A Comparison of the Radioactive Waste Produced for Different Nuclear Energy Development Scenarios

Dinka Lale
University of Dubrovnik, Department of Electrical Engineering and Computing
Ćira Carića 4, 20000 Dubrovnik, Croatia
dinka.lale@unidu.hr

Dubravko Pevec, Vladimir Knapp, Mario Matijević
University of Zagreb, Faculty of Electrical Engineering and Computing
Unska 3, 10000 Zagreb, Croatia
dubravko.pevec@fer.hr; vladimir.knapp@fer.hr, mario.matijevic@fer.hr

ABSTRACT

Climate change is increasingly affecting humanity. Electrical energy generation based on nuclear technologies can compete with the other energy generating technologies due to constant capacity factors and low greenhouse gas (GHG) emissions. The specific GHG emissions of nuclear power plants are among the lowest of any electricity generation method. Global primary energy needs rise more slowly than in the past, but still an increase of 25% between today and 2040 is expected according to World Energy Outlook 2018. 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 13929.6 TWh produced electricity in the year 2040. In addition, we assume that all thermal power plants will be replaced by uranium or thorium fuel cycle nuclear power plants by the year 2056. This paper describes a comparison of six different long term nuclear energy development scenarios according to production of radioactive waste. In the first scenario only pressurized water reactors (PWR) power plants will be used by the end of this century. In the second scenario PWR power plants will be used until 2050 and after that year fast breeder reactor (FBR) nuclear power plant will be introduced gradually. In the third scenario PWR power plants will be used until 2050 and after that year molten salt thorium reactors (MSTR) power plants will be introduced gradually. These scenarios are compared according to production of radioactive waste (volume and activity).

Keywords: *Climate change, GHG emissions, Fast breeder reactors, Thorium fuel cycle, Radioactive waste*

1 INTRODUCTION

Global warming is a new problem that humanity is facing, so finding a solution is one additional problem. Economic development on the one side, as well as the constant increase in earth population on another, causes an increasing energy consumption. Also, the production and use of primary and electric energy causes the release of carbon dioxide into the atmosphere. Green House Gas (GHG) emissions are the main cause for climate change, which is increasingly affecting our planet. Humanity is in constant search for new energy sources to meet its own energy needs [1] [2].

Previous Intergovernmental Panel on Climate Change (IPCC) reports request a limit of 2°C increase of the Earth's surface average temperature. The IPCC, 2018 report, calls for a restriction on the increase in the average Earth's surface temperature of 1.5°C compared to the pre-industrial period. Unfortunately, the result of the analyses in the IPCC report is that these 1.5°C will be reached between 2030 and 2052, depending on the further emission of greenhouse gases into the atmosphere [2].

To measure how the climate is changing, scientists have looked at key indicators. The average temperature of the Earth`s surface over the last decade is 1.1 ºC higher compared with the late 19th century. Each of the last four decades has been successively the warmest on record since 1850. Levels of gases that trap heat in our atmosphere continue to increase rapidly – current carbon dioxide levels are now the highest in at least 2 million years. They result from burning fossil fuels and deforestation [3].

The latest IPCC report [3] tells us that changes in climate are rapid, widespread and intensifying and that humans are the main cause of these changes. Understanding these changes and the consequences of future emissions will help governments and communities to make decisions and take actions.

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 [1] [3] [4]. In that case, it is important to determine the amount of radioactive waste produced.

2 MOTIVATION

The aim of this paper is to determine radioactive waste amount for different scenarios of nuclear energy use in the future.

Electrical energy generation based on nuclear technologies can compete with the other energy generating technologies due to constant capacity factors and low GHG emissions. The specific GHG emissions of nuclear power plants are among the lowest of any electricity generation method [1] [4].

In addition, uranium and thorium reserves have been estimated by the categories in the Red Book 2018. Changes of uranium reserves are analysed and found to be increased in almost all categories with exploitative prices every year. It can be assumed that uranium reserves will be higher than those listed in the Red Book of 2018 in the future. Furthermore, as uranium demand grows, the cost of exploitation of $ 260 per kilogram of uranium will be acceptable. The current marginal cost of uranium exploiting is $ 180 per kilogram of uranium. The identified uranium reserves are 6 142 200 tonnes of uranium, conventional uranium reserves are 12 284 200 tonnes of uranium, and the total uranium reserves are 50 Mt of uranium. For thorium, its supplies are considerable. The consumption of thorium in the thorium fuel cycle is lower than the consumption of uranium in the uranium fuel cycle. The International Thorium Energy Organization lists low and high estimates of thorium reserve. The low is 6 711 800 tonnes of thorium and the high is 7 571 800 tonnes of thorium [1] [5] [6] [7] [8].

When it comes to electricity production in nuclear power plants, the problem of radioactive waste is always emphasized. Radioactive Waste (RW) is a demanding problem that is raising tensions and misunderstanding amongst the general public, experts and policy makers. It is necessary to examine the amount of RW produced during the electricity production. This paper aims to indicate which nuclear technology produces the least amount of radioactive waste [1].

The specific volume and activity of RW for Pressured Water Reactors (PWR), Fast Breeder Reactor (FBR) and Molten Salt Thorium Reactor (MSTR) power plants were calculated and given in [1]. Based on these data, the volume and activity of RW produced at nuclear power plants of various types were calculated. These power plants are used to produce presumed electricity globally by the end of this century, which is described in the scenarios in this paper.

3 SCENARIOS

We assumed the future demand for primary energy by the end of the century in the world and then the future electricity demand globally by 2100.

Two different scenarios of increased nuclear energy growth in the future in the world are described. Scenario 1 assumes a moderate increase in nuclear capacity by 2100, while scenario 2 assumes a significant increase in nuclear capacity by the end of the century. Scenario 1 is divided into 3 different sub-scenarios depending on what type of nuclear power plant and fuel cycle it is planned to be used in the future (Figure 1). Scenario 1a uses only PWR power plants and the uranium fuel cycle without reprocessing (Figure 2). Scenario 1b uses PWR power plants until 2050, when FBR power plants are introduced using the uranium cycle with reprocessing (Figure 3). Scenario 1c uses PWR power plants until 2050 when MSTR power plants with a thorium fuel cycle are gradually introduced. For all fuel cycles which are planned to be used in the described scenarios capacity factor is 0.80 by the year 2030. It gradually increases from 0.80 (year 2030) to 0.90 (year 2060). After 2060 a large capacity factor of 0.90 is assumed [1].

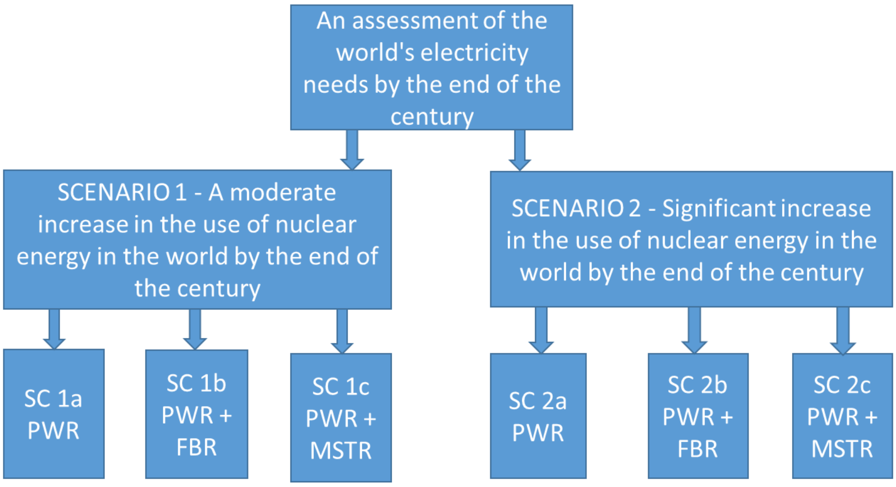

Figure 1: An assessment of the world's electricity needs by the end of the century is the starting point for scenario 1, which is further divided into scenario 1a, scenario 1b and scenario 1c, and scenario 2, which is further divided into scenario 2a, scenario 2b and scenario 2c, all depending on the share of nuclear energy as well as the use of different types of nuclear power plants

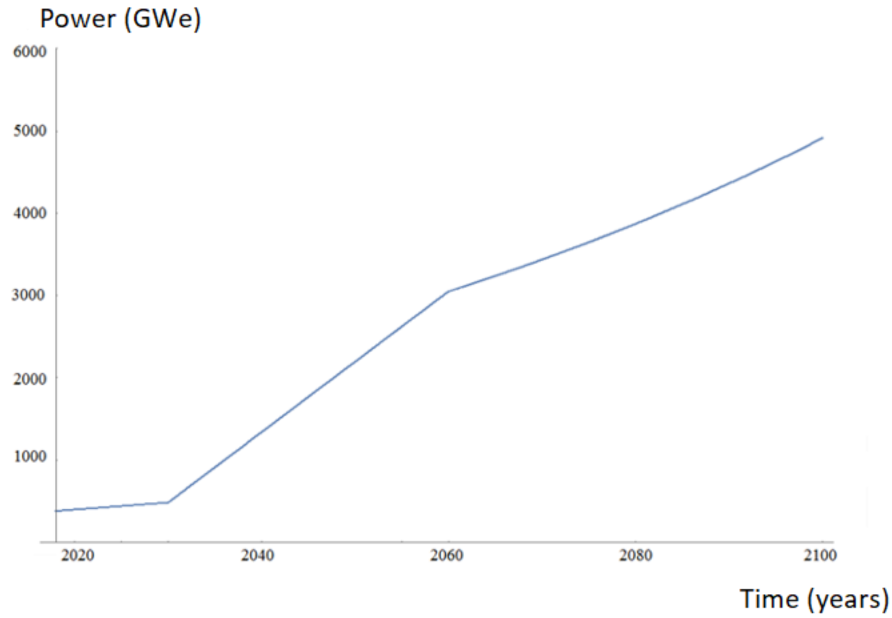

Figure 2: Assumed installed capacity of PWR type nuclear facilities for scenario 1a up to 2110

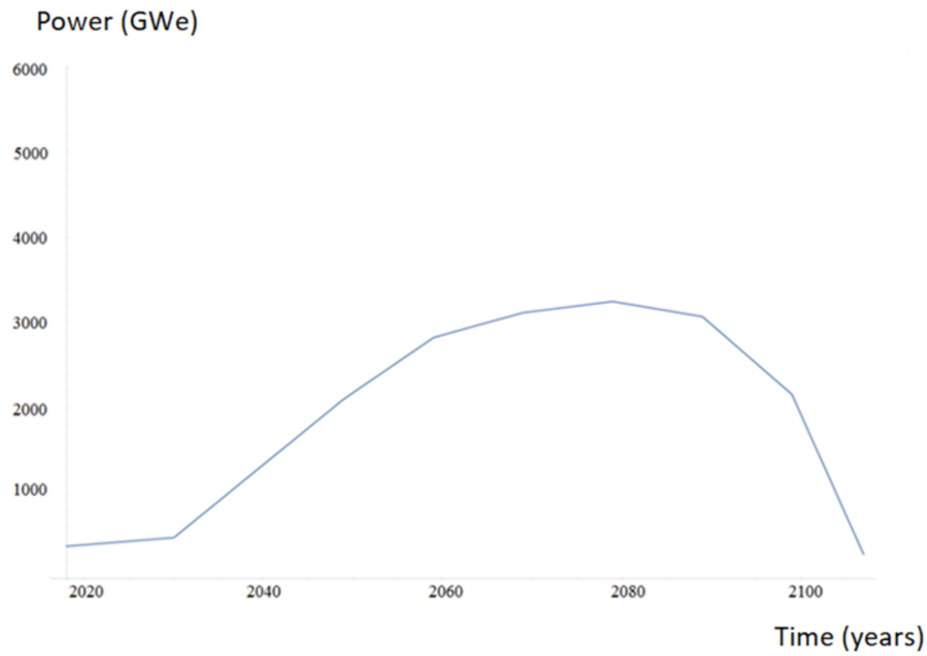

Figure 3: Assumed installed nuclear capacity in PWR facilities for scenario 1b and scenario 1c up to 2110

Scenario 2 is equally divided into three sub-scenarios 2a, 2b and 2c, depending on which type of nuclear power plant and fuel cycle which is planned to be used in the future (Figure 1). Scenario 2a uses only PWR power plants and the uranium fuel cycle without reprocessing (Figure 4). Scenario 2b uses PWR power plants until 2050, when FBR power plants are introduced using the uranium cycle with reprocessing (Figure 5). For all fuel cycles which are planned to be used in the described scenarios a large capacity factor of 0.90 after 2060 is assumed [1].

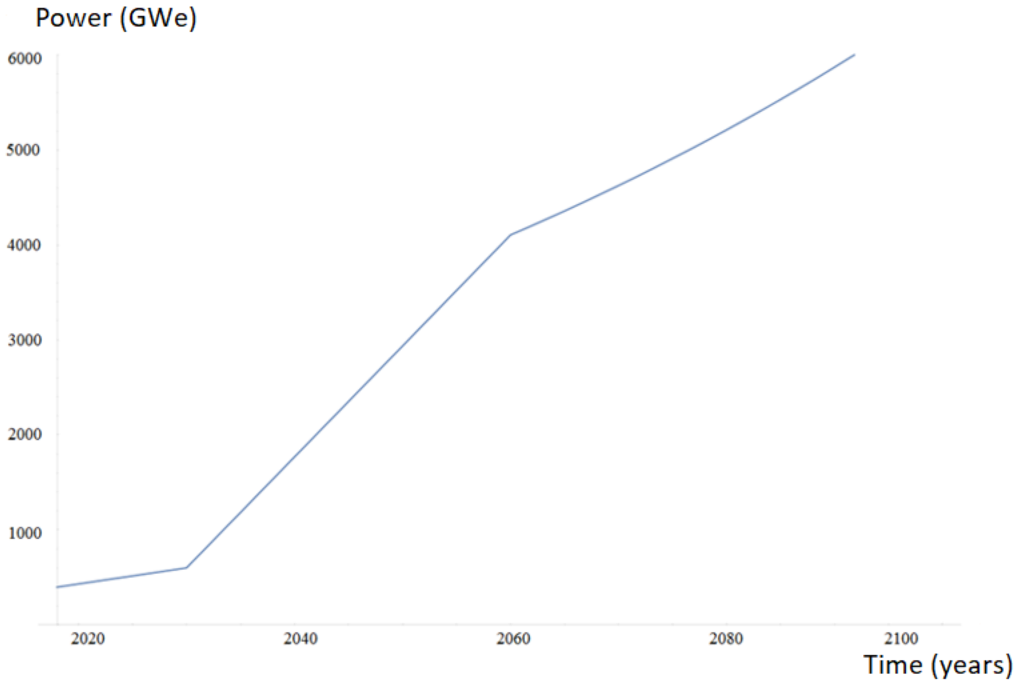

Figure 4: Assumed installed capacity of PWR type nuclear facilities for scenario 2a up to 2110

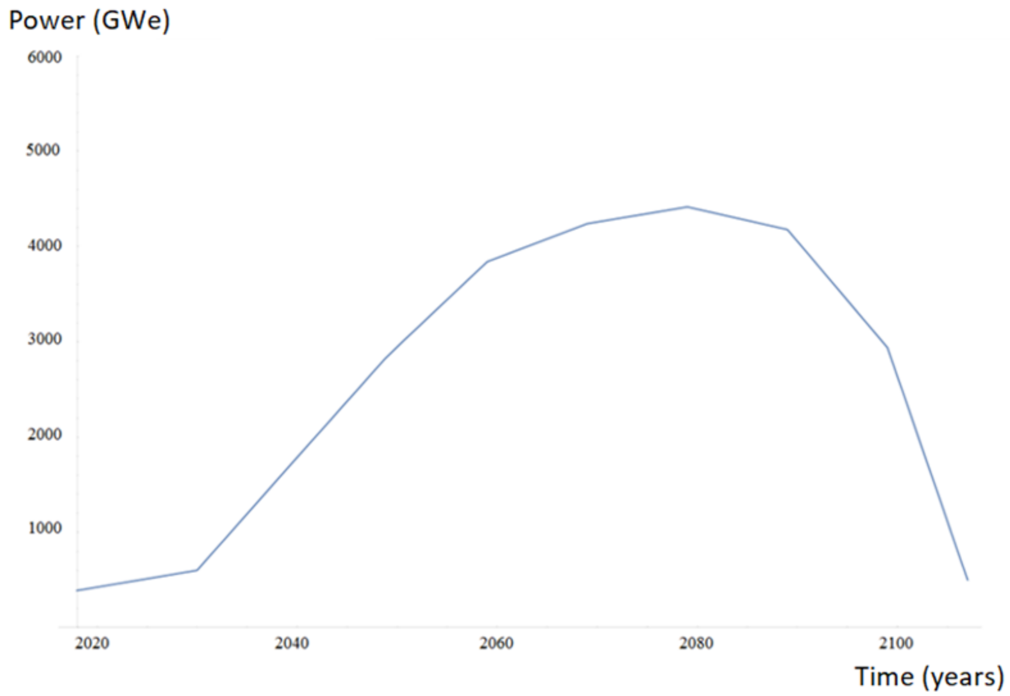

Figure 5: Assumed installed nuclear capacity in PWR facilities for scenario 2b and scenario 2c up to 2110

4 RADIOACTIVE WASTE

RW of various types results from any activity that makes use of nuclear materials, including medical and industrial uses. However, nuclear energy is the most important source of such wastes because of the large volumes generated and its long-lived nature [9].

RW is typically classified as either low-level (LLW), intermediate-level (ILW), or high-level (HLW), depends, primarily, on its level of radioactivity. LLW comprises some 90% of the volume but only 1% of the radioactivity of all radioactive waste. ILW makes up some 7% of the volume and has 4% of the radioactivity of all radioactive waste. HLW accounts for just 3% of the volume, but 95% of the total radioactivity of producing waste [10].

Values of specific volumes and activities of RW (volume or activity of radioactive waste per unit of electricity produced) are determined for PWR power plants, FBR power plants and MSTR power plants.

Certain data come directly from references [11] and [12]. Additional data for PWR power plants were calculated using data from [13-19] and are presented in [1]. FBR data are calculated using [20, 21, 22] and also given in [1]. Data for MSTR are less available. MSTR data are calculated using literature [10, 11, 23-26] and given in [1].

5 RESULTS

Using the specific data for RW the total volumes and activities of produced RW are calculated for all scenarios.

In terms of total waste volume (Table 1), scenario 1c is the most favourable compared to scenario 1a and scenario 1b. With regard to the total radioactive waste activity in terabecquerels (TBq) scenario 1c is the most favourable compared to scenario 1a and scenario 1b (Table 2).

Table 1: Total volume of RW in m^3 generated in the process of electricity generation from nuclear sources by 2100 for the described scenario 1a, scenario 1b and scenario 1c

	Scenario 1a	Scenario 1b	Scenario 1c
Total volume [m^3]	$1{,}079\cdot10^{10}$	$9{,}033\cdot10^{9}$	$9{,}006\cdot10^{9}$

Table 2: Total activity of RW in TBq generated in the process of electricity generation in nuclear power plants by 2100 for scenario 1a, scenario 1b and scenario 1c

	Scenario 1a	Scenario 1b	Scenario 1c
Total activity [TBq]	$1{,}667\cdot10^{12}$	$7{,}381\cdot10^{11}$	$6{,}897\cdot10^{11}$

In terms of total waste volume (Table 3), scenario 2c is the most favourable compared to scenario 2a and scenario 2b. According to the total radioactive waste activity in TBq scenario 2c is the most favourable compared to scenario 2a and scenario 2b (Table 4).

Table 3: Total volume of RW in m^3 generated in the process of electricity generation from nuclear sources by 2100 for the described scenario 2a, scenario 2b and scenario 2c

	Scenario 2a	Scenario 2b	Scenario 2c
Total volume [m^3]	$1{,}459\cdot10^{10}$	$1{,}219\cdot10^{10}$	$1{,}216\cdot10^{10}$

Table 4: Total activity of RW in TBq generated in the process of electricity generation in nuclear power plants by 2100 for scenario 2a, scenario 2b and scenario 2c

	Scenario 2a	Scenario 2b	Scenario 2c
Total activity [TBq]	$2{,}252\cdot10^{12}$	$9{,}969\cdot10^{11}$	$9{,}310\cdot10^{11}$

Figure 6 shows the total volume of RW generated in scenarios 1a, 1b and 1c by the end of the century.

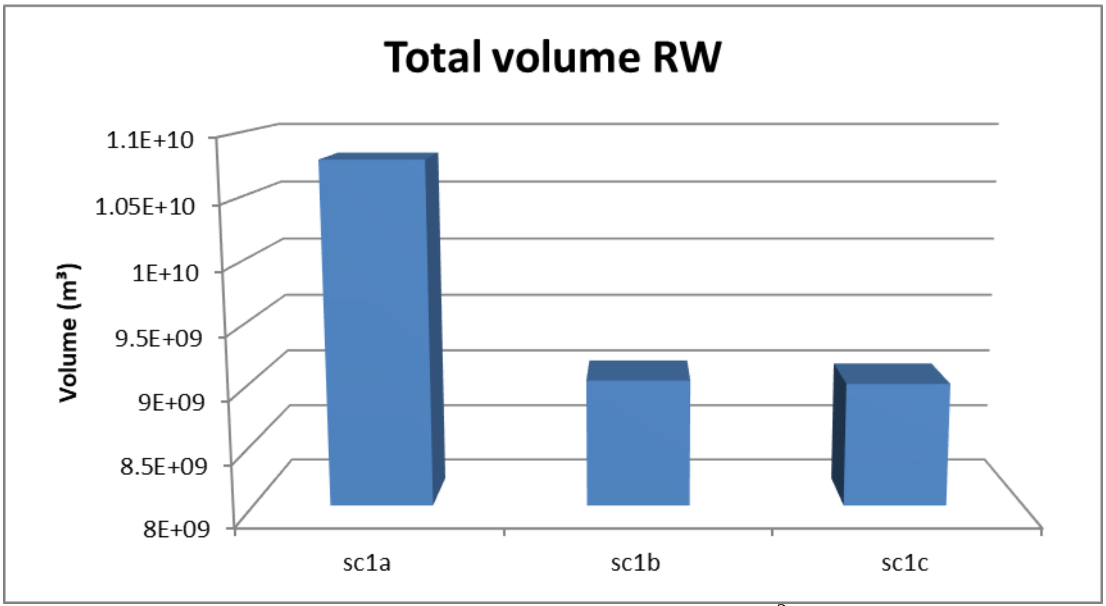

Figure 6: Comparison of the produced volume of total RW in m^3 for scenario 1a, scenario 1b and scenario 1c

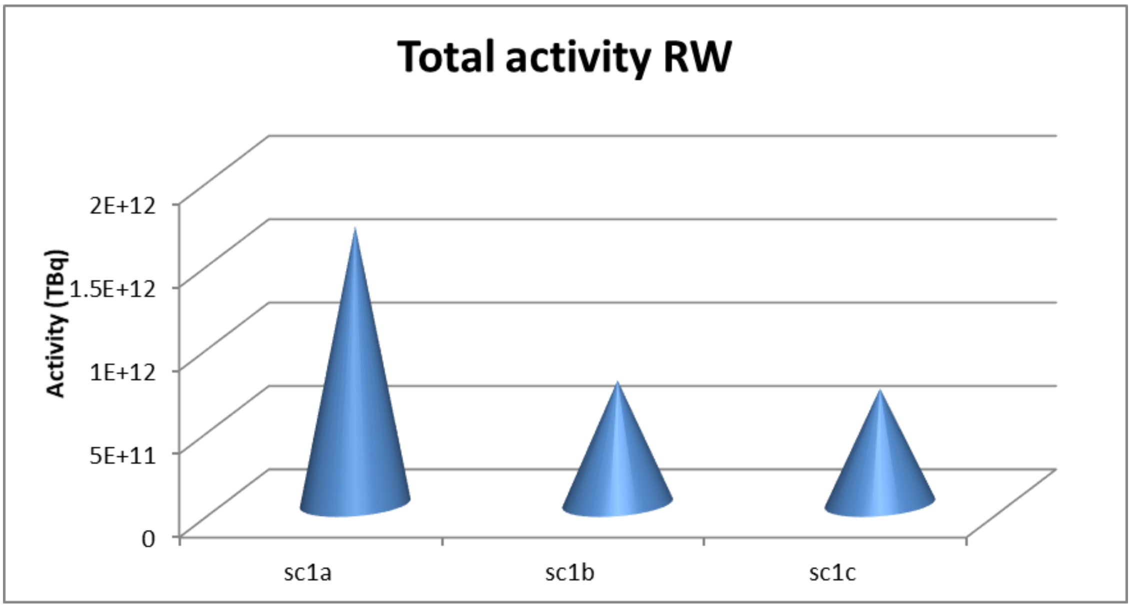

Figure 7: Comparison of generated total RW activity in TBq for scenario 1a, scenario 1b and scenario 1c

The total RW activity is highest for scenario 1a and lowest for scenario 1c (see Figure 7).

Figure 8 shows a comparison of the total RW volume produced for scenario 2a, scenario 2b and scenario 2c.

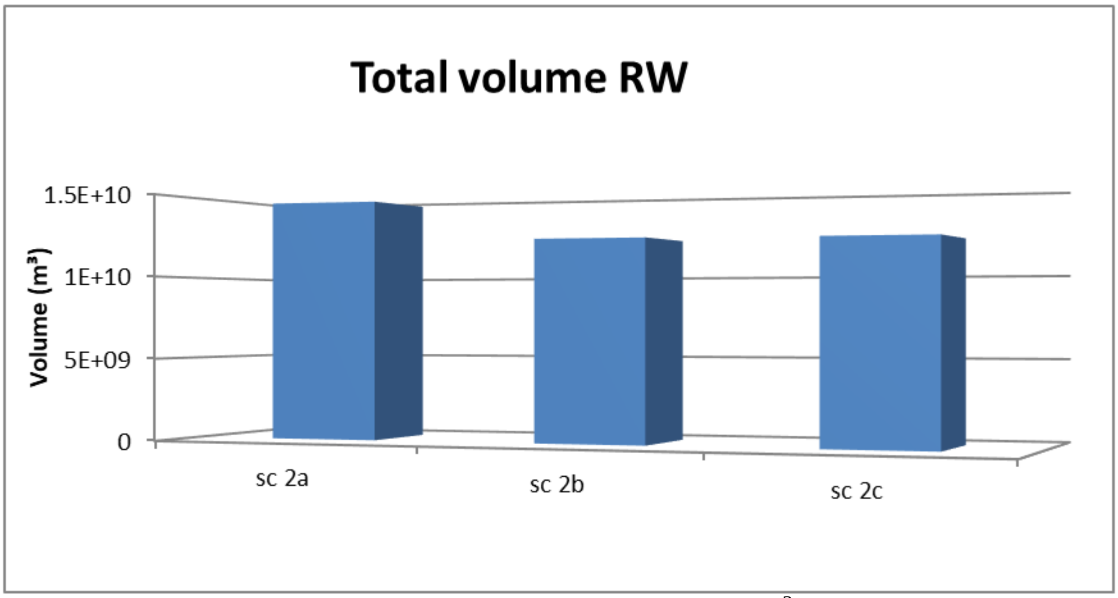

Figure 8: Comparison of the produced volume of total RW in m^3 for scenario 2a, scenario 2b and scenario 2c

The most unfavourable, in terms of total volume in m^3, is scenario 2a, while scenario 2c is the most favourable because it produced the smallest RW volume in m^3 (see Figure 8).

Figure 9 shows the total activity of RW for scenarios 2a, 2b and 2c by the end of the century.

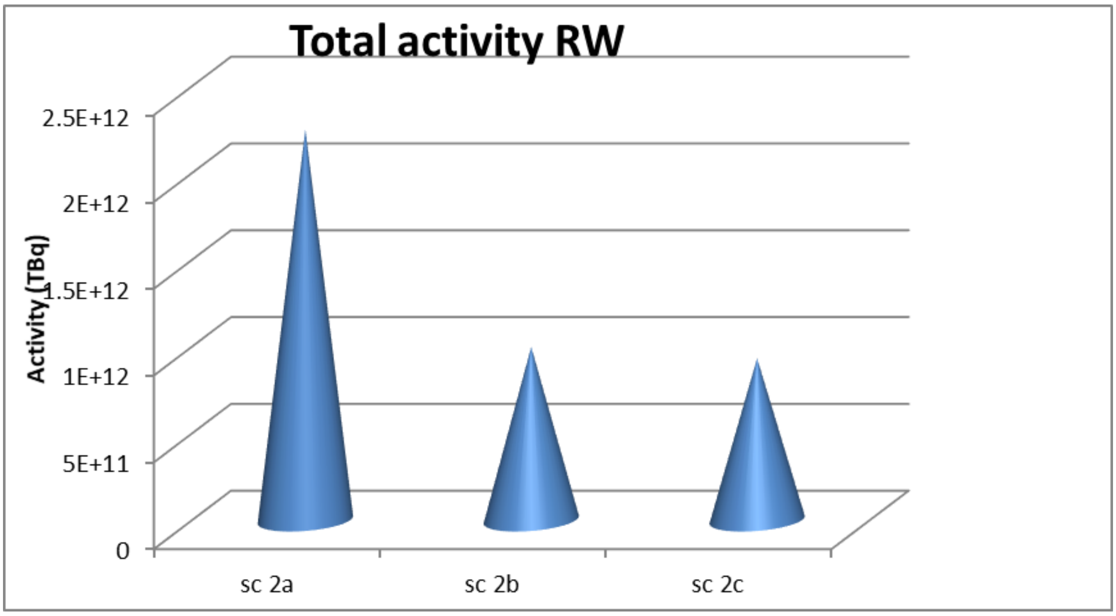

Figure 9: Comparison of generated total RW activity in TBq for scenario 2a, scenario 2b and scenario 2c

Scenario 2c is the most favourable in terms of total RW activity produced compared to scenario 2a and scenario 2b (see Figure 9).

In addition to the fact that the MSTR of nuclear power plants produces less volume and activity of RW, as shown in the calculations in [1], it should be emphasized that the radiotoxicity, which was not discussed in this paper, is significantly reduced for the thorium fuel cycle than for uranium fuel cycle [27]. After 300 years, the radioactivity of the thorium fuel cycle waste is 10,000 times lower than that of the uranium fuel cycle waste.

6 CONCLUSION

Taking into account all the data presented concerning the assumed scenarios of future nuclear energy growth globally (the total volume of RW and total RW activity for all scenarios) we conclude that scenario 1c which uses PWR power plants and MSTR power plants by the end of the century, is the optimal solution in relation to scenario 1a and 1b. Also, the scenario 2c using PWR power plants and MSTR power plants by 2100 is optimal over scenario 2a and scenario 2b, i.e. the scenarios which use MSTR nuclear technology are the most favourable.

One disadvantage of scenario 1c and scenario 2c, is that MSTR power plants were not commercially utilised such as PWR power plants or in much less percentage FBR power plants. However, there is still enough time to develop MSTR technology and significant efforts are being made to realize MSTR as part of the development of Generation IV reactors.

The advantage of using thorium is cited in many articles [23], [24], [26], [27] and [28]. The idea of using MSTR power plants in the future should not be rejected if the only reason is the lack of experience in operating MSTR power plants in relation to PWR power plants or FBR power plants.

Scenario 1c is more realistic compared to the optimistic scenario 2c, which has a significant share of nuclear energy in total electricity production, and thereby a higher volume and activity of radioactive waste produced. However, the CO2eq emission savings are very high for scenario 2c. Therefore, it is reasonable to conclude that scenario 2c is the most favourable scenario from a climate point of view.

REFERENCES

[1] Lale D. „Procjena dostatnosti zaliha nuklearnoga goriva u slučaju značajnoga doprinosa nuklearne energije u rješavanju problema globalnoga zatopljenja“, doctoral thesis, Faculty of electrical engineering and computing, Zagreb, 2020.

[2] IPCC Summary for Policymakers, 2018, Retrieved February 10, 2019, from: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf

[3] Climate change 2021: “The Physical Science Basis”, Sixth Assessment Report, Working Group I: The Physical Science Basis

[4] WNA Report, “Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources”, 2011, Retrieved October 12, 2017, from: http://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf

[5] OECD-NEA, „Uranium 2018: Resources, Production and Demand“, (Red book 2018), OECD 2018 NEA No. 7413, Retrieved January 14, 2019, from: https://www.oecd-nea.org/ndd/pubs/2018/7413-uranium-2018.pdf

[6] OECD-NEA, „Uranium 2016: Resources, Production and Demand“, (Red book 2016), OECD 2016 NEA No. 7301, Retrieved March 25, 2018, from: https://www.oecd-nea.org/ndd/pubs/2016/7301-uranium-2016.pdf

[7] Knapp, V., Pevec□, D. „Promises and limitations of nuclear fission energy in combating climate change“, Energy Policy, Volume 120, 2018., str. 94-99

[8] Pevec, D., Knapp, V., Matijević, M., “Availability of the nuclear fuel for long-term expansion of nuclear power”, *In Proceedings of the* 8^{th} *International Conference of the Croatian Nuclear*

Society " Nuclear Option in Countries with Small and Medium Electricity Grids", Dubrovnik, Croatia, 2010.

[9] Nuclear Energy Agency, Retrieved April 29, 2022, from: https://www.oecd-nea.org/jcms/c_12892/radioactive-waste-management

[10] Radioactive Waste Management, WNA, Retrieved April 28, 2022, from: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx

[11] IAEA, „Estimation of Global Inventories of Radioactive Waste and Other Radioactive Waste“, IAEA – TECDOC – 1591, 2008, Retrieved January 17, 2018, from: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1591_web.pdf

[12] OECD, „Advanced Nuclear Fuel Cycle and Radioactive Waste Management“, NEA, 2006, 5990pdf, Retrieved January 15, 2018, from: https://www.oecd-nea.org/ndd/pubs/2006/5990-advanced-nfc-rwm.pdf

[13] OECD NEA, „Uranium 2005: Resources, Production and Demand“, (Red Book 2006) OECD NEA No. 6098, 2006, Retrieved January 15, 2018, from: https://www.oecd-nea.org/ndd/pubs/2006/6098-uranium-2005.pdf

[14] World Nuclear Association, 2018, Retrieved August 10, 2018, from: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx

[15] Tehnički podaci NE Krško, Retrieved December 27, 2019, from: https://www.nek.si/hr/o-nuklearnoj-tehnologiji/tehnicki-podaci

[16] AEA, „Waste From Innovative Types of Reactors and Fuel Cycles“, A Preliminary Study, International Atomic Energy Agency, Nuclear Energy Series, 2019, No. NW-T-1.7

[17] LILW Data, Retrieved December 27, 2019, from: http://www.arao.si/lilw-data

[18] NEK, Retrieved September 21, 2018, from: https://www.nek.si/en/about-nek/production

[19] IAEA, „Options for Management of Spent Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes“, Nuclear Energy Series No. NW-T-1.24, Vienna 2018

[20] Rybin, A.A., Momot, O.A., „Radioactive waste from decommissioning of fast reactors (through the example of BN-800)“ Conf. Ser. 781 012013, 2017.

[21] Guidez, J., Prêle, G., „Superphenix Technical and Scientific Achievements“, ISBN 978-94-6239-245-8 ISBN 978-94-6239-246-5 (eBook), DOI 10.2991/978-94-6239-246-5, 2017, Library of Congress Control Number: 2016955925, © Atlantis Press

[22] Density of Concrete, Retrieved December 31, 2019, from: https://hypertextbook.com/facts/1999/KatrinaJones.shtml

[23] Baker Schaffer, M., „Abundant thorium as an alternative nuclear fuel Important waste disposal and weapon proliferation advantages“, RAND Corporation, United State, Energy Policy 60, 2013., page 4–12

[24] LeBlanc, D., „Molten salt reactors: A new beginning for an old idea“, Physics Department, Carleton University, Canada K15 5B6, Ottawa Valley Research Associates Ltd., Canada, Nuclear Engineering and Design, NED-5613; 2010, No. of Pages 13

[25] Aniza, C.N., Zainul Bahri, C., Amran Ab. Majid, Wadeeah M., A., “Advantages of liquid fluoride thorium reactor in comparison with light water reactor”, AIP Conference Proceedings 1659, 040001, Published Online: 29 April 2015, Retrieved September 12, 2019, from: https://doi.org/10.1063/1.4916861

[26] Pool, L.M., “Advantages & disadvantages of thorium fuelled nuclear power when generated in the Liquid Fluoride Thorium Reactor compared to uranium fuelled nuclear power & stakeholders in the decision making process”, Supervisors: Conny Dröge-Pott & Egbert Dommerholt, Co-marker: Arnd Mehrtens, Commissioned by: IBS-lectoraat, #343236, 2014.

[27] Hargraves, R., Moir, R., “Liquid Fluoride Thorium Reactors An old idea in nuclear power gets re-examined”, American Scientist, Volume 98, 2010., Retrieved September 23, 2019, from: http://thorconpower.com/docs/hargraves_moir_2010.pdf

[28] Knapp, V., Pevec, D., Matijević, M., Lale, D., „Molten Salt Thorium Reactor - A Promising Nuclear Technology to Stop Global Warming“ // Proceedings of the 10th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids, Zadar, Croatia, 2014., page 149-157