The development of nuclear power and related environmental evaluation due to nuclear accidents

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Abstract. Nuclear power has played a pivotal role in meeting the growing global energy demand. However, the development of nuclear energy has been punctuated by a series of high-profile accidents, such as Chernobyl and Fukushima, which have raised significant concerns regarding its environmental impact. This paper aims to evaluate nuclear energy through data by using additional methods and to provide an overview of historical development of nuclear power technology and nuclear accidents. In order to evaluate thoroughly, the method of ratio estimation had been applied to find the trend for nuclear energy in previous decades and the potential development in the future. As a result, it emphasizes the effectiveness of nuclear energy changes structure of energy outputs in some countries. France, for instance, has already placed nuclear power as the main source for clear energy output. The paper proofs the development of nuclear power has been marked by significant improvements in safety and environmental consciousness. However, the specter of nuclear accidents looms large, necessitating ongoing vigilance and robust environmental evaluation processes. Despite that, the paper still contains additional assumption needed to be solved or explained.

1 Introduction

The utilization of nuclear power has emerged as a pivotal aspect of modern energy production, promising substantial benefits in terms of efficiency, reliability, and reduced greenhouse gas emissions. However, this technological advancement also brings with it complex challenges, particularly concerning the potential environmental ramifications stemming from nuclear accidents. These accidents have underlined the critical need for thorough and accurate environmental evaluations, not only to gauge the immediate impacts but also to comprehend the long-term consequences on ecosystems, human health, and the broader environment. Three famous nuclear accidents showcase the consequences of using nuclear energy: On March 11, 2011, the accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) in Japan shocked the world. Approximately one hour after a powerful earthquake of approximately 9.0 magnitude struck the Pacific Ocean near Japan's eastern coastline, two enormous tsunamis were generated, and these subsequently hit Japan. The occurrence of the tsunamis was a direct result of the earthquake [1]. The earthquake caused significant damage to the main electric power grid, rendering it inoperative.

Additionally, the backup power supply was affected by seawater intrusion, resulting in a loss of power. Consequently, the cooling systems of the four nuclear reactors were disrupted. This disruption led to heightened pressure levels and the generation of hydrogen gas due to the extreme heating of the cooling water. Over the subsequent days, the release of large amounts of radioactivity into the atmosphere was triggered by hydrogen explosions. In order to prevent further escalation of damage and more substantial releases of radioactive materials, plant managers made the decision to use seawater as a cooling medium [2]. Besides, Large quantities of radioactive substances were released into the Pacific Ocean, causing irreversible effects on the marine ecosystem. Over 80% of the radionuclides released into the atmosphere during the Fukushima disaster are believed to have dispersed offshore, with subsequent deposition occurring in the Pacific Ocean [3]. Radionuclides originating from Fukushima were detected in seawater and marine organisms across the Pacific Ocean, as evidenced by various studies[4]. The Monticello nuclear power plant on the banks of the Mississippi River suffered a radioactive water leak on Nov. 21 last year, causing 1.5 million liters of tritium-containing effluent to escape; The Chernobyl nuclear accident occurred on April 26, 1986, during a technical test conducted in Unit 4 of the Chernobyl Nuclear Power Plant (NPP). The accident was triggered by inappropriate reactor operation at a low power level, which resulted in the "xenon-poisoning" of the reactor. Unfortunately, the reactor staff did not properly recognize this issue, which led to improper operation of the reactor's control rods [5]. The operating error resulted in a rapid and uncontrolled increase in power within the RBMK-1000 reactor, leading to its thermal destruction. This, in turn, caused at least one

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(steam) explosion and ignited the graphite moderators [6]. Initially, Chernobyl's "exclusion zone" covered a 30 km radius (2800 km2) around the Nuclear Power Plant (NPP). In the months that followed the accident, around 116,000 people residing within the "exclusion zone" were evacuated to areas with lower contamination levels. Unfortunately, the evacuation process started 3 to 11 days after the accident, which, for some of the affected population, was considered delayed and resulted in increased exposure to radiation [7].

Nuclear power provides a reliable baseload source of electricity that is not dependent on weather conditions like solar and wind power [8]. Nuclear plants have very high capacity factors, typically around 90%, meaning they produce close to their maximum output consistently. Moreover, nuclear power emits virtually no greenhouse gases or air pollutants during operation, helping countries meet climate change goals and air quality standards [9]. The IPCC has identified nuclear power as a key technology for reducing CO2 emissions. More importantly, nuclear power diversifies a country's energy mix, reducing dependence on any single source and improving energy security [10]. Many studies have argued for an "all of the above" strategy, which includes nuclear power to stabilize the electricity supply. All these factors demonstrate that nuclear energy can effectively meet the world's energy needs to a large extent. However, the use of nuclear energy does have some environmental impacts and accidents, such as radiation risks, waste disposal, water pollution and other problems. Accidents like Fukushima and Chernobyl released huge amounts of radiation, leaving the region a wasteland; The disposal of nuclear waste has been an unsolved problem, and nuclear waste remains very dangerous for thousands of years, requiring safe long-term storage and environmental isolation. Nuclear power plants require a large amount of cooling water, and untreated direct discharge into the ocean can have a significant negative impact on Marine life.

There are numerous papers to discuss the topic of nuclear energy focused on development and evaluation. *Research status of nuclear power: A review,* its systematic approach to organizing the various aspects of nuclear power research. The categorization of topics enables readers to navigate through the complexities of the subject matter more effectively. By using a theory of Cross-country comparisons to identify the degree of development of nuclear power research in a country, which is impressive; *Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts* establishes that the aftermath of the Chernobyl incident significantly surpassed the consequences of the Fukushima accident across various aspects. Both accidents released a substantial number of volatile radionuclides such as noble gases, iodine, cesium, and tellurium. Besides, the author summarized the release of refractory elements, including actinides, during the Chernobyl incident was notably higher by approximately four orders of magnitude compared to Fukushima.

A partial of research, however, still has a space to improve. For instance, the data shown nuclear generation by countries in a paper named *nuclear power as foundation of a clean energy future: A review* (Published in 2019) is already outdated. Although the author did a comprehensively analysis, that is based on 2013 data analysis, which needs to update a new one. Also, the innovate nuclear reactors are developed some new predictable technologies in recent years, and its functions and advantages are already change; *Research status of nuclear power: A review* is not well understood or investigated, requiring further investigation.

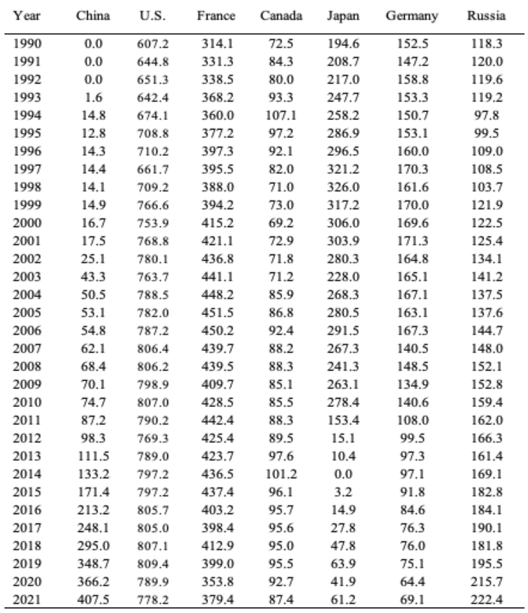
The primary objective of this research is to analyze the annual energy generation data of different nuclear energy developed countries and to evaluate the importance of nuclear energy in the country through different analytical methods. Also, the development of nuclear reactors and different nuclear leakage incidents in the world will be discussed and evaluated.

2 Materials and Methods

2.1 Data

All of the data in this paper is obtained from a data archive at www.ourworldindata.org, where articles and charts were referenced in nearly 50,000 media articles last year; and over 20,000 of these references were in large media outlets with international reach. On this website, we have collected data on renewable energy (Hydro, Wind, solar), fossil fuel consumption (oil, coal, natural gas), and nuclear power generation for seven countries from 1990 to 2021, including China, U.S, France, Canada, Japan, German, and Russia. These seven countries were chosen as the main data analyzers because they are relatively advanced in nuclear energy production and their economies are in a relatively stable and favorable condition.

The annual nuclear power generation from 1990 to 2021 for the seven selected countries is shown in Fig .1. Annual generation of different types of new energy and fossil fuels in China, U.S, France, Canada, Japan, German, and Russia, is shown in Fig 2-8, respectively.



Year	China	U.S.	France	Canada	Japan	Germany	Russia
1990	0.0	607.2	314.1	72.5	194.6	152.5	118.3
1991	0.0	644.8	331.3	84.3	208.7	147.2	120.0
1992	0.0	651.3	338.5	80.0	217.0	158.8	119.6
1993	1.6	642.4	368.2	93.3	247.7	153.3	119.2
1994	14.8	674.1	360.0	107.1	258.2	150.7	97.8
1995	12.8	708.8	377.2	97.2	286.9	153.1	99.5
1996	14.3	710.2	397.3	92.1	296.5	160.0	109.0
1997	14.4	661.7	395.5	82.0	321.2	170.3	108.5
1998	14.1	709.2	388.0	71.0	326.0	161.6	103.7
1999	14.9	766.6	394.2	73.0	317.2	170.0	121.9
2000	16.7	753.9	415.2	69.2	306.0	169.6	122.5
2001	17.5	768.8	421.1	72.9	303.9	171.3	125.4
2002	25.1	780.1	436.8	71.8	280.3	164.8	134.1
2003	43.3	763.7	441.1	71.2	228.0	165.1	141.2
2004	50.5	788.5	448.2	85.9	268.3	167.1	137.5
2005	53.1	782.0	451.5	86.8	280.5	163.1	137.6
2006	54.8	787.2	450.2	92.4	291.5	167.3	144.7
2007	62.1	806.4	439.7	88.2	267.3	140.5	148.0
2008	68.4	806.2	439.5	88.3	241.3	148.5	152.1
2009	70.1	798.9	409.7	85.1	263.1	134.9	152.8
2010	74.7	807.0	428.5	85.5	278.4	140.6	159.4
2011	87.2	790.2	442.4	88.3	153.4	108.0	162.0
2012	98.3	769.3	425.4	89.5	15.1	99.5	166.3
2013	111.5	789.0	423.7	97.6	10.4	97.3	161.4
2014	133.2	797.2	436.5	101.2	0.0	97.1	169.1
2015	171.4	797.2	437.4	96.1	3.2	91.8	182.8
2016	213.2	805.7	403.2	95.7	14.9	84.6	184.1
2017	248.1	805.0	398.4	95.6	27.8	76.3	190.1
2018	295.0	807.1	412.9	95.0	47.8	76.0	181.8
2019	348.7	809.4	399.0	95.5	63.9	75.1	195.5
2020	366.2	789.9	353.8	92.7	41.9	64.4	215.7
2021	407.5	778.2	379.4	87.4	61.2	69.1	222.4

Fig. 1 Nuclear power generation (TWh) between 1990-2021

Year	Geo Biomass Others	Solar	Wind	Hydro	Nuclear	Fossil
1990	0.06	0.00	0.00	126.74	0.00	7563.27
1991	0.06	0.00	0.01	124.69	0.00	7968.69
1992	0.11	0.00	0.13	130.69	0.00	8386.55
1993	0.12	0.00	0.21	151.85	1.60	9003.10
1994	0.46	0.01	0.38	167.43	14.76	9509.28
1995	3.01	0.01	0.62	190.58	12.83	9741.28
1996	1.53	0.01	0.09	187.97	14.34	10305.78
1997	2.72	0.01	0.20	195.98	14.42	10351.44
1998	2.48	0.01	0.36	198.89	14.10	10363.47
1999	2.52	0.02	0.47	196.58	14.95	10752.91
2000	2.54	0.02	0.59	222.41	16.74	11085.26
2001	2.55	0.03	0.72	277.43	17.47	11595.46
2002	2.55	0.05	0.84	287.97	25.13	12657.19
2003	2.54	0.06	1.00	283.68	43.34	14859.57
2004	2.53	0.08	1.28	353.54	50.47	17332.89
2005	5.32	0.08	1.95	397.02	53.09	19713.34
2006	7.13	0.10	3.71	435.79	54.84	21612.99
2007	9.86	0.11	5.48	485.26	62.13	23448.26
2008	14.87	0.15	13.10	636.96	68.39	23943.34
2009	20.86	0.28	27.61	615.64	70.05	25087.56
2010	24.90	0.70	49.40	711.38	74.74	26642.34
2011	27.63	2.61	74.10	688.05	87.20	28883.00
2012	30.13	3.59	103.05	862.79	98.32	29581.56
2013	37.13	8.37	138.26	909.61	111.50	30523.66
2014	46.27	23.51	159.76	1059.69	133.22	30937.32
2015	54.07	39.48	185.59	1114.52	171.38	31034.00
2016	62.13	66.53	240.86	1153.27	213.18	31191.84
2017	79.60	117.80	304.60	1165.07	248.10	31973.58
2018	93.73	176.90	365.80	1198.89	295.00	32888.71
2019	112.73	224.00	405.30	1272.54	348.70	33692.99
2020	135.63	261.10	466.50	1321.71	366.20	34232.88
2021	169.93	327.00	655.60	1300.00	407.50	36222.59

Fig. 2 New energy and fossil fuel generation (TWh) in China (1990-2021)

Year	Geo Biomass Others	Solar	Wind	Hydro	Nuclear	Fossil
1990	57.46	0.37	2.82	292.28	607.22	344.95
1991	60.55	0.48	2.98	287.33	644.81	420.84
1992	64.82	0.41	2.92	251.43	651.34	406.70
1993	66.92	0.48	3.04	279.25	642.41	423.47
1994	66.35	0.50	3.48	259.34	674.15	464.67
1995	63.27	0.51	3.20	311.22	708.84	484.87
1996	64.83	0.54	3.27	347.55	710.24	499.69
1997	65.82	0.53	3.32	355.97	661.73	521.46
1998	65.62	0.52	3.06	322.09	709.16	534.11
1999	66.48	0.52	4.53	316.61	766.58	538.37
2000	66.58	0.52	5.65	272.76	753.89	535.78
2001	66.83	0.57	6.81	210.24	768.83	541.57
2002	71.79	0.60	10.46	258.17	780.06	591.69
2003	71.33	0.61	11.30	269.97	763.73	631.16
2004	71.95	0.70	14.29	262.55	788.53	675.07
2005	72.60	0.75	17.99	266.43	781.99	704.60
2006	73.08	0.82	26.86	285.54	787.22	741.29
2007	73.87	1.10	34.80	243.04	806.42	818.36
2008	73.55	1.63	55.92	251.05	806.21	938.40
2009	73.16	2.08	74.63	271.53	798.85	925.56
2010	75.06	3.01	95.61	257.27	806.97	972.44
2011	75.78	4.74	121.39	316.10	790.20	1020.87
2012	77.04	9.04	142.24	274.03	769.33	1074.03
2013	80.67	16.04	169.54	266.55	789.02	1133.01
2014	84.07	29.22	183.49	255.75	797.17	1120.85
2015	83.74	39.43	192.65	246.45	797.18	1230.11
2016	82.72	55.42	229.29	263.76	805.69	1283.44
2017	82.80	78.06	256.87	296.81	804.95	1286.79
2018	81.89	94.31	275.42	289.51	807.08	1268.25
2019	76.82	107.97	298.87	285.47	809.41	1253.32
2020	74.31	132.04	341.35	282.78	789.88	1167.04
2021	75.49	165.36	383.60	257.69	778.19	1217.94

Fig. 3 New energy and fossil fuel generation (TWh) in the U.S. (1990-2021)

Year	Geo Biomass Others	Solar	Wind	Hydro	Nuclear	Fossil
1990	1.91	0.00	0.00	53.87	314.08	1601.26
1991	2.10	0.00	0.00	57.60	331.34	1707.94
1992	2.13	0.00	0.00	68.96	338.45	1677.70
1993	1.97	0.00	0.00	64.90	368.19	1606.06
1994	2.16	0.00	0.00	78.79	359.98	1551.73
1995	2.33	0.00	0.00	73.12	377.23	1585.17
1996	2.42	0.00	0.01	66.04	397.34	1654.88
1997	2.68	0.00	0.01	63.76	395.48	1624.68
1998	2.65	0.00	0.02	62.09	387.99	1718.93
1999	2.85	0.00	0.04	72.51	394.24	1722.83
2000	2.99	0.01	0.05	66.36	415.16	1719.71
2001	3.33	0.01	0.13	74.27	421.08	1725.44
2002	3.54	0.01	0.27	60.40	436.76	1697.53
2003	3.72	0.01	0.39	58.94	441.07	1730.17
2004	3.78	0.01	0.60	59.56	448.24	1742.17
2005	3.87	0.01	0.96	51.48	451.53	1742.59
2006	3.84	0.01	2.18	56.30	450.19	1711.23
2007	4.22	0.02	4.07	57.60	439.73	1675.24
2008	4.44	0.04	5.69	63.65	439.45	1661.72
2009	4.58	0.17	7.91	56.99	409.74	1587.68
2010	4.92	0.62	9.95	62.71	428.52	1609.97
2011	5.48	2.08	12.05	44.79	442.39	1503.19
2012	6.35	4.02	15.11	58.78	425.41	1500.31
2013	7.81	4.74	16.05	70.84	423.68	1501.05
2014	8.32	5.91	17.25	62.83	436.48	1364.99
2015	8.84	7.26	21.35	54.56	437.43	1392.82
2016	9.64	8.16	21.31	59.92	403.20	1422.17
2017	10.33	9.10	24.54	48.96	398.36	1437.18
2018	10.55	10.41	28.53	63.92	412.94	1404.10
2019	10.74	11.75	34.62	56.03	399.01	1384.47
2020	10.67	12.93	39.75	61.17	353.83	1204.73
2021	11.19	14.61	36.97	57.97	379.36	1303.04

Fig. 4 New energy and fossil fuel generation (TWh) in France (1990-2021)

Year	Geo Biomass Others	Solar	Wind	Hydro	Nuclear	Fossil
1990	3.95	0.00	0.00	295.68	72.46	1916.02
1991	3.98	0.00	0.00	307.28	84.34	1860.18
1992	4.47	0.00	0.06	315.17	80.02	1928.26
1993	4.82	0.00	0.06	322.21	93.28	1946.97
1994	5.73	0.00	0.06	327.86	107.08	2009.36
1995	7.14	0.00	0.06	334.06	97.16	2095.40
1996	7.53	0.01	0.06	354.59	92.12	2139.88
1997	8.17	0.01	0.06	348.68	81.95	2201.38
1998	8.99	0.01	0.06	330.87	70.99	2231.21
1999	8.94	0.01	0.16	345.00	72.98	2293.16
2000	8.92	0.02	0.26	356.76	69.16	2356.58
2001	9.67	0.02	0.33	331.52	72.86	2350.01
2002	10.05	0.02	0.41	349.27	71.75	2428.99
2003	9.42	0.02	0.69	336.14	71.15	2495.39
2004	9.80	0.01	0.95	338.40	85.87	2508.97
2005	9.16	0.02	1.57	361.96	86.83	2469.93
2006	8.94	0.02	2.47	352.89	92.44	2464.81
2007	8.99	0.03	3.01	367.62	88.19	2579.58
2008	7.98	0.04	3.79	377.49	88.30	2506.02
2009	8.94	0.11	6.64	368.69	85.13	2392.14
2010	10.30	0.26	8.72	351.38	85.53	2471.71
2011	10.21	0.57	10.19	375.72	88.29	2535.40
2012	10.91	0.88	11.31	380.27	89.49	2528.76
2013	11.04	1.50	11.15	391.79	97.58	2576.82
2014	9.80	2.12	12.82	382.50	101.21	2607.89
2015	9.99	2.89	26.97	382.19	96.05	2617.33
2016	11.36	4.03	30.93	385.43	95.69	2544.80
2017	10.85	3.57	31.51	394.59	95.57	2591.32
2018	10.54	3.80	33.14	385.89	95.03	2653.27
2019	10.31	4.08	32.88	381.77	95.47	2648.05
2020	9.39	4.28	35.64	386.54	92.65	2421.13
2021	9.70	5.16	35.12	380.85	87.36	2483.22

Fig. 5 New energy and fossil fuel generation (TWh) in Canada (1990-2021)

Year	Geo Biomass Others	Solar	Wind	Hydro	Nuclear	Fossil
1990	11.34	0.00	0.00	86.90	194.57	4374.01
1991	11.65	0.00	0.00	94.42	208.69	4428.32
1992	11.85	0.01	0.00	80.05	217.04	4502.18
1993	11.56	0.02	0.00	92.58	247.70	4460.20
1994	13.47	0.03	0.00	64.46	258.25	4712.57
1995	14.30	0.04	0.00	78.79	286.89	4876.48
1996	15.25	0.05	0.00	77.17	296.50	4966.40
1997	16.44	0.10	0.00	86.44	321.16	4982.26
1998	16.17	0.14	0.01	89.08	325.97	4837.62
1999	16.49	0.22	0.04	83.79	317.23	4976.21
2000	16.11	0.34	0.11	84.47	305.95	5035.61
2001	16.03	0.50	0.25	81.54	303.86	4988.12
2002	16.94	0.69	0.41	80.60	280.34	5021.03
2003	17.88	0.95	0.83	92.47	228.01	5200.92
2004	18.05	1.27	1.44	91.67	268.32	5122.87
2005	21.69	1.63	1.91	77.56	280.50	5157.83
2006	21.53	2.00	2.14	88.81	291.54	5086.07
2007	22.20	2.31	2.74	74.51	267.34	5130.28
2008	21.29	2.59	2.95	75.16	241.25	5100.91
2009	20.33	3.05	3.43	70.47	263.05	4527.24
2010	21.83	3.98	3.93	88.50	278.36	4790.78
2011	21.11	5.44	4.46	82.49	153.38	4841.04
2012	22.13	7.37	4.73	77.10	15.12	5189.08
2013	23.18	12.91	5.13	79.33	10.43	5133.33
2014	23.63	23.55	5.01	81.71	0.00	4996.62
2015	28.49	34.54	5.22	85.77	3.24	4853.51
2016	23.67	43.33	5.34	79.43	14.87	4761.28
2017	27.39	54.24	5.83	79.29	27.75	4755.59
2018	30.13	62.11	6.44	81.11	47.82	4643.38
2019	32.16	67.75	6.75	73.64	63.88	4477.79
2020	34.80	75.14	7.82	77.41	41.86	4113.94
2021	35.76	86.27	8.25	77.64	61.22	4205.64

Fig. 6 New energy and fossil fuel generation (TWh) in Japan (1990-2021)

Year	Geo Biomass Others	Solar	Wind	Hydro	Nuclear	Fossil
1990	1.44	0.00	0.07	17.34	152.47	3703.87
1991	1.51	0.00	0.10	15.85	147.23	3620.40
1992	1.56	0.00	0.28	18.64	158.80	3497.78
1993	1.66	0.00	0.60	18.96	153.28	3492.76
1994	1.91	0.00	0.91	20.20	150.70	3456.35
1995	2.05	0.01	1.50	21.56	153.09	3462.44
1996	2.14	0.01	2.03	18.82	160.02	3578.19
1997	2.30	0.01	2.97	18.95	170.33	3496.78
1998	2.72	0.02	4.49	19.00	161.64	3481.88
1999	2.94	0.02	5.53	20.69	170.00	3392.88
2000	3.40	0.00	9.50	24.90	169.61	3391.78
2001	5.20	0.10	10.50	23.20	171.30	3460.38
2002	6.40	0.20	15.80	23.70	164.84	3408.06
2003	8.95	0.31	19.09	18.32	165.06	3405.06
2004	10.64	0.56	26.02	20.75	167.07	3366.81
2005	14.71	1.31	27.77	19.64	163.05	3308.26
2006	18.93	2.27	31.32	20.03	167.27	3360.62
2007	24.62	3.14	40.51	21.17	140.53	3214.11
2008	28.03	4.51	41.39	20.44	148.49	3225.88
2009	30.90	6.72	39.42	19.03	134.93	3018.43
2010	33.95	11.96	38.55	20.95	140.56	3134.53
2011	36.91	19.99	49.86	17.67	107.97	3032.67
2012	43.23	26.74	51.68	21.76	99.46	3052.56
2013	45.59	30.62	52.74	23.00	97.29	3147.40
2014	48.39	34.56	58.50	19.59	97.13	2963.16
2015	50.46	37.17	80.62	18.98	91.79	2981.13
2016	51.10	36.67	79.92	20.55	84.63	3062.10
2017	51.08	37.89	105.69	20.15	76.32	3065.36
2018	50.97	43.46	109.95	17.69	76.00	2951.88
2019	50.32	44.38	125.89	19.73	75.07	2811.78
2020	51.09	48.64	132.10	18.32	64.38	2545.10
2021	50.90	49.00	117.70	19.10	69.13	2655.22

Fig. 7 New energy and fossil fuel generation (TWh) in Germany (1990-2021)

Year	Geo Biomass Others	Solar	Wind	Hydro	Nuclear	Fossil
1990	0.07	0.00	0.00	166.85	118.33	9246.80
1991	0.07	0.00	0.00	168.09	119.98	9100.94
1992	0.06	0.00	0.00	172.59	119.63	8716.63
1993	0.06	0.00	0.00	174.29	119.19	8065.39
1994	0.06	0.00	0.00	175.93	97.82	7340.46
1995	0.06	0.00	0.00	176.26	99.53	6898.25
1996	0.06	0.00	0.00	154.31	109.03	6647.38
1997	0.06	0.00	0.00	157.43	108.50	6237.44
1998	0.06	0.00	0.00	158.50	103.72	6234.79
1999	0.06	0.00	0.00	160.49	121.87	6265.97
2000	0.08	0.00	0.00	164.08	122.46	6357.78
2001	0.11	0.00	0.00	173.90	125.36	6431.02
2002	0.17	0.00	0.01	162.17	134.14	6427.90
2003	0.37	0.00	0.01	155.67	141.17	6577.55
2004	0.45	0.00	0.01	175.68	137.47	6606.42
2005	0.45	0.00	0.01	172.61	137.64	6597.73
2006	0.51	0.00	0.01	173.29	144.65	6915.32
2007	0.48	0.00	0.01	177.05	147.99	6942.08
2008	0.49	0.00	0.01	164.78	152.06	7010.48
2009	0.50	0.00	0.00	174.20	152.78	6595.96
2010	0.54	0.00	0.00	166.48	159.41	6897.14
2011	0.56	0.00	0.01	163.06	162.02	7171.50
2012	0.50	0.00	0.01	163.45	166.29	7182.12
2013	0.48	0.01	0.00	181.15	161.38	7050.27
2014	0.55	0.16	0.10	173.39	169.07	7073.82
2015	0.48	0.34	0.15	167.99	182.81	6920.01
2016	0.45	0.47	0.15	184.61	184.05	7051.23
2017	0.52	0.54	0.14	185.16	190.12	7086.87
2018	0.50	0.62	0.24	190.64	181.76	7372.34
2019	0.52	0.99	0.31	194.38	195.54	7292.44
2020	0.51	1.86	1.14	212.44	215.74	6909.20
2021	0.52	2.31	2.58	214.53	222.44	7556.90

Fig. 8 New energy and fossil fuel generation (TWh) in Russia (1990-2021)

2.2 Ratio Estimation

In order to be able to better evaluate the impact of nuclear energy, the data had been presented by using three ratio estimations: The first one is the ratio of nuclear energy to fossil fuel, which was determined by analyzing the multi-year trend of nuclear energy in seven countries, compared with conventional fossil fuels; The second one is the ratio of nuclear energy to clean energy (Clean energy is equal to the combination of nuclear energies and renewable energies), also based on time development, it focuses on the development status of clean energy and nuclear energy in each country, and determines the overall ratio through data integration analysis; The third one is the ratio of nuclear energy to the whole energy use. By summarizing energy sources other than nuclear energy, the total share of nuclear energy in the seven countries is obtained.

3 Results and Discussion

As described above, the data show the change in nuclear energy per year from 1990 to 2021 for seven different countries. As can be seen from Fig. 9 the trend of growth of nuclear energy in some countries is clear. For example, China accelerates its nuclear energy energy output from about 2020, growing from 16.74 KWh to a staggering 407.5 KWh, with the most pronounced growth from 2015 to 2020, boosting nearly 240 KWh in just a few years; however, there are some countries where the trend in nuclear energy production has a clear plunge. Japan, for example, had relatively stable nuclear energy production until 2011, basically staying in the 250KWh to 330Kwh range, but suddenly dropped to 15.2KWh in 2012 and even stopped nuclear energy production during 2014.

We believe the likely reason for the decline is due to the Fukushima Accident. The Government temporarily shut down the production of this energy source because of a huge nuclear-energy-induced disaster in the country.

On top of that, analyzing the data as well as the images, we were surprised to find that Russia's nuclear leak: the Chernobyl incident, did not drastically affect the country's overall nuclear energy production. The exact reasons for this are unknown to us, and we presume that it was influenced by internal government policy, coupled with the fact that Russia's base of nuclear power plants was relatively large at the time, so that the loss of production from one site would not greatly affect the country's overall production.

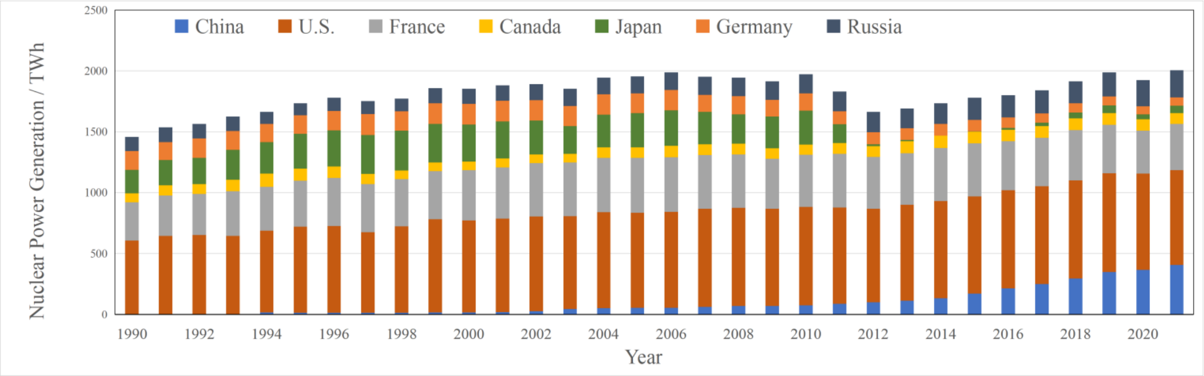


Fig. 9 the trend of growth of nuclear energy in Seven countries from 1990s to 2021s

3.1 Changes of Nuclear Energy

Fig. 10 shows the distribution of the average value of each non-polluting energy source over a ten-year period in seven countries, Fig. 10 for 1990 to 1999 and Fig. 10 for 2012 to 2021. Distributed energy sources include Geo Biomass other energy, Solar Generation, Wind Generation, Hydro Generation, and Nuclear Generation. It can be seen that from 1990 to 2021, the U.S. and France will mostly utilize nuclear energy to generate energy. In the U.S., nuclear energy accounts for 50% of the total, and in France it accounts for more than 75%, while other sources account for relatively little. This shows the value and benefits of nuclear energy to help a country's economy. About 75% of France's electricity comes from nuclear power, which is far ahead of other countries. At the same time, France, through the use of nuclear power, has gradually moved away from carbon emissions in electricity generation, so that France's per capita emissions are less than half that of Germany and Britain. It can also be seen from **Fig. 4** that nuclear energy has become the most important energy structure in France. Meanwhile, the two charts for China also show that although China is relatively new to Hydro Generation, nuclear energy output has been much higher in the last decade, at nearly 30%. Additionally, there is a subtle change in the clean energy supply structure of two of these countries. Japan's share of Hydro Generation is much higher in 2012-2021 than in 1990-1999, accounting for nearly 40% of the total; meanwhile, nuclear energy output declines due to nuclear accidents. In Germany, nuclear energy production has also changed. Whereas nuclear generation dominated overall clean energy in 1990-1999, it has declined to about 30% in the last decade.

In summary, the distribution of clean energy in the seven countries confirms the effectiveness of nuclear energy. With increasing technological maturity, nuclear energy will become the dominant clean energy source, and may even replace fossil fuel generation in the future. However, the decline in the overall share of nuclear energy in Germany is not well explained, and requires further in-depth discussion of the historical context of technological development in each country at the time.

3.2 Fossil Fuels and New Energy

In order to explore the importance of nuclear energy in each country, this section will analyze the situation from three different perspectives: **Fig. 11a** is the ratio of Nuclear Generation to fossil fuel for seven countries from 1990 to 2021; **Fig. 11b** is the ratio of Nuclear Generation to Clean Energy (including Geo-Biomass Other, Solar Generation, Wind Generation, Hydro Generation, and Nuclear Generation); **Fig. 11c** is the ratio of Nuclear Generation to a country's total energy output (including Geo-Biomass Other, Solar Generation, Wind Generation, Hydro Generation, and Nuclear Generation).

Fig. 11a can be concluded that the nuclear energy production of each country from 1990 to 2021 has been on a general upward trend, but the ratio to oil production has been in a declining state, which is due to the fact that nuclear energy production per year is much lower than that of oil production, which side by side reflects the fact that the demand for oil has increased considerably in recent decades. For example, the ratio of nuclear energy production to oil production in the United States has fallen from 1.76 in 1990 to about 0.64 in 2021, and U.S. oil production has risen from 344 TWh to 1,217 TWh. In addition to this, this chart shows that there are many countries that are already trending toward nuclear energy as a primary source of energy, even though oil is currently the more dominant source of energy. For example, in France, although the ratio of nuclear energy production to oil production is on a downward trend, the decrease in the ratio has slowed down since 2008, proving that nuclear energy production is gradually equalizing with oil production.

In addition, **Fig. 11a**'s ratio began to increase upwards between 1998 and 2000 for a number of reasons, notably the acceptance of the benefits of nuclear energy, the construction of nuclear power plants, and the promulgation of relevant policies.

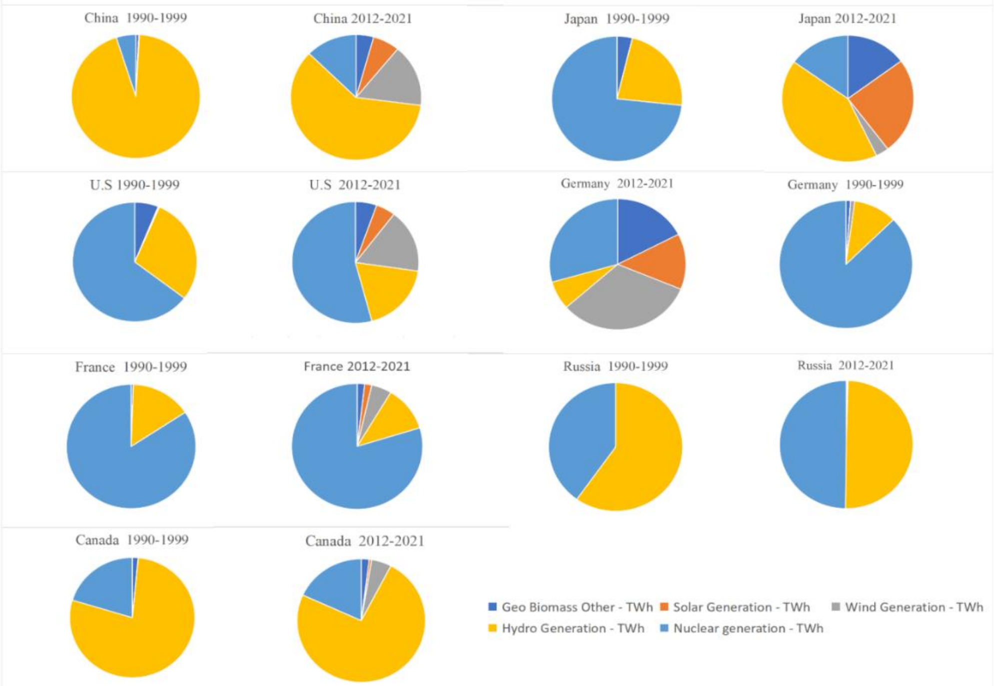


Fig. 10 the distribution of the average value of each non-polluting energy source over a ten-year period in seven countries

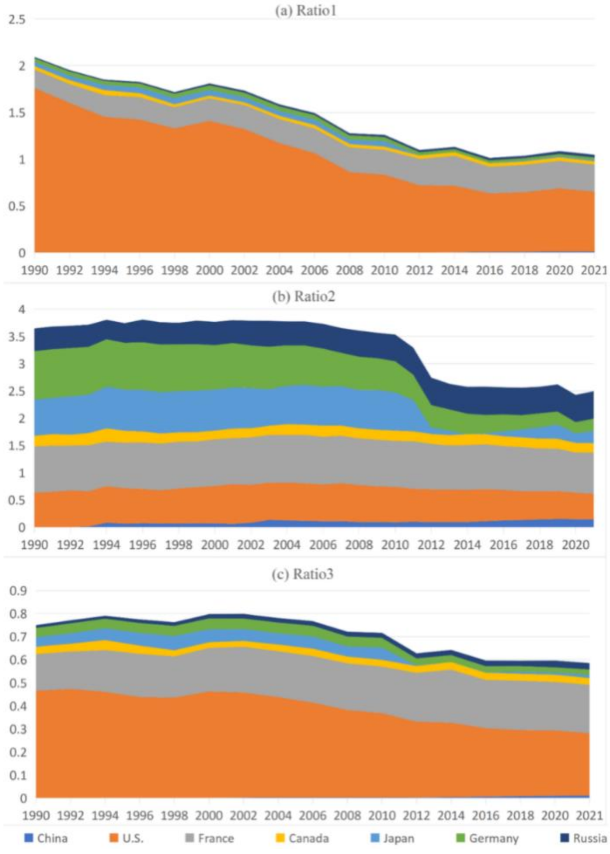


Fig. 11 (a)the ratio of Nuclear Generation to fossil fuel for seven countries from 1990 to 2021 (b) the ratio of Nuclear Generation to Clean Energy (including Geo-Biomass Other, Solar Generation, Wind Generation, Hydro Generation, and Nuclear Generation); (c)the ratio of Nuclear Generation to a country's total energy output (including Geo-Biomass Other, Solar Generation, Wind Generation, Hydro Generation, and Nuclear Generation).

Fig. 11b visually shows that most countries are producing less nuclear energy compared to clean energies year after year. For example, the ratio for the United States has gone from about 1.76 in 1990 to about 0.63 in 2021, indicating that the yearly increase in clean energy production has made the denominator of the ratio larger, and the nuclear energy production in a single year is not as much as that of clean energies, which leads to a decrease in the ratio year by year. However, there are some exceptions, such as China, where the ratio has basically been on an upward trend since 1993. Prior to 1993, the ratio was zero, indicating that China had not yet begun to produce nuclear energy. However, from a formulaic point of view, clean energies remain one of the most important energy sources for China compared to nuclear energy.

The rise in China's nuclear energy production is due to a number of factors, and we hypothesize, based on the historical background, that China was in the midst of its **"reform and opening up"** wave, which brought in many outstanding experts and equipment in science and technology to develop China's nuclear energy business, leading to a general upward trend in nuclear energy production from 1993 to 2021.

Fig. 11c shows that the ratio of nuclear energy to energy use is generally decreasing in the seven countries, but not as much as **Fig. 11a** and **Fig. 11b**. The reason for this is that the annual production of nuclear energy in each country is not as large as the total national production. For example, in the United States, the ratio decreases from 0.46 in 1990 to 0.27 in 2021; however, in France, the ratio tends to increase, although it remains roughly unchanged as shown in the Fig. 11a and Fig. 11b. It increases from 0.15 in 1990 to 0.21 in 2021, which shows that France is gradually shifting the focus of its production to nuclear energy and moving towards the production of clean energy.

3.3 History of nuclear plant construction

The evolution of nuclear plant construction stands as a testament to humanity's unceasing pursuit of innovative and sustainable energy solutions. From its initial steps in the mid-20th century to the present day, the development of nuclear power facilities has borne witness to both technological triumphs and formidable challenges. Since 1950, scientists had been conducted advanced technology of nuclear plants.

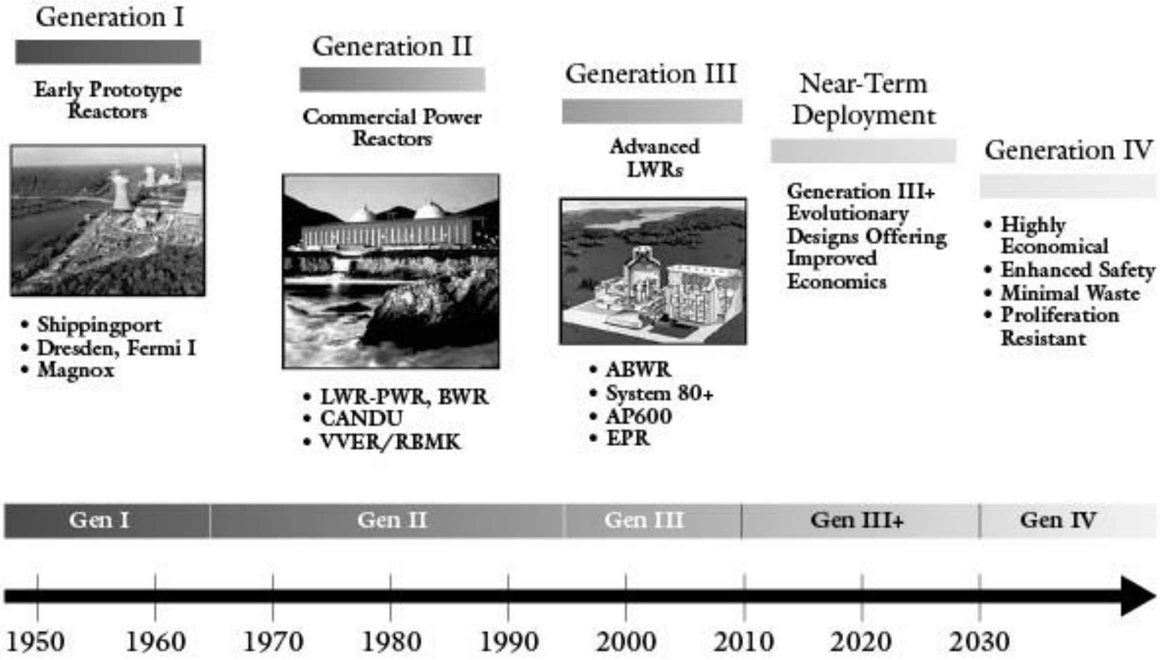


Fig. 12 Reprinted from U.S. Department of Energy, Office of NuclearEnergy, "Generation IV Nuclear Energy Systems:Program Overview" (Department of Energy, n.d.), http://nuclear.energy.gov/genIV/neGenIV1.html.

Generation I

Generation I reactors encompass the pioneering prototype and power reactors that laid the foundation for civilian nuclear power. This generation encompasses early-stage prototype reactors hailing from the 1950s and 1960s, notable examples being Shippingport (1957–1982) in Pennsylvania, Dresden-1 (1960–1978) in Illinois, and Calder Hall-1 (1956–2003) in the United Kingdom. These reactors primarily operated at power levels aimed at showcasing feasibility. In the United States, the Nuclear Regulatory Commission (NRC) oversees Generation I reactors, subject to regulations outlined in Title 10, Code of Federal Regulations, Part 50 (10 CFR Part 50). Wylfa Nuclear Power Station in Wales stands as the sole remaining commercial Generation I facility. While its closure was initially slated for 2010, the UK Nuclear Decommissioning Authority shifted plans in October 2010, extending Wylfa's operation until December 2012.

Generation II

Generation II systems originated in the late 1960s and have since become the predominant type among the world's 400+ commercial pressurized water reactors (PWRs) and boiling water reactors (BWRs). These reactors, often referred to as light water reactors (LWRs), incorporate conventional active safety mechanisms, some of which are automated and can also be initiated by nuclear reactor operators. Notably, certain engineered systems operate passively, functioning independently of operator intervention or auxiliary power availability. Generation II reactors represent a specific category of commercial nuclear reactors meticulously designed to balance economic viability and operational reliability. These reactors typically have an operational lifespan of around 40 years. Notable examples of Generation II reactors include pressurized water reactors (PWR).

Generation III

Generation III nuclear reactors represent a significant advancement over their predecessors, blending cutting-edge innovations with fundamental design elements. These improvements encompass various aspects such as fuel technology, thermal efficiency, modular construction, and safety systems, with an emphasis on passive safety features. The primary goal of Generation III reactors is to achieve extended operational lifespans, often spanning 60 years or more before requiring major overhauls and reactor vessel replacements. However, further research is needed to confirm the feasibility of operating nuclear plants beyond 60 years. Unlike earlier generations, Generation III reactors adhere to Nuclear Regulatory Commission (NRC) standards outlined in 10 CFR Part 52. Prominent Generation III designs include the Westinghouse AP-600 and GE Nuclear Energy's Advanced Boiling Water Reactor (ABWR), with Japan pioneering the introduction of ABWR units in 1996. Other concepts include the Enhanced CANDU 6 by Atomic Energy of Canada Limited (AECL) and System 80+ by Combustion Engineering. Currently, only four Generation III reactors are operational, all falling under the ABWR category, and none are active in the United States.

Generation III+ and Generation IV+

Generation III+ reactor designs represent a significant leap in nuclear safety compared to Generation III counterparts, with the development initiated in the 1990s. These designs incorporate passive safety measures, eliminating the need for human intervention during abnormal events and relying on natural processes like gravity or convection for safety. They also adhere to defined Western safety standards, setting global safety benchmarks. However, challenges include increased nuclear waste production, the need for extensive power grids, and public acceptance issues. This evolution underscores nuclear technology's journey towards enhanced safety while addressing complex challenges. Notably, the last remaining commercial Gen I plant, the Wylfa Nuclear Power Station in Wales, continued operations until December 2012 despite being scheduled for closure in 2010.

3.4 Historical Nuclear Accidents

Throughout the history of nuclear technology, several notable accidents have served as cautionary tales, shaping the global discourse on nuclear safety. From the early days of nuclear experimentation to more recent incidents, each event has contributed to our understanding of the complex challenges associated with harnessing nuclear power. In particular, several nuclear accidents need to be introduced based on **Fig. 13.**

Fukushima (2011):

The Fukushima Daiichi nuclear disaster in 2011 was a catastrophic event triggered by a massive earthquake and tsunami that struck Japan. The Fukushima Daiichi Nuclear Power Plant, located on the northeastern coast of Japan, experienced a loss of power and cooling capabilities, leading to partial core meltdowns in three of its operational reactors. This resulted in the release of radioactive materials into the environment and necessitated the evacuation of tens of thousands of residents from the affected area.

The disaster had profound consequences, not only for Japan but also for the global nuclear industry and energy policy. It raised serious questions about the safety of nuclear power plants, emergency preparedness, and the long-term management of nuclear waste. In their study, Tokonami et al. (2012) examined a group of 62 individuals, including both residents and evacuees from regions severely affected by contamination around the Fukushima Nuclear Power Plant. Their primary aim was to ascertain the thyroid doses resulting from inhalation exposure. The findings revealed that the median committed equivalent dose stood at 4.2 mSv for children and 3.5 mSv for adults. Notably, the highest recorded thyroid doses reached 23 mSv for children and 33 mSv for adults in this cohort**[11]**. In response to the disaster, many countries reevaluated their nuclear energy policies, with some opting to reduce their reliance on nuclear power or phase it out entirely. Fukushima served as a stark reminder of the potential risks associated with nuclear energy and the importance of stringent safety measures and international cooperation in managing these risks. The ongoing decommissioning efforts at Fukushima Daiichi underscore the enduring challenges and complexities involved in dealing with the aftermath of a nuclear disaster.

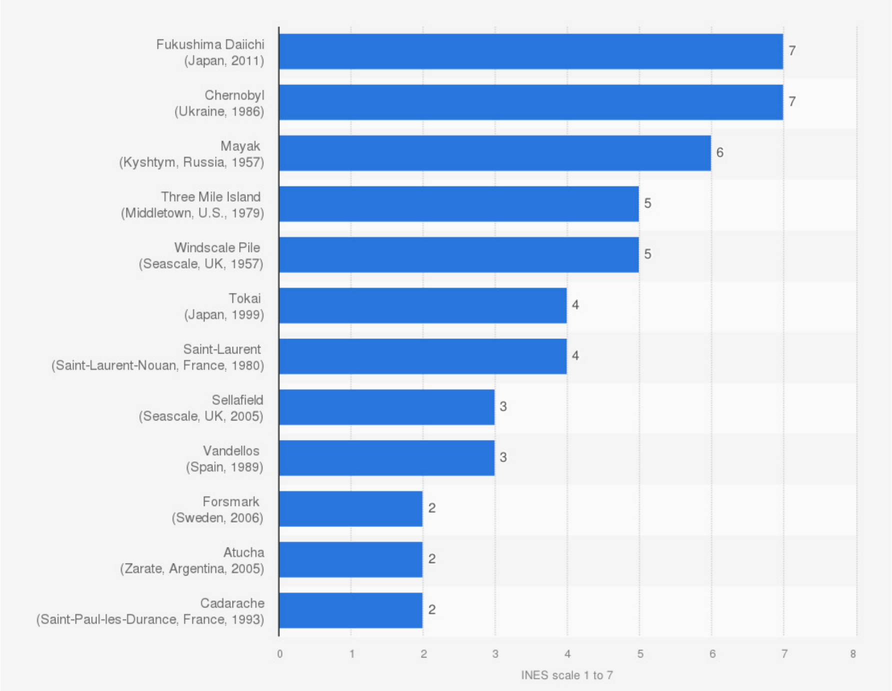


Fig. 13 Nuclear accidents globally between 1957 and 2011, rated by INES(International Nuclear and Radiological Event Scale) scale. This figure is obtained from IAEA(International Atomic Energy Agency).

Chernobyl (1986):

The Chernobyl disaster is widely regarded as the most catastrophic nuclear accident in history. It occurred at the Chernobyl Nuclear Power Plant in the Soviet Union (now Ukraine) during a late-night safety test. Due to design flaws and a series of human errors, an uncontrolled power surge caused a steam explosion, followed by a graphite fire in the reactor core. This led to the release of a massive amount of radioactive material into the atmosphere over several days. The accident resulted in the immediate deaths of two plant workers and the subsequent deaths of many cleanup personnel due to acute radiation sickness. The release of radioactive contaminants had long-term health and environmental impacts, including an increased incidence of cancers and the displacement of nearby populations.

Mayak(1957):

The Kyshtym disaster serves as a stark testament to the perils arising from insufficient safety precautions in the pursuit of nuclear technology. This calamity transpired on the early morning of September 29, 1957, at the Mayak Production Association facility located within the Soviet Union, yielding extensive repercussions for both ecological integrity and human well-being. Stemming from a combination of technical breakdowns, secrecy, and a disregard for the potential risks tied to nuclear substances, this incident was provoked by a catastrophic malfunction within the cooling system of a storage tank that housed high-level liquid radioactive waste. The primary purpose of this cooling mechanism was to avert the overheating of the waste and the subsequent discharge of perilous radioactive particles into the atmosphere. However, due to inadequate maintenance and technical oversight, this cooling system faltered. Consequently, the temperature within the tank surged, ultimately culminating in a chemical explosion that liberated an immense volume of radioactive materials into the surroundings.

4 Conclusion

This paper uses the latest data and formulas to analyze and evaluate nuclear energy from different perspectives, visualizing the status of nuclear energy in seven different countries. At the same time, the paper also provides a detailed description and evaluation of nuclear plantations. At the end of the paper, a review of nuclear accidents and a rating of nuclear accidents are presented.

In this study, it is found (Section 3.1, 3.2, and 3.3) that the use of nuclear energy is gradually increasing in many countries. The efficacy of nuclear energy is being strongly recognized, both in terms of environmental protection and cost. However, there is still instability in nuclear power plants. As can be seen from the nuclear accidents in Section 3.4, the impact of a nuclear energy accident on humans and the environment is enormous. These accidents, nevertheless, are relatively small probability events. With the development of science and technology, the security facilities of nuclear power plants and nuclear reactors have been updated and upgraded, which means that the probability of nuclear accidents will become smaller and smaller in the future, while the production and efficiency will become even better and become the main source of clean energy. Although the paper already evaluated and analyzed the nuclear energy thoroughly, there is still some room for improvement in this paper, such as the assumptions mentioned in 3.2 need to be proved and the data visualization needs to be more diversified.

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