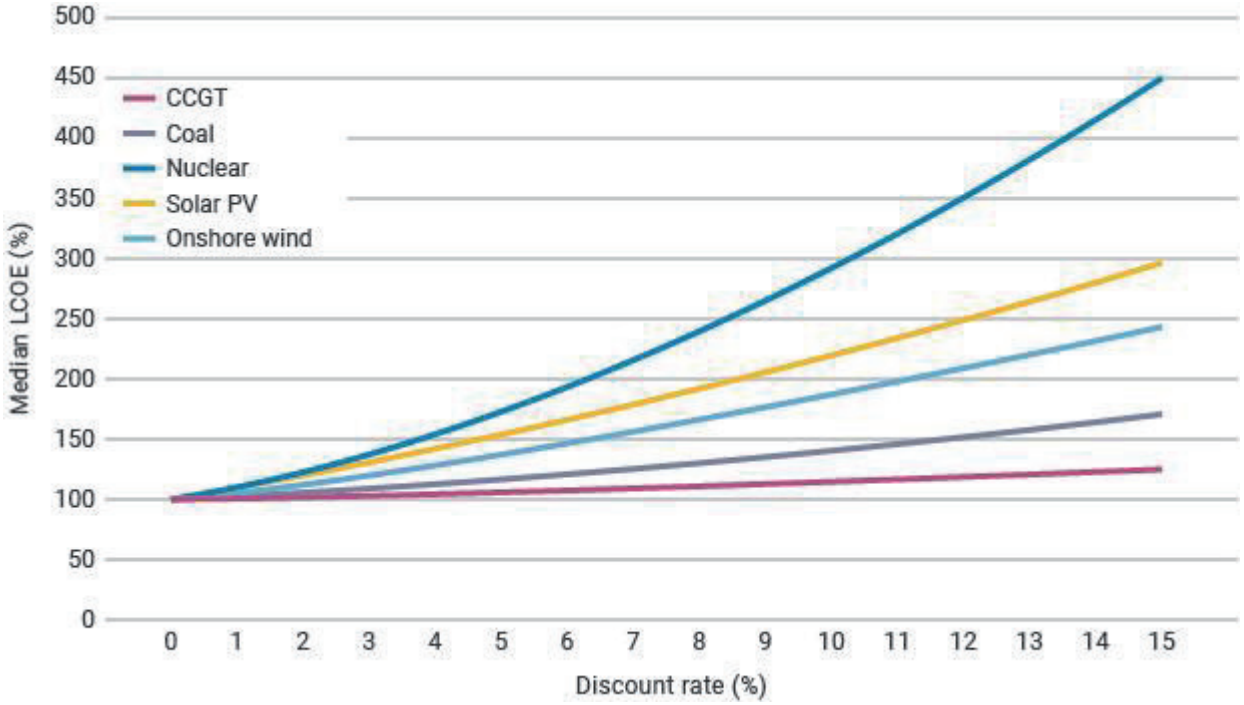
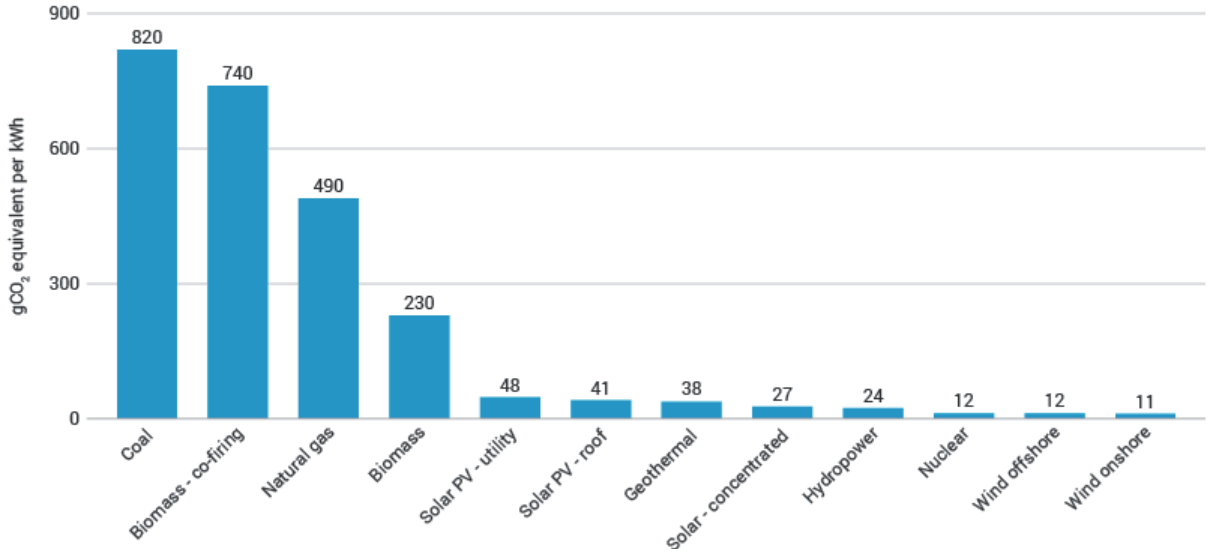


Fig. 2. Effect of discount rate on levelized costs of electricity (LCOE)

At a 3% discount rate, nuclear is the lowest cost option for all countries [5].

Nuclear energy averages 0.4 euro ¢/kWh, much the same as hydro, coal is over 4.0 ¢/kWh and gas ranges 1.3-2.3 ¢/kWh [6].

Fig. 3. Average life-cycle CO2 equivalent emissions



UN IPCC has provided a median value among peer-reviewed studies of 12 g CO_2 equivalent/kWh for nuclear, similar to wind and lower than all types of solar as described in Figure 3.

In March 2022 the United Nations Economic Commission for Europe (UNECE) estimated a range of 5.1 – 6.4 g CO_2 equivalent per kWh for nuclear, the lowest among all low-carbon technologies.

The transport and energy production are the largest emitters of GHG into the atmosphere. Electricity production in nuclear power plants causes very low GHG emissions. It is therefore necessary to increase the share of nuclear power plants in the future [2] [9]. A further question is which type of nuclear power plants to prefer considering the price and radioactive waste [10].

Pressurized Water Reactors (PWR) are the most developed and currently the most widely used. However, from the point of view of the produced radioactive waste, the use of Fast Breeder Reactor (FBR) and reactors that use thorium is more favourable. It cannot be expected that newer types of reactors will be used to a greater extent any time soon. But it is necessary to take into account their advantages and think about their use in the future [1].

Nuclear power plant construction is typical of large infrastructure projects around the world. Despite this, nuclear power plant costs and delivery challenges tend to be under-estimated [11].

II. Scenarios

We assume 3 different scenarios according to different share of nuclear energy in the total energy produced. Scenario 1 predicts

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an increase in the use of nuclear energy that follows the increase in the total world production of electricity, so that the share of nuclear energy will be around 9% by 2070. Scenario 2 assumes a high increase in nuclear capacity by 2100. This Scenario predicts that in 2040, nuclear energy will have a share of 25% in the total world electricity production. In 2070, it is predicted that all fossil fuel power plants will be phased out, and the share of nuclear energy will be 44%. Scenario 3 assume a very significant increase in nuclear capacity by the end of the century. Scenario 3 predicts that all fossil fuel power plants will be phased out in 2057, when the share of nuclear energy in the total world electricity production will be 51%.

In Scenario 1 we assumed very small increase in the use of nuclear energy in the future. Table 1 shows nuclear energy share, fossil fuel power energy's share and the share of renewable energy sources with hydropower plants (RES) for Scenario 1. At the same time, the use of fossil fuel power plants is slowly decreasing.

TABLE I
NUCLEAR SHARE, FOSSIL FUEL POWER PLANT SHARE AND RES SHARE (%) IN TOTAL ENERGY PRODUCTION BY THE END OF A CENTURY FOR SCENARIO I

The year	Nuclear energy share (%)	Fossil fuel power plant share (%)	The share of RES (including hydropower plants) (%)
2030	10.5	52.1	37.4
2040	9.4	42.5	48.1
2050	9.0	34.8	56.2
2060	9.4	28.4	62.2
2070	9.9	23.2	66.9
2080	10.4	19.0	70.6
2090	10.9	15.5	73.6
2100	11.5	12.7	75.8

It is very ungrateful and unrealistic to assume that the largest share of electricity produced in the future will come from renewable energy sources. This Scenario was intended to show that nuclear energy should be more represented in the overall production of electricity due to its economy. Apart from the fact that it is a constant and safe source of electricity, it is financially very favourable. The ecological aspect will be discussed later, too. It will also be shown that nuclear energy is favourable in terms of environmental impact and carbon dioxide emissions into the atmosphere. Nevertheless, it is assumed that an efficient way of energy storage will be found in the future.

In Scenario 2 we assumed moderate reduction in the use of fossil fuel power plants. Table 2 shows the share of nuclear capacity, thermal power plants and the share of renewable energy sources for Scenario 2 by the end of the century.

TABLE II
THE SHARE OF NUCLEAR POWER PLANTS, FOSSIL FUEL PLANTS AND PLANTS BASED ON RES (INCLUDING HYDROPOWER PLANTS) (%) IN THE PRODUCTION OF ELECTRICITY IN THE WORLD BY THE END OF THE CENTURY FOR SCENARIO 2

The year	Nuclear energy share (%)	Thermal power plant share (%)	The share of RES (including hydropower plants) (%)
2030	11.8	52.0	36.2
2040	25.8	31.2	43.0
2050	34.7	10.9	54.4
2060	43.7	3.8	52.5
2070	44.5	0	55.5
2080	45.4	0	54.6
2090	46.3	0	53.7
2100	47.2	0	52.8

The increase in the share of nuclear energy is high. The share of use of fossil fuel power plants is continuously decreasing. Fossil fuel power plants are the biggest polluters of all electricity production facilities. For this reason, efforts are being made to reduce the use of fossil fuel power plants in the future due to limited fossil fuel supplies. At the same time, the development and utilization of technologies using renewable energy sources are encouraged. Poland, where the share of fossil fuels in electricity production was 73% in 2023, can be taken as an example. Thus, Poland is responsible for as much as 0.89% of the total global CO_2 emissions [12]. Annual CO_2 emission in Poland amounts to approximately 340 million tonnes (227 billion m^3). Compared to the emissions in the European Union, Poland was ranked as the fourth country with the largest greenhouse gas emissions (GHG) in 2018 which causes a major air pollution problem [13]. In 2010 Poland lost 48544 years of life to air pollution. Economic cost from air pollution was US$ 101 billion [14]. Despite significant efforts to reduce polluting air emissions, during and after the economic transition in the 1990s, Poland remains home to many of the most polluted cities in the European Union (EU). Annual average ambient concentrations of fine particulate matter (PM 2.5 concentrations) are often multiple times the maximum levels allowed under EU law (25 $\mu g/m^3$) and the WHO (World Health Organisation) air quality guideline value (10 $\mu g/m^3$). The most widespread exceeds of EU air quality Limit Values are seen in south and southwestern Poland [15].

In Scenario 3 we assume a very significant increase in nuclear capacity by the end of the century and the complete abolition of fossil fuel power plants by 2057. Table 3 shows the assumed increase.

TABLE III
THE SHARE OF NUCLEAR POWER PLANTS, FOSSIL FUEL PLANTS AND PLANTS BASED ON RES (INCLUDING HYDROPOWER PLANTS) (%) IN THE PRODUCTION OF ELECTRICITY IN THE WORLD BY THE END OF THE CENTURY FOR SCENARIO 3

The year	Nuclear energy share (%)	Thermal power plant share (%)	The share of RES (including hydropower plants) (%)
2030	13.9	40.6	45.5
2040	22.7	17.6	59.7
2050	36.7	6.1	57.2
2060	58.7	0	41.3
2070	59.9	0	40.1
2080	61.1	0	38.9
2090	62.3	0	37.7
2100	63.5	0	36.5

Renewable energy sources and hydropower take the largest share for the first couple of decades while conditions are created for a large increase in the share of nuclear energy in Scenario 3.

The use of renewable energy sources has greatly increased in developed countries in the last few decades. The assumption is that this increase will be even greater in the coming years as we discussed already in the introduction. A large increase in the use of renewable energy sources (especially wind generators and solar photovoltaic technology) is still expected in developing countries.

III. LEVELISED COST OF ELECTRICITY

WEO 2022 uses the levelised cost of electricity (LCOE) as a well established, transparent, and intuitive metric, widely used in policy making, modelling and public discussion [5]. It is the total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period, hence typically cost per megawatt hour. It takes into

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account the financing costs of the capital component (not just the 'overnight' cost) [11]. We will use the value LCOE but a little bit modified. We used the mean LCOE value that we obtained as the LCOE arithmetic mean of all systems larger than 1 MW.

We calculated average LCOE for nuclear power plants and fossil fuel power plants and they are 44.74 USD/MWh and 92.57 USD/MWh, respectively.

Predictions for the use of different renewable energy sources in the future from WEO2022 were taken into account. The average value for solar technology, onshore wind technology, offshore wind technology, hydropower technology and biomass is calculated. LCOE for solar technology, wind technology, hydropower, and biomass is 68.16 USD/MWh, 72.82 USD/MWh, 77.64 USD/MWh, and 88.56 USD/MWh, respectively. Then, the average LCOE value for renewable energy sources is calculated according to what proportion of which source will be used in the future. These predictions are taken from WEO 2022.

IV. Results

We used the data of the total produced electricity from Chapter 2 and the mean LCOE value from Chapter 3. After the calculation, the following figures are obtained.

The Figure 4 shows the distribution of financial resources invested in different types of power plants (fossil fuel power plants, nuclear power plants and renewable energy power plants) for Scenario 1 until the end of the century.

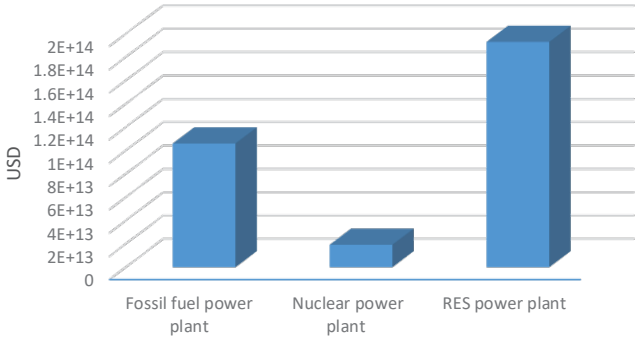

Fig. 4. Costs for the Scenario 1

The Figure 5 shows the distribution of financial resources invested in different types of power plants (fossil fuel power plants, nuclear power plants and renewable energy power plants) for Scenario 2 until the end of the century.

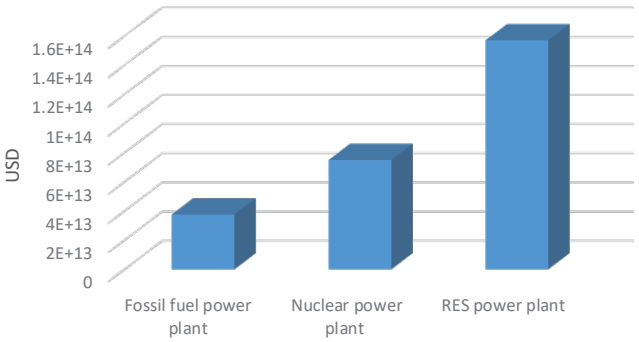

Fig. 5. Costs for the Scenario 2

The Figure 6 shows the distribution of financial resources invested in different types of power plants (fossil fuel power plants, nuclear power plants and renewable energy power plants) for Scenario 3 until the end of the century.

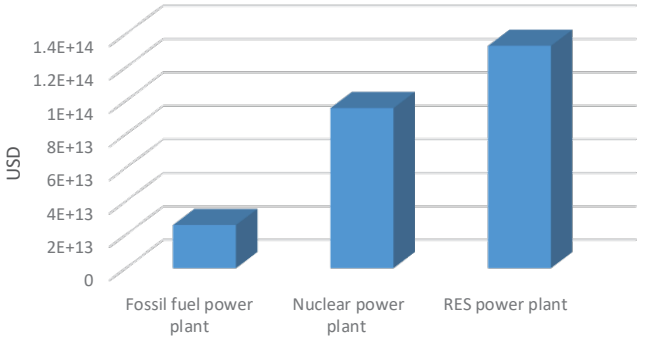

Fig. 6. Costs for the Scenario 3

The Figure 7 shows a comparison of the costs for all three scenarios to the year 2100.

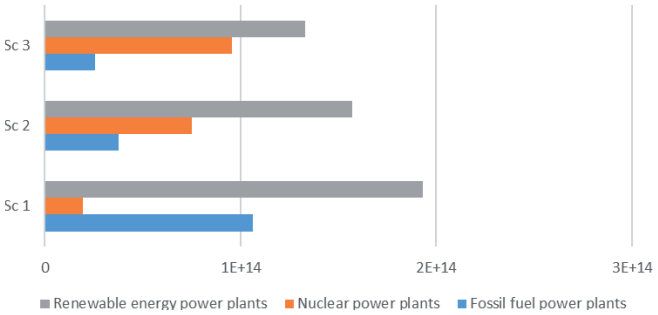

Fig. 7. The comparison of costs for all 3 scenarios by the end of the century

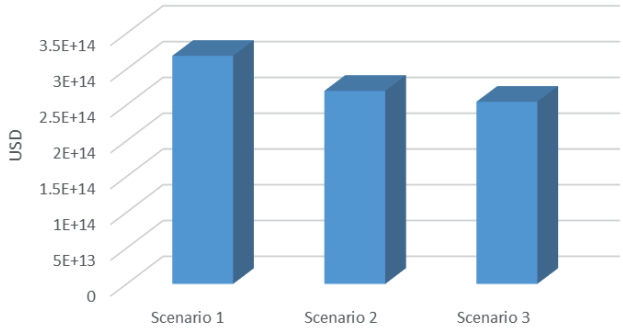

Fig. 8. The total costs for all 3 scenarios by the year 2100.

From the Figure 8 it is evident that the most money for produced electricity in the world by the end of the century is spent in the first Scenario. The first Scenario implies the smallest increase in the use of nuclear energy in the future. From the Figure 8 we can see that electrical energy in kWh obtained from nuclear sources results in the lowest financing costs for a long time.

It is preferable to use nuclear energy in combination with energy from renewable energy sources due to the low impact on the environment and climate change.

V. GHG Emissions

Another important factor affecting electricity markets is the cost of carbon dioxide (CO_2) emissions, which should make nuclear power more attractive by raising the costs of fossil-fired competitors [16]. Using data for GHG emissions per produced TWh of electricity from different energy sources [17], [18], mean values were calculated for each source of electrical energy individually. Predictions for the use of different types of fossil fuels and renewable energy sources in the future from WEO 2022 were also taken into account.

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The calculated values for GHG emissions are presented in Figure 9. Scenario 1 has by far the highest CO_2 emissions compared to Scenario 2 and Scenario 3. This is especially evident from the column (red) showing the assumed emissions from fossil power plants (Figure 9.).

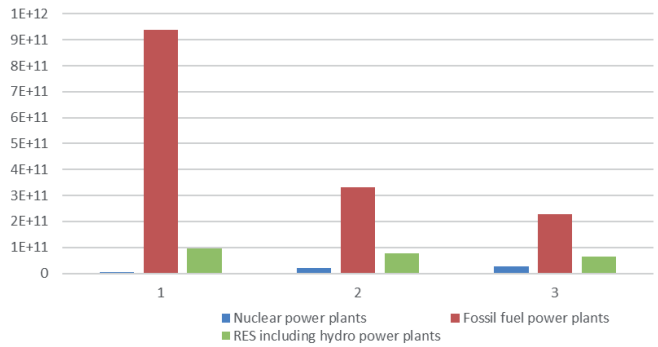

Figure 9. GHG emissions according to energy sources for Scenario 1, 2 and 3

VI. Conclusion

Electricity production is one of the strategic plans of every country. Most countries in the world have to plan electricity production with their neighbours as well as countries in the wider region. It is known that nuclear energy is a safe and reliable source of electricity. In addition, it is an energy source that is environmentally friendly due to low GHG emissions.

In this paper, scenarios were analysed that predict a medium, high and very high share of the use of nuclear energy in the world by the end of this century. It turned out, as we expected, that nuclear energy is among the most profitable energy sources. In scenarios predicting a higher percentage of nuclear power than today, less money was spent than in scenarios with a low nuclear power share.

Nuclear energy, in addition to being a safe, reliable, and environmentally friendly source, is also an economically very profitable source of electricity.

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