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Nuclear Energy As a Reliable And Safe Source of Power Generation

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NUCLEAR ENERGY AS A RELIABLE AND SAFE SOURCE OF POWER GENERATION

by

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DEDICATION

This thesis to dedicated to everyone who believed in me and guided me towards the right course throughout my academic endeavors. Thank you for your support.

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ABSTRACT

SARUP DHUNGANA: Nuclear Energy as a Reliable and Safe Source of Power Generation

(Under the direction of Dr. Tejas Pandya)

There is a high demand of energy for generating civil applicable power in the world and in the USA, correspondingly. The world has been consuming various sources to extract the power to meet its demands. Most of the power sources include renewable and non-renewable sources like fossil fuels, natural gas, coal, water, solar, wind, and nuclear power. Although most of these sources have many advantages in terms of their capacity and cost of production, nuclear power can be categorized as the emerging driving force in the United States and in the world for power generation, because of its reliability and safety. In terms of reliability, nuclear power proves to be above other sources in the amount of CO_2 it produces per kWh, and the capacity factor it possesses, which betters most of the other currently active energy sources. Likewise, there are different types of nuclear reactors in use, and each of these types have their own individual features and mechanisms. However, the reputation of nuclear power has never been good and accepted by the globe because of the history it owns. Some of the infamous nuclear disasters like Chernobyl, Fukushima Daichi, and the Three Mile Island stand as a thorn to this developing energy industry. Through the event analysis of these accidents, however, it can be observed that there was certain mechanical as well as operational failures which led these disasters to occur. Understanding what caused these accidents proves vital for the nuclear industry to move forward in the direction of safety. There have been many design changes that has ensured the safety of these nuclear reactors and ensured that disasters like the previously mentioned ones won't occur again in the present or in the future. Likewise, different international organizations have been implementing strict laws and rules to make the safety application of nuclear power run smoothly. This paper reviews all this information by briefly analyzing the statistics present in the energy world and presents nuclear energy as a reliable and safe source for power generation.

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LIST OF ABBREVIATIONS

kW = kilowatt

MW = Megawatt

GW = Gigawatt

kWh = kilo-Watt hours

TWh = Tera-Watt hour

Btu = British Thermal Unit

EJ = Exajoule

CO_2 = Carbon dioxide

gCO_2 = grams of Carbon dioxide

GT = Gigaton

MPa = Mega Pascal

PWR = Pressurized Water Reactors

BWR = Boiling Water Reactors

PHWR = Pressurized Heavy Water Reactors

GCR = Gas-Cooled Reactors

RBMK = Reacktor Bolshot Moshchnosty Kanaly

TMI = Three Mile Island

ARS = Acute Radiation Syndrome

RCS = Reactor Coolant System temperature

OECD = Organization for Economic Cooperation and Development

IPCC = Intergovernmental Panel on Climate Change

USNRC = United States Nuclear Regulatory Commission

NRA = Nuclear Regulation Authority of Japan

IEA = International Energy Agency

WANO = World Association of Nuclear Operators

IAEA = International Atomic Energy Agency

INPO = Institute of Nuclear Power Operations

1. Introduction

1.1 Energy Consumption

Energy can be defined as the most fundamental quantity of any existing work performed by the nature and humans. With the rapid growth in technology and innovations and increased standard of life all around the world, it is expected to have a significant increase in demand and consumption of energy and their sources of production. The world constantly has been using different forms of energy sources like fuels, nuclear, water, and other renewable industries to extract a large amount energy for different applications; civil (electricity generation) being one of them [1]. Energy sources are found to be measured in different physical units like barrels, gallons for liquid fuels, cubic feet for natural gas, and electricity in kilowatt-hours or British Thermal Units (Btu) [2].

This report will be primarily discussing and comparing the units in kilowatt-hours and its factors. Although the report is based on consumption of the energy in USA, a study of energy usage around the world is vital to increase the knowledge of the energy production occurring worldwide. Thus, discussing about global demand and then US energy demand would a key to figure out the suitable alternative sources to the energy problem.

Through these phases of introduction, this paper presents an overview of nuclear energy and its advantages over other sources in terms of reliability. This paper also discusses the reputation the nuclear energy shares with the world, the reasons behind the reputation, and describes further regarding the safety improvements they have had to ensure the unlikeliness of repeated accidents, which solidifies nuclear as a safe energy producing reservoir.

1.1.1 Universal Demand of Energy

It is important to understand what the demand of the world is and how it has been progressing so far to fully understand the domestic consumption and to study different resources for efficient and sustainable commercial energy generation. As seen in the chart below, the world consumes most of the energy through oil and then electricity, and that has been the trend before 1975 and is still the same. The unit of electricity consumption in the chart below is shown as EJ (Exajoule), and 1 Exajoule is nearly equal to $2.7 * 10^{12}$ kWh. According to the graph, in 2019 the total final consumption by source was about 418 EJ, where electricity, at 82.3 EJ, constituted about 20% of the total energy usage [3]. Although energy was and still is highly consumed through oil, the graph shows that in the present context, electricity consumption has significantly risen as well, which depicts the high usage of electricity in the current world.

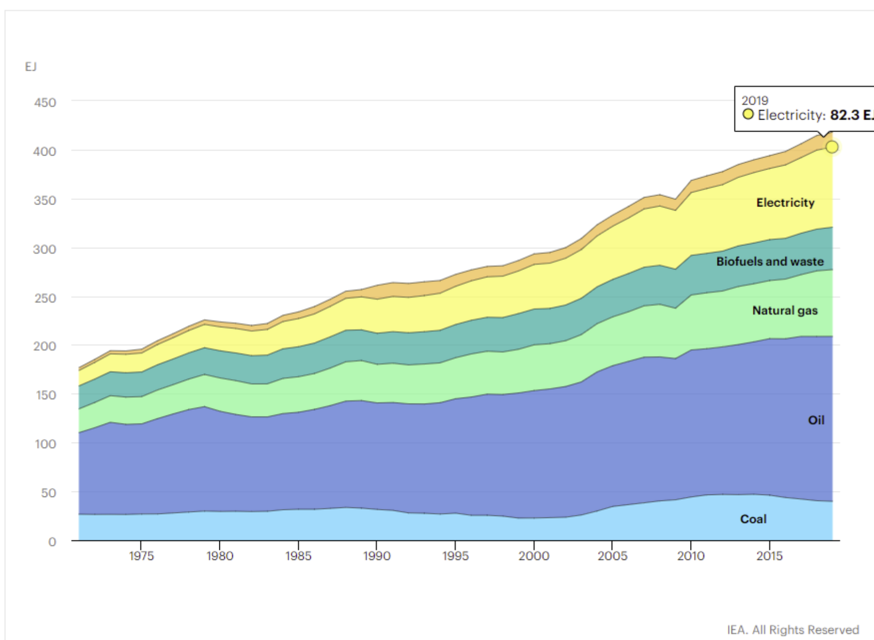

Figure 1: Energy consumption in the world through different energy sources from 1975-2020 [3]

Likewise, concentration of energy usage inside the globe is also vital to understand which countries are consuming energy in a higher degree. From the figure below extracted from the World Nuclear Association, it is evident that OECD (Organization for Economic Cooperation and Development) countries (association of 37 different nations from Europe, North America, and Asia) have the largest consumption of energy when compared to other regions of the world, at around 10000 Tera-Wh [4]. It is projected, however, that counties from Asia are highly demanding the use of electricity, and by 2030, their demand is going to be as equal to the demands of the OECD countries. This information highlights the growing utilization and demands of energy in the economically developed countries.

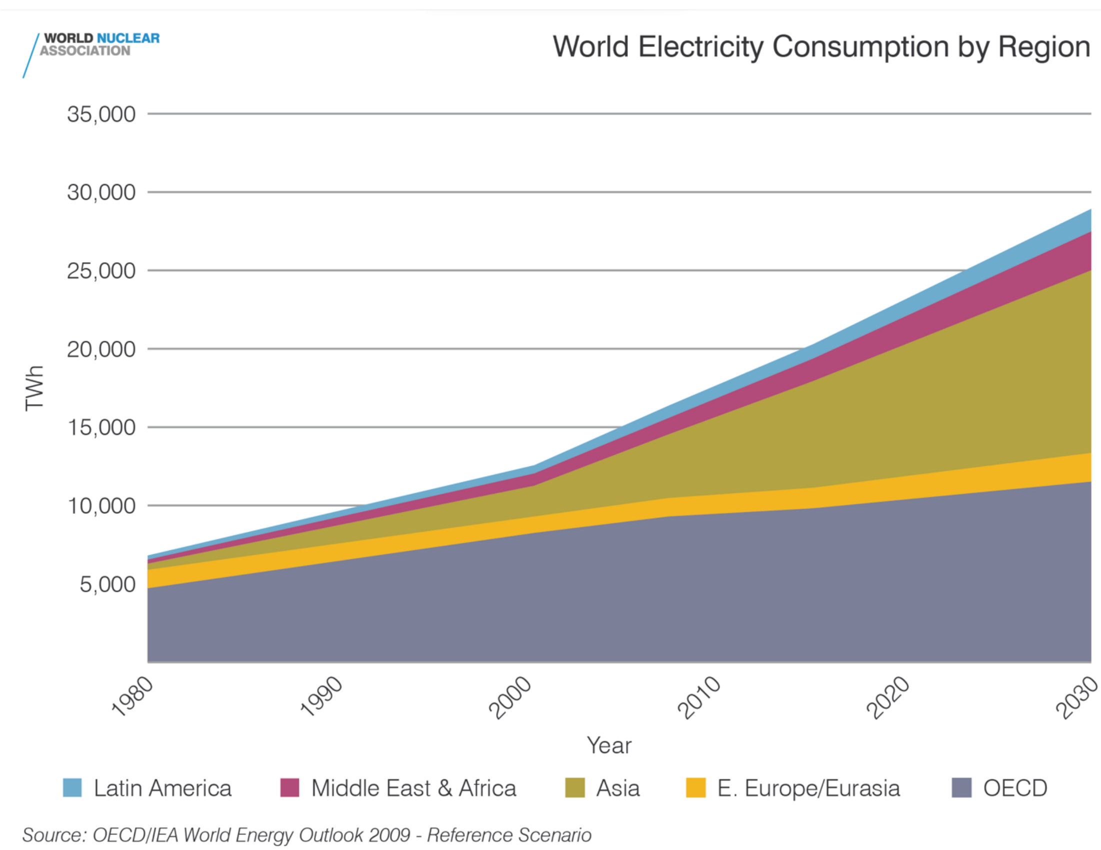

Figure 2: World Electricity Consumption by Region [4]

1.1.2 Demand in the USA

The United States, which is also a member of the OECD countries, is the second largest consumer of electric energy in the world, with the first being China. As of 2021, USA consumes over 4.01 trillion kWh of electric energy annually [5].

The main reasons behind such a huge demand of energy in USA are mainly population, the weather and frequency of change, lifestyles of the people and rise in economy. The graph below shows the net generation of electricity using all fuels (renewable and non-renewable), and in 2018, the generation is at its peak, with 4.178 trillion kWh being generated [6]. Although there is a dip from the demand of 2018 to the demand of 2021, the reason behind it could be the pandemic era, and it is not supposed to be a continuous pattern.

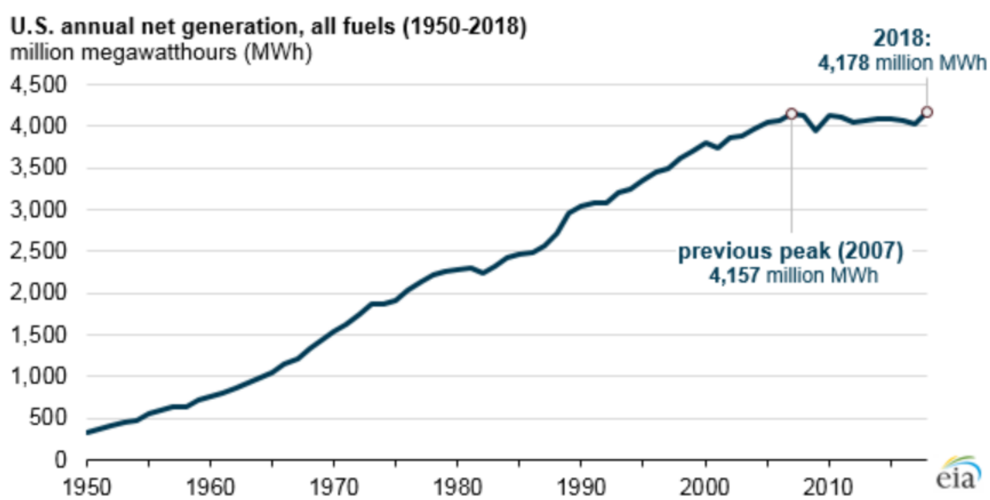

Figure 3: U.S. annual net generation of all fuels from 1950-2018 [6]

There are many sources of energy from where USA consumes its fair share of electricity. The table shown below represents the energy sources that the USA uses. It is visible from the given statistics that a large amount of fossil fuels is being consumed to generate energy, with its share at about 70% of the total energy consumption in the United States. This can be backed up by the fact that fossil fuels are easily available, they generate enough power to always meet the baseline load. USA gets a large amount of oil supply from the large oil reserves present in the countries of the Middle East and Russia, and own large oil reserves [7].

Likewise, energy demands are also met by alternative energy resources like nuclear, water, wind, etc., which in total constitutes the rest of the 30%. However, only 43% of the total production capacity is promoted, and this might be because of the economic stability of the nation, and its independency to meet the demands within the actual net production.

Energy source	total in the United States	percentage in the United States
Fossil fuels	6,665.48 bn kWh	70,0 %
Nuclear power	856.99 bn kWh	9,0 %
Water power	666.55 bn kWh	7,0 %
Renewable energy	1,333.10 bn kWh	14,0 %
Total production capacity	9,522.12 bn kWh	100,0 %
Actual total production	4,095.00 bn kWh	43.0 %

Table 1: Energy sources and their usage in the U.S.A [8]

1.2 Identification of Energy Sources

Expanding worldwide energy consumption imposes the development of sustainable technologies and sources capable of harvesting previously untapped energy resources while minimizing environmental damage. The energy sources can be categorized into primary and secondary sources. Fossil fuels like natural gas, coal, and petroleum, and nuclear energy, and renewable energy sources are all primary energy sources whereas solar and wind are secondary energy sources [9].

The pie chart presented below in this section describes the percentages of energy consumed in the world. It is evident that coal and gas (fossil fuels) are the most utilized sources, whereas other renewable sources of energy like hydro, nuclear, solar, wind, geothermal, tidal, and oil are also considered as an alternative. Fossil fuels, since are depleting very fast due to over consumption all around the world, cannot be considered as a dependable source of energy in the world in the upcoming future. Thus, the energy sources that occurs naturally and close to an infinite amount, also called as renewable sources, are also in strong need of consideration.

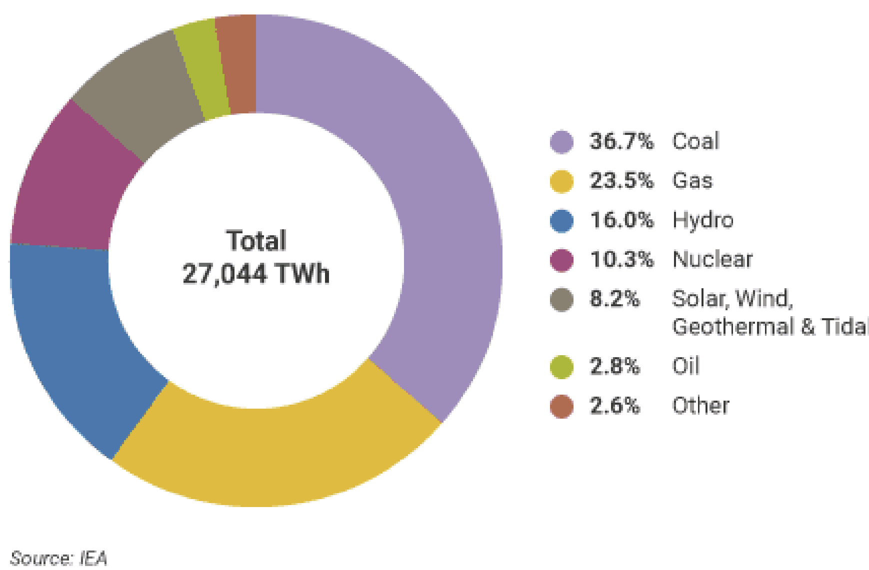

Figure 4: Total Power Consumption in the world via different energy resources (2019) [10]

From the pie chart analysis shown above, it is seen that out of 27,044 kWh of energy consumed in the world in 2019, almost 40% of the total consumed energy is generated using renewable sources [10]. Among the renewable sources, nuclear ranks second out of all energy resources being consumed the most (10.3%). To stand out as a product that requires careful attention, the research goes into further detail about what nuclear power is and how it differs from other renewable energy sources.

2. Nuclear Power

Nuclear energy can be defined as the energy released when a nuclear fusion or fission takes place, and this energy can be utilized to produce electricity. In other words, nuclear energy is generated by breaking atoms in a reactor to heat water into steam, which is then used to power a turbine and create electricity [11].

The graph shown below from the World Nuclear Association portrays that in 2020, nuclear energy was utilized to provide more than 2500 TWh (1 TWh = 1 billion kWh) of electricity. Likewise, the graph also shows that the regions that generate their energy using nuclear power mostly includes countries from Europe, Russia, and Asia, which are the economically dominant nations in the present context.

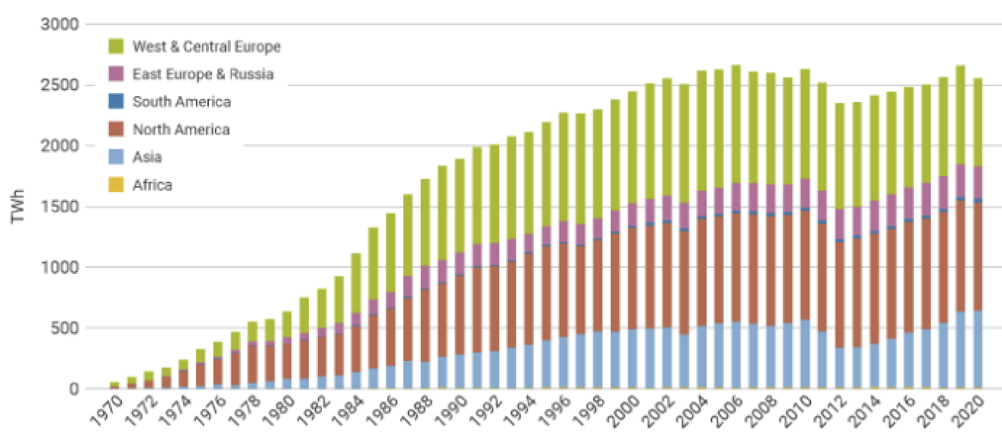

Figure 5: Nuclear Power usage for electricity generation by Region (1970-2020) [10]

The next chart below portrays the use of nuclear power by country from the year 2020, and as it can be seen, USA is on top of that list, producing 789.9 TWh of energy.[10] Other economically developed countries like China and France ranks in second and third. This statistic is a proof of how nuclear energy has been adopted as an alternative means of energy production by the leading powerful nations.

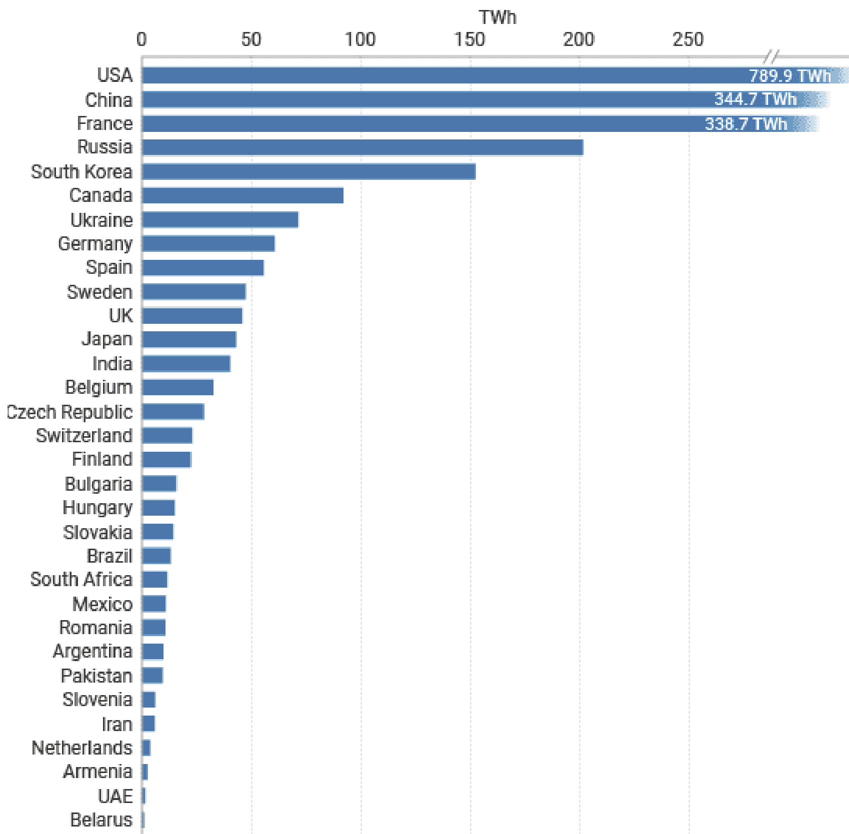

Figure 6: Nuclear Power Usage for electricity generation by countries [10]

There are many benefits to select nuclear energy as a reliable source of electricity generation because of its provision of services the field of national security, climate change, leadership, international development, and electrical reliability [12].

Moreover, the most impactful reliability factors of this energy source are the emission of pollutants, mainly CO_2 per kWh of electricity generated, and its capacity factors when compared to other energy resources, and they are identified below:

2.1 CO_2 emission / kWh

CO_2 emission occurs every time through natural processes like exchange between oceans and atmosphere, emissions through plants and animals during respiration, and decomposition of the organic matter via microorganisms. All these activities keep CO_2 emissions in balance by continuing it as a cyclic process, however the extraction and burning of fuels like coal, oil, and natural gas releases extra CO_2 in the atmosphere, depleting the atmosphere and increase in climate change through global warming [13].

The graph below sourced from IEA portrays the amount of carbon dioxide (in Gigatons, where 1 gigaton = 1 billion metric tons) being released into the atmosphere through energy consumption by all the available sources. According to the graph, from 1900 to 2020, the amount of CO_2 released has increased by 1700%, with the emission during 1990 being at around 2 Gt CO_2, and in 2020 being almost 36 Gt CO_2 [14]. This excessive rise of CO_2 emission is dangerous to all living forms in the world, because of its adverse effects on the atmosphere, and excessive increase in the radiation levels.

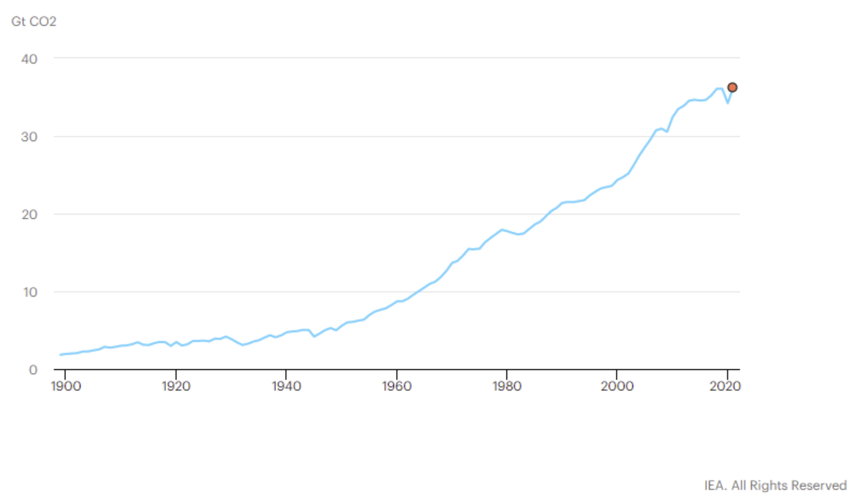

Figure 7: CO_2 emission in the world from 1900-2020 [14]

The most accountable industry while discussing about CO_2 emission is the energy industry, since a lot of fuel is burned to produce electricity. The graph below shows the energy resources and its contribution in release of these harmful gases. It is obvious from the stats that the fossil fuels are the primary contributors for release of CO_2, with about 820 gCO_2 equivalent per kWh being emitted by coal. Likewise, even some alternative sources like biomass and natural gas contribute to high levels of release of CO_2. However, the nuclear energy releases about only 12 gCO_2 equivalent per kWh, which is minimal to almost none when compared to the fossil fuels and is bested only by wind [15]. The main reason behind this is the fact that nuclear uses low enriched uranium as a fuel and the fission of 1 g of uranium provides the same energy equivalent to 10 tons of oil [1]. This stat clearly suggests that nuclear energy promotes cleaner planet and healthier atmosphere, thus presenting itself as a very reliable source of energy.

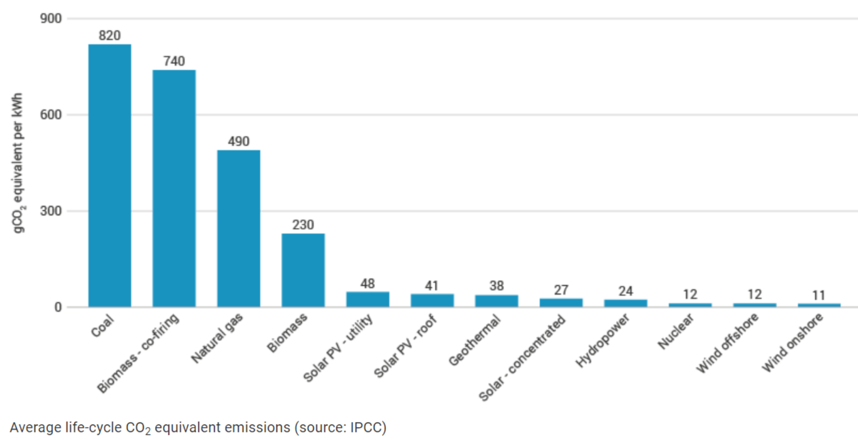

Figure 8: gCO_2 equivalent per kWh via different energy sources [15]

2.2 Capacity Factor

The net capacity factor can be described as the dimensionless ratio of a specific period's total electrical energy output to maximum achievable electricity produced during that time [16]. This can be explainable for any source of energy for electricity generation in terms of their longevity and reliability and is a vital measure to define the installation of an energy producing industry, and to compare between the different available sources.

The graph below displays the change in capacity factor of the nuclear industry from 1975 to the current date. As it can be observed, nuclear energy had a capacity factor of 92.7% during 2021 [17]. An example to illustrate this can be described as given; a nuclear power plant is able to produce 927 kW day if it is specified to produce 1 MW Day (24000 kWh) of electricity. This statistic concludes that nuclear energy has a very high productivity, since less that 10% of the net production is lost in the specified period. Also, the rise in the capacity factor of nuclear energy can be seen in greater amount from 1960-early 2000, which might have been because of advancements in design and technology related to it.

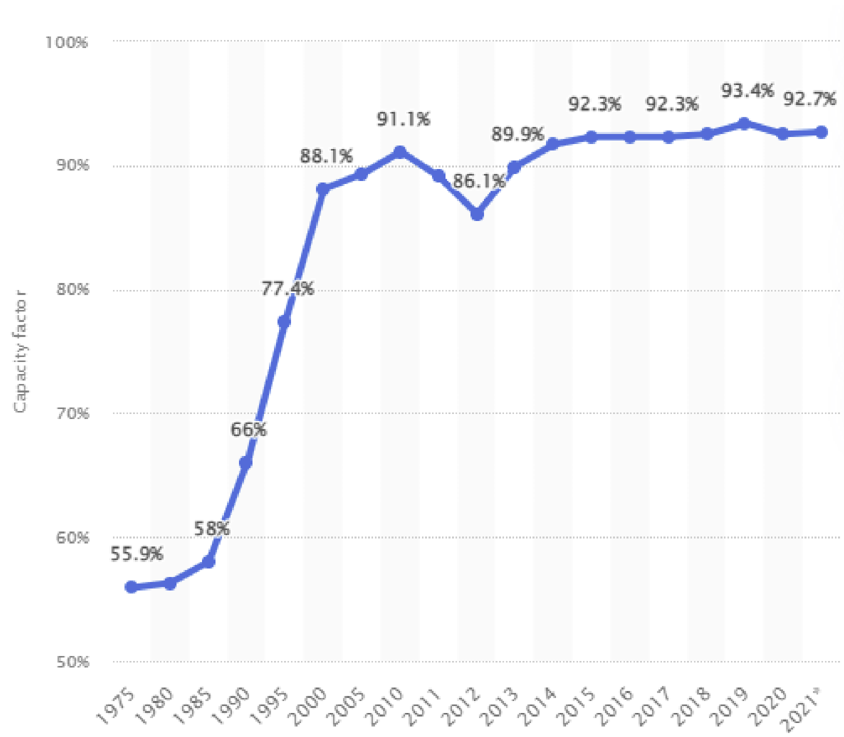

Figure 9: Capacity factor of nuclear energy from 1975-2021 [17]

Likewise, the figure below shows the capacity factor value by respective energy sources in the year 2020. Although nuclear was bettered by wind when it came to low CO_2 emissions, the figure clearly shows that with a capacity factor of more that 92%, nuclear energy is more reliable and productive than wind by more than 2.5 times [18]. The closest energy resources in terms of their capacity factor are geothermal and natural gas, but then again, they have a very high rate of CO_2 emissions. Thus, nuclear energy is proven to be the only source which is highly balanced in terms of promoting healthier world and productive operation, with its renewable factor already consolidating its position as a reliable powerhouse for electricity generation.

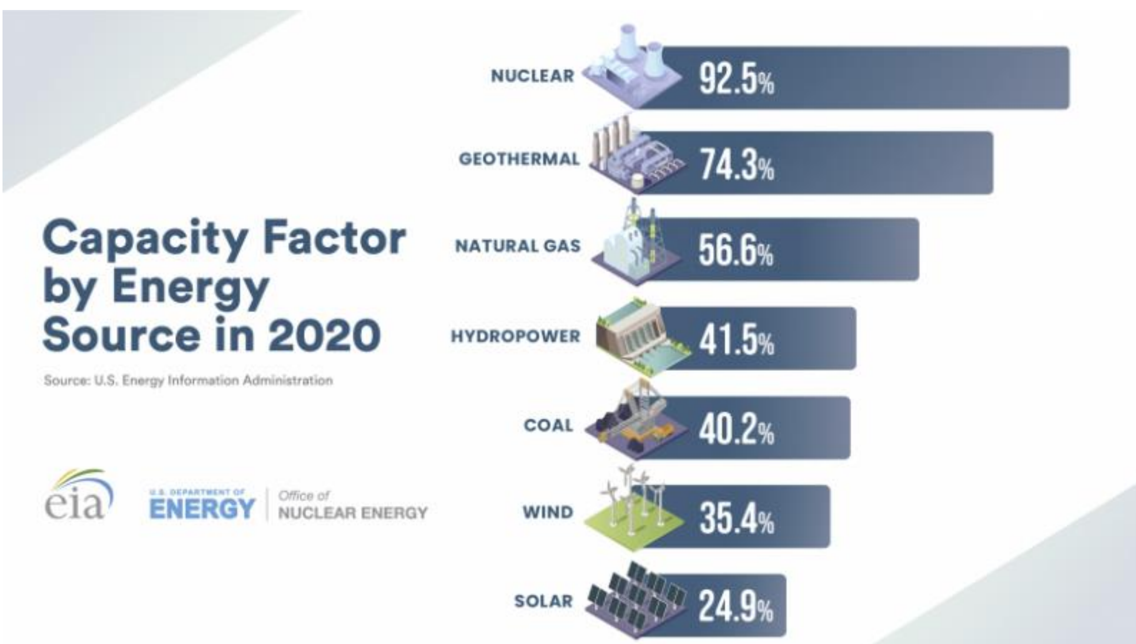

Figure 10: Capacity Factor by Energy Source in 2020 [18]

3. Common Types of Nuclear Reactors

Nuclear reactors are the primary source of conducting nuclear reactions, thus producing energy. There are different types of nuclear reactors that are used for various purposes like shipboard operations, which includes propulsion and electricity generation [1]. Some of the nuclear reactors presently being used around the globe, but not in the United States are Pressurized heavy-water reactor (PHWR) and Gas-cooled reactors (GCR). There are currently 16 PHWR and 6 GCR based nuclear power plants in the world; PHWR are in use in Argentina, India, China, Pakistan, South Korea, and Romania, whereas GCR are in use only inside the United Kingdom [19].

In this report, the reactors used only for electricity generation purposes inside the United States are considered. The list of these electricity producing nuclear reactors were extracted from the United States Nuclear Regulatory Commission (USNRC) website, and the domestic nuclear reactors from the USA are described below:

3.1 Pressurized Water Reactors (PWRs)

These are classified as a type of Light Water Reactor and are present as the largest numbers of licensed nuclear power plants in the United States, with an estimated 62 PWRs used for the nation’s electrical operations [20].

The PWRs use enriched uranium dioxide as its fuel, and as the name of the reactor suggests, it uses water as a coolant and a moderator, and these waters are used from several sources like oceans, lakes, or rivers [21].

The coolant is maintained in its liquid state by applying high amount of pressure in the reactor vessel; generally, the PWRs are pressurized to 15-16 MPa, and are made to perform at a temperature range of 300 – 325 ^oC [1].

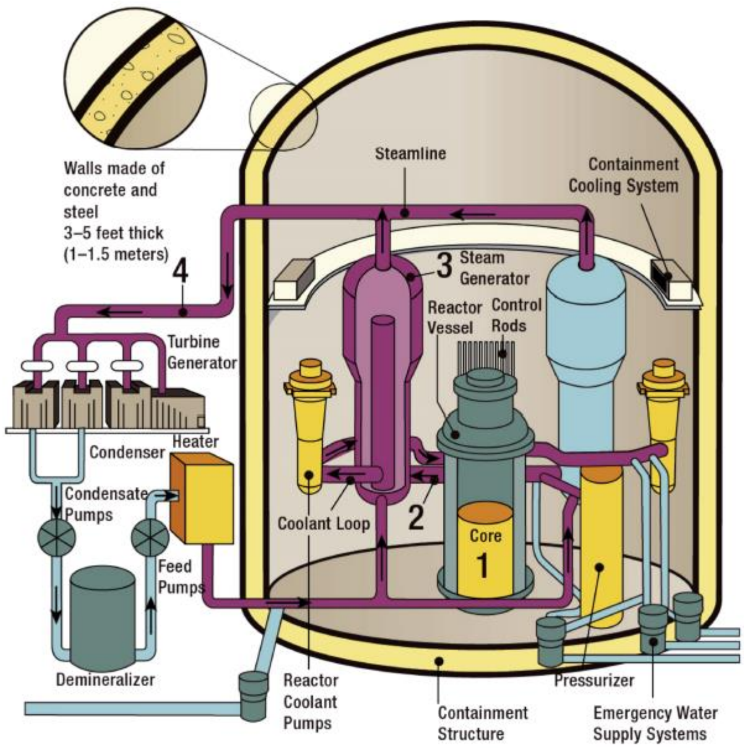

Figure 11: Schematic of a PWR [20]

The diagram shows that the core lies at the bottom of the reactor vessel present inside the containment vessel, and there are a pair of fluid loops present in these reactors. The primary objective of these loops is to circulate the pressurized coolant (water) inside the reactor core and then towards the steam generators, where steam at a lower pressure of about 6 MPa is generated and then fed to the turbine and then the generator by forcing the flow outside the containment vessel [1]. The turbine is not shielded from the steam because the steam going towards the turbine were not exposed to the reactor core, hence not carrying any radioactive materials or corrosive elements [1]. The steam exiting the turbine are reused by sending them to the cooling tower to liquify, which are then again sent to the steam generator in a cyclic process.

3.2 Boiling Water Reactors (BWRs)

These are the other types of Light Water Reactors and are make up the remaining licensed nuclear power plants in the United States, with an estimated 31 PWRs used for the nation's electrical operations *[20]*. The BWRs also use enriched uranium dioxide as its fuel and uses water in the form of steam desired fluid (coolant and moderator). The water fed is maintained in its vapor state by applying low amount of pressure in the reactor vessel; generally, the BWRs are pressurized to 7 MPa, and are made to perform at a temperature range of 285 ^{o}C [1].

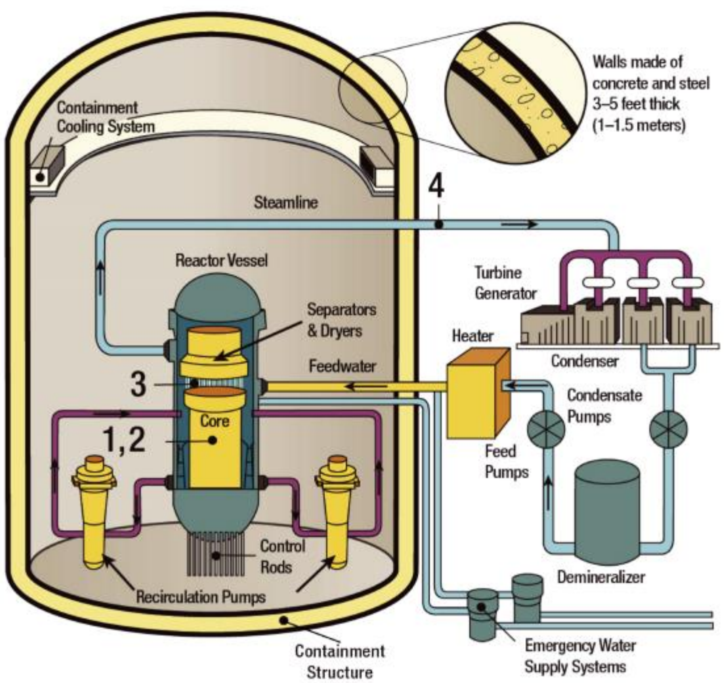

Figure 12: Schematic of a BWR [20]

BWRs only have one fluid loop to transfer the steam-water mixture from the reactor core to the turbine and generator, as seen in the figure. The water droplets from the mixture are removed in the separator which are present in the upper portion of the reactor vessel. The power output of the reactor is determined by the recirculation pumps since they allow the coolant flow rate to be changed in the core. Also, the turbine and all the piping must be shielded since the vapor released from the BWR are in direct contact with the reactor core, hence are radioactive [1].

4. Nuclear Energy's Reputation

Even with the developments seen in the nuclear energy field with its potential advantages regarding high productivity and reliability, nuclear power has always been a controversial issue in the United States. Development of nuclear power plants usually creates concerns around its safety, cost effectiveness, use of the source for nuclear weapon propagation, and problems regarding nuclear waste clearance. Making of nuclear weapons has been considered as more of a subject outside of concern for this report, as the research is only subjected within electricity production.

The exiting nuclear fuels use by the nuclear power reactors possesses high radioactive levels in them, mainly due to the existence of radioactive products emitted by fission and isotopes formed through activation of neutrons. There are about 80,000 metric tons of used spent fuel in the USA in the present context that has been stored in about 75 sites in 35 states, but there has not been any development of permanent storage of the waste source [22].

Likewise, there have been some notable nuclear disasters in the world, with mainly Chernobyl (Ukraine), Fukushima Daichi (Japan), and the Three Mile Island (USA), which have been able to attain the publicity and alarmed the world, highlighting the unsafe characteristics of nuclear energy. These disasters need to be discussed in order to understand how nuclear energy proved to be unsafe in the past, and the corresponding failures can be analyzed to make them preventable in the future, ensuring the nuclear energy as a safe source of electricity generation.

4.1 Chernobyl

The nuclear disaster in Chernobyl took place on 26 April 1986; and being considered as one of the worst nuclear disasters in the history in terms of both casualties and cost, this occurred in the No. 4 nuclear reactor in the Chernobyl Nuclear Power Plant in the Pripyat City located in northern Ukrainian SSR of the then Soviet Union [23].

The cause of this disaster was mainly because of two reasons: design flaw and mistakes from the operators handling the safety testing procedures. The reactor used in this power plant at the time was a 1000 MW reactor of RBMK (Reacktor Bolshot Moshchnosty Kanaly) type, a Soviet-designed boiling light water reactor and built graphite moderated pressure tube type reactor [24]. A diagram resembling the RBMK 1000 is shown below:

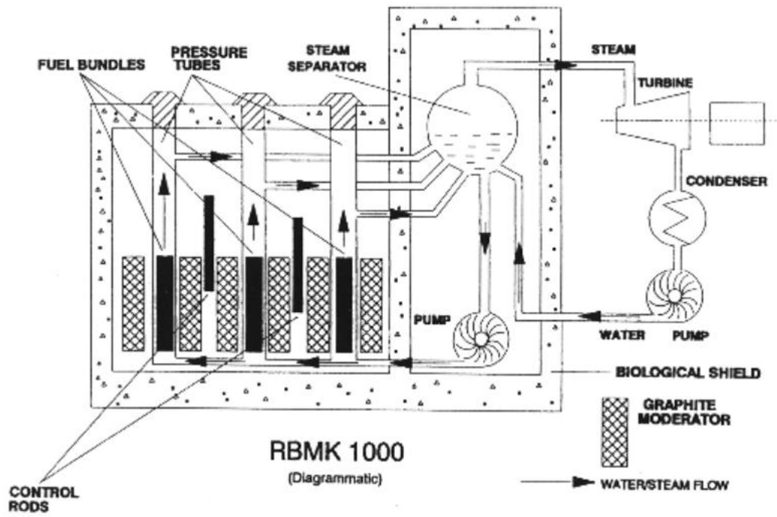

Figure 13: Schematic of a RBMK 1000 [24]

As seen above, the RBMK consists of two loops through which the steam reaches the turbines directly, and there is no heat exchanger in between. The pump also feeds water to the bottom of the fuel bundles present in the vertical pressure tubes containing slightly enriched (2% U-234) uranium dioxide fuel [1].

Each of the two loops also contain four more coolant (water) circulating pumps, which circulate around the pressure tubes. Graphite acts as a moderator between these fuel bundles, and its primary objective is to increase the efficiency of neutrons by slowing them down, aiding in fission generation of the fuel. These moderators act when the various control rods present are lowered or raised, hence taking the reactivity of the reactor in control. Other safety feature like an emergency core cooling system, a passive/active core cooling system designed to feed water to the core in the event of a coolant loss, was also incorporated within the design [25].

On the night of 26th April, safety test was conducted in the number four RBMK reactor in the Chernobyl plant, and the test procedure required deactivating the emergency core cooling system, and rules required consent from the Chernobyl site chief engineer, which was given [26]. However, the RBMK reactors at that time had a positive void coefficient, which means that an increase in steam bubbles or voids from boiling cooling water magnified the nuclear chain reaction, since neutron absorption was reduced [1]. Even graphite, the moderator remains intact, which further supports the nuclear chain reaction. So, as the test started, power started to increase with no cooling system acting, which produced more steam in the core, and this additional heat raised the cooling circuit temperature resulting in more steam (positive feedback loop). The controllers were blocked from being inserted into the pressure tubes since the enormous power level destroyed the fuel bundles. Once the fuel encountered the high steam generated inside the core, a steam explosion occurred which lifted the reactor upper plate which weighed about 1000 ton [1].

This caused the reactor core exposed to the atmosphere, since RBMK reactors didn't have inbuilt containment structure. The reaction between the steam, the fuel, and the moderator (graphite) then caused a second explosion, which was the main cause behind the radioactive gases release in the air. This reaction was also a chained fission reaction, as a result of which radioactive gases kept on being thrown to the surroundings at a significant level. Radiation poisoning occurred with the moderator, which slowly put out the fire, and helicopter were used to dump tons of boron, dolomite, sand, clay, and lead to the burning core to limit and eradicate the escape of radioactive gases [1].

This disaster was rated as a Level 7 – Major Accident on the seven-point International Nuclear Event Scale and is one of its kind; the only disaster of commercial nuclear power which caused radiation-related mortalities, killing 30 people within three months, approximately 350000 people's evacuation from the affected areas, and eventual death of 4000-27000 because of Acute Radiation Syndrome (ARS), mental stress and evacuation [27].

4.2 Fukushima Daiichi

The nuclear disaster in Fukushima Daiichi happened on 11 March 2011 and was the largest nuclear disaster that occurred after Chernobyl [28]. This occurred at the Fukushima I Nuclear Power plant, where a series of equipment failures, nuclear meltdowns, and releases of radioactive materials occurred following the 9.0 earthquake and the resulting tsunami experienced in Fukushima Sea in Japan [29]. This was rated as a Level 7 – Major Accident on the seven-point International Nuclear Event Scale [30].

The power plant comprised of six boiling water reactors that generated steam using the heat emitted from the fuel rods present, which them rotated a turbine to produce about 4.5 GW of electricity [28]. A schematic diagram of the then used reactor, called Mark-I type BWR, is shown in the figure below.

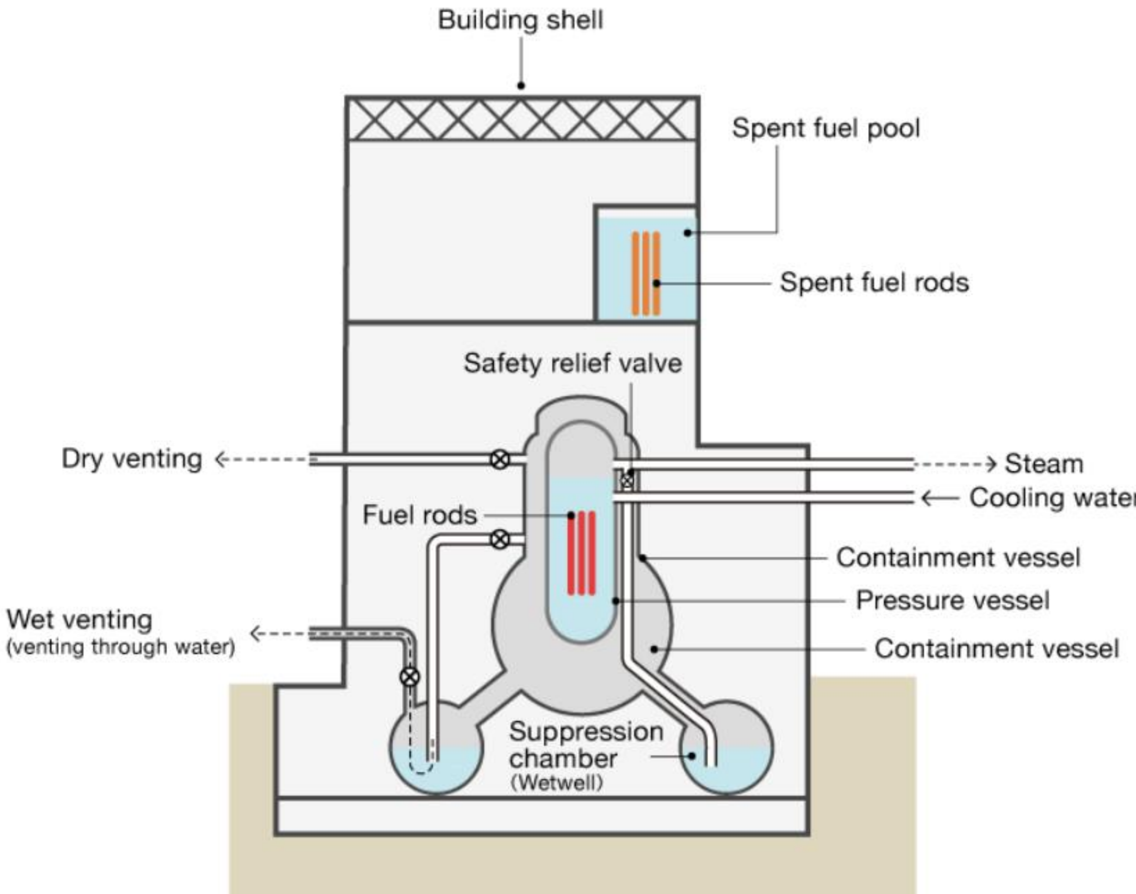

Figure 14: Schematic of Mark I type BWR used in Fukushima Daichi [31]

In the night of this nuclear disaster, the three-unit reactors (1,2, and 3) in the Power Station were running, whereas the other three (Unit 4, 5, and 6) were closed for maintenance purposes [31]. In the running reactors, however, control rods were inserted, which helped for operational and emergency shutdown. The Tsunami, at least 45 feet high, easily broke into the defensive sea wall of the power station which was at about 18-19 feet, and destroyed all the primary and secondary power sources, which as a result cut off the instrumentation, lights, and coolant circulating pumps [1].

As there was no coolant to stop the melting down of the reactor core, and because of the delayed decision of saltwater flooding in the reactors by the government (against costly reactors) for cooldown, the water started to boil in the reactors, resulting in drop of water level, more reheat, and eventually the meltdown of the first three previously running reactor units [32]. Because of the high intensity temperature and subsequential high pressure of the melting reactors, explosive hydrogen gas was produced as a result of a reaction between residual water and the nuclear fuel metal. These gases transformed into damaging radioactive isotopes of Iodine and Cesium, which exploded into the atmosphere as the cooldown and shut-off of the reactors became a struggle [33].

Although the post-disaster health issue associated with radiation were not reported after the control of this disaster, significant deaths were reported associated with the mental issues and stress led by the mandatory evacuations and food consumption from the affected premises. It was reported that 2 workers were affected by radiation burns, while 1 of them died eventually from the radiation; however, around 2200 people died from evacuation [32]. This caused a complete shutoff of all Japanese power plants by 2011, and nuclear power was then completely discarded as an alternative solution for energy demand solution, although nuclear energy was able to re-establish itself as an integral part of Japan's energy solution in the upcoming years [1].

4.3 Three Mile Island

The Three Mile Island accident happened on March 28, 1979, because of a partial meltdown of the Three Mile Island, Unit 2 (TMI-2) reactor in Pennsylvania, United States [34]. Ranked at Level 5 – Accident with Wider Consequences on the seven-point International Nuclear Event Scale, this accident can be enlisted as the most noteworthy disaster in the history of U.S commercial nuclear power plant [35].

The TMI nuclear power consisted of two pressurized water reactors. TMI-1, which was in service since 1974 was used to generate a net amount of 775 MW of electricity, whereas TMI-2, very newly made at the time of this accident, was designed to produce a net amount of 880 MW of electricity [36].

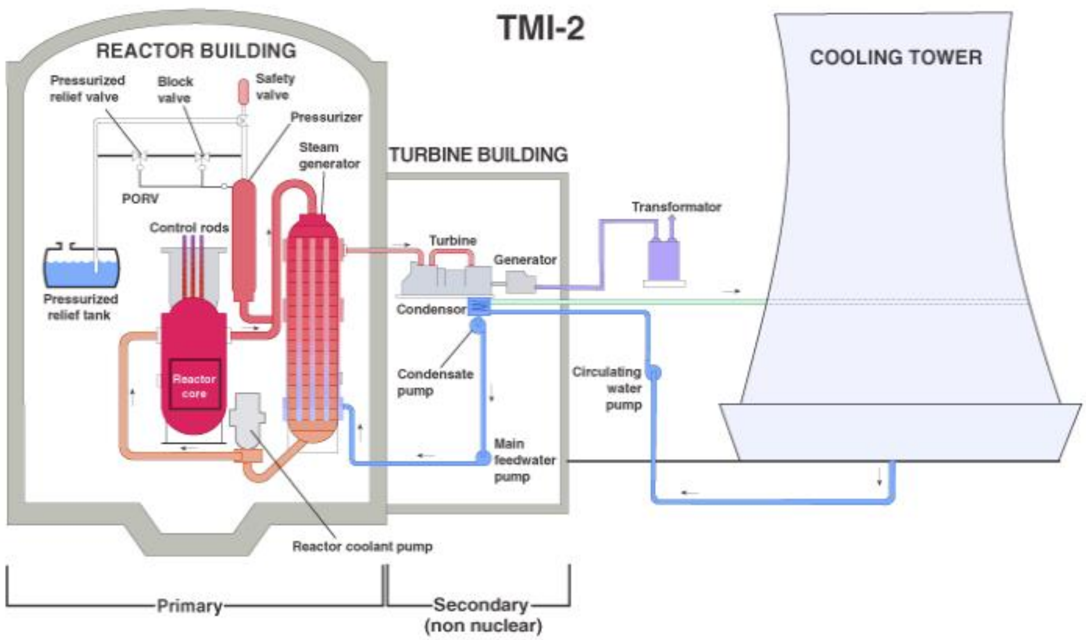

Figure 15: Schematic of the TMI-2 type PWR [36]

As seen in the figure above, the feedwater pump in the system was primarily used for transporting water to the steam generator. The steam generator, with the coolant flowing in them, contributed to removing the heat away from the reactor core. However, in the night of the accident, a mechanical failure took place because of the blockage that occurred in the filters/condensate polishers present in the secondary water loop, which protected the steam generators from minerals and other impurities. These blockages were usually fixed with ease using compressed air, but in that night, this method was not successful. Because of this, the compressed air was then blown through the water to clear out the impurities;

however, some water found its way through the pressure relief valves and left them stuck open [34].

This blocked the feedwater pumps from sending coolant (water) into the steam generators, causing stoppage of the turbine and the reactor as well. This immediately initiated the increase in pressure in the primary system (the piping of the plant), which again triggered the opening of more pilot operated pressure relief valves. Since they were already stuck open, they didn't close as the pressure fell to the proper levels. However, the long instrument design provided misleading information to the plant staffs, making them believe that the valves were closed, and pressurized water level was high enough, while in reality, the plant was going through a loss of coolant accident [34].

The operators also were trained to reduce the flow of replacement water because of the misleading information portrayed by the instrument deign failure, and the training given to them mentioned that the pressurized water levels were the only dependable indication of the amount of cooling water in the system. The open valves continued to let the coolant pour out in the form of steam. Because of the loss of coolant, the reactor's fuel core was uncovered, and Reactor Coolant System temperature (RCS) rose, causing the damage of fuel rods and release of radioactive material into the escaping coolant [37].

The operators were able to identify the blocked valve closure, and closed those stuck relief valves the next morning, preventing loss of coolant; however, thew superheated steam bubbles blocked the flow of water into the core cooling system [36].

To eradicate these steam bubbles, high pressure injection of water was performed by the operators to collapse steam bubbles, and a system of pipes and compressors were used to move the gas to waste gas decay tanks, but the compressors leaked, resulting in the release of radioactive waste, especially the noble gases [36].

The released radioactive noble gases were biologically inert and with very short lifespan, thus it was estimated that approximately 2 million people around TMI-2 during the accident are estimated to have received an average radiation dose of only about 1 millirem above the usual background dose (Exposure from a chest X-ray is about 6 millirem) [34]. Even if this accident had relatively less to no health impacts compared to other previously discussed nuclear disasters, this accident changed the commercial face of nuclear industry and the USNRC since there was an upsurge in the distress of the community against the nuclear power plants. TMI-2's damaged nuclear reactor system was cleaned up for over 12 years at a cost of $973 million, resulting in a significant loss of investment [36].

5. Comparison between Past vs Now

After the occurrence of these three main disasters explained above, significant measures were taken to ensure the safety of the nuclear energy prospect in the upcoming future. The evolution of nuclear energy took place with analysis on each of the mentioned disasters, and concerns were highlighted and acted upon with more efficiency. The major steps taken were regarding the design changes in the plants, and implementation of strict rules and regulations for increasing safety standards by the respective governing bodies. With nuclear energy in high demand and nuclear power plants abundantly present around the world, the safety standards, rules and regulations have been revised and made sure that commercial nuclear power plants do not behave like a nuclear bomb. It is worth mentioning that for a nuclear explosion to take place, the fuel enrichment needs to be beyond 20%, whereas the fuel used in these nuclear power plants are not enriched beyond 5% [38].

Although the disasters that were discussed previously had significant damages and stood out as setbacks to the growing nuclear industry, it is quite remarkable that there were only 3 vital nuclear disasters in the 60-year history of civil nuclear power generation [24]. Some of the vital changes in the nuclear world that has taken place, which differentiates the past from the present are enlisted below:

5.1 Design Changes

The progression of the nuclear reactors since its development includes technological modernizations in terms of reactor "generators" and evaluating the reactors since the first establishment at around 1950s to about 2030s, four generations have been recognized [1].

Generation I power reactors consists of the reactors which started the commercial nuclear power during 1950s period. They were established more as a pilot project; made to operate at power levels considered as feasible through simple experiments. It is reported that all the Generation I reactors have been retired.

Generation II reactors were started to be established at around 1960s, and until the end of the 1990s, and these are types of the reactors used in the present. They include PWR, PHWR, and BWR, and their lifespan is about 40 years or greater. RBMK 1000 from Chernobyl was an early Generation II design but had a lot in common with the prototypical Generation I graphite pile reactors [39]. Likewise, Fukushima Daichi 's three destroyed reactors were also generation II reactors, and so was the reactor from the TMI disaster.

After the disaster in Chernobyl, no new RBMK reactors were built, and the ones which remain has their designs modified under the recommendation of International Atomic Energy Agency including speeding up the control-rod insertion time by about a third, to 12 seconds, and using uranium of a slightly higher enrichment in the core, which essentially means the reactor doesn't have to be driven as hard to spin the turbines [40]. The measures, according to nuclear specialists, have significantly lowered the technological chance of a replay of the Chernobyl disaster. Similarly, after finding out that Fukushima Daichi would have been preventable had the state-of-the-art safety approaches were implemented, the Nuclear Regulation Authority (NRA) of Japan enforced new regulatory standards which requested enhancement of the design basis in such a way that protection against tsunamis and earthquakes were considered strongly [41].

Likewise, the reactors have further evolved into Generation III, focusing on larger disposal of spent fuel and improvements in its technology, standard designs, and practices in construction. Generation III reactors are supposed to have a lifespan of over 80 years. These reactors are estimated to reduce capital cost, accidents in core melts, waste disposal amount, and have high strength against aircraft and other external impacts [42].
Although there are no Gen III reactors in service as of today, they have been undergoing in advanced planning stages, and are already in construction in some countries like Japan, Russia, China, etc. For example, in Japan, a General Electric–Hitachi ABWR was built in under four years, from 2013 to 2017 [1].

Moreover, Generation III+ have been modelled to be even safer than Generation III reactors, ensuring passive safety features that uses natural convection and do not require operators' interferences [1]. Currently, there are 30 of these proposed inside the United States, out of which 24 applications have received and 4-6 are in proceeding status [43].

There is high likelihood for Generation III+ reactors to be built if Gen II and Gen III become highly reliable. The figure below shows the different generations of nuclear power, and also includes a visionary Gen IV for the future after 2030s.

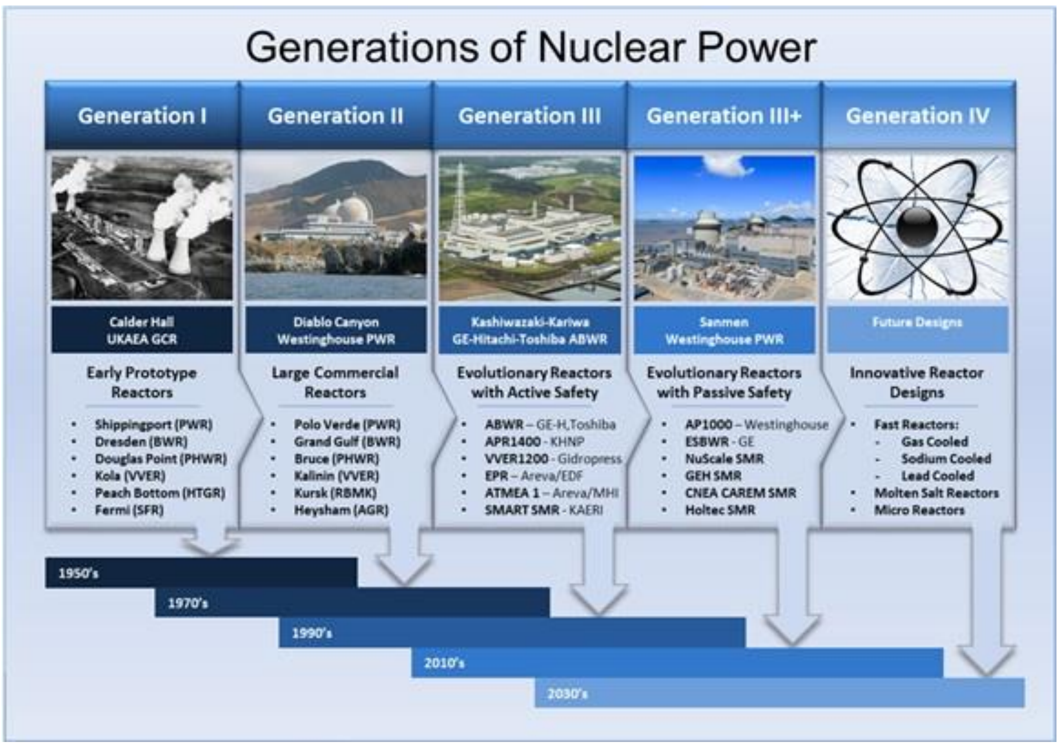

Figure 16: Different generations of Nuclear Power [44]

5.2 Safety regulating Organizations

Every aspect of power generation has its fair share of risks, but the safety standards has been regulated in all the fields to ensure their use as a safe measure. Likewise in nuclear, there are different organizations, national and international, which have constantly evaluated the past flaws and placed strict rules and regulations while operating a nuclear power plant.

World Association of Nuclear Operators (WANO) has been the lead organization internationally since 1989, but amongst the governments, International Atomic Energy Agency (IAEA) was established by United Nations in 1957 to act as an auditor of world nuclear safety [45].

IAEA's role is to fundamentally monitor the operating nuclear power plants in all countries around the globe and provide a nuclear safety inspectorate to attain constant communication. WANO, on the other hand, was formed a couple years after Chernobyl, and today it links all 115 power plants operating in 34 countries [45].

Likewise, the Institute of Nuclear Power Operations (INPO) was established in USA after the Three Mile Accident in 1979. It includes all the US members who are associated with the current or to be constructed US based nuclear power plants. Its goal is to improve plant protection and self-regulation via critical analysis, and it served as a foundation for WANO's international growth [45].

Moreover, USNRC is another leading organization inside the United States that has enlisted the safety requirements and regulations for different layers of protection and safety. Below is a table that highlights some of the regulatory requirements set by USNRC which are effectively employed by a nuclear power plant.

NRC Standards/Codes	Titles for regulatory requirements
10 CFR Part 20	Standards for Protection Against Radiation.
10 CFR 50.34a	Design objectives for equipment to control releases of radioactive material in effluents - nuclear power reactors.
10 CFR 50.36a	Technical specifications on effluents from nuclear power reactors
10 CFR 50.72	Immediate notification requirements for operating nuclear power reactors
10 CFR 50.73	Licensee event report system
NUREG-0472	Design Criteria 60, Control of Releases of Radioactive Materials to the Environment
NUREG-0473	Design Criteria 64, Monitoring Radioactivity Releases

Table 2: NRC Standards/Codes and their titles for regulatory requirements [45]

All these organizations with their set of standards and presented regulations approved by the respective governments and the world have also ensured the safe present and future of the nuclear industry.

6. Conclusion

The thorough analysis of the potentiality of the nuclear energy, the history behind its reputation, and the evolution of nuclear energy from its past helped to conclude the fact that nuclear energy is indeed a very reliable and safe source of power generation. The scale in which production and consumption of electricity via nuclear industries affects the environment was minimal, whereas the capacity in which it functions was the maximum among other sources of energy compared. However, the world is yet to fully comprehend the prospect of the development of nuclear plants because of the lack of understanding about the suitability and safety approaches this source carries. The three nuclear disasters seem to make big news worldwide causing the growth of nuclear energy to decline, yet the same world doesn't realize that casualties through use of fossil fuel consuming products or relatable accidents occurs at a higher frequency than the nuclear disasters. Unparallel advertisements of the currently consumed energy sources against the nuclear energy is vivid, and this mighty be one of the major hinderance towards the global scale acceptance of nuclear energy now and even in the future. Likewise, the geo-political wars can also play an adverse role in growth of nuclear dependency around the world. Nevertheless, the reliability and safety factors of the nuclear power plants should not be neglected, and the sooner the world learns about its productivity and acts accordingly, the better the growth and development will take place in energy distribution for civil applications.

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