Nuclear Power in the Sustainable Energy Transition

Moses Jeremiah Barasa Kabeyi
Industrial Engineering Department, Durban University of Technology, Durban South Africa
moseskabeyi@yahoo.com

Oludolapo Akanni. Olanrewaju
Industrial Engineering Department, Durban University of Technology, Durban South Africa
oludolapoo@dut.ac.za

Abstract

The economic viability of a power plant is dependent on the cost of the electricity generated which is influenced by a wide range of factors and inputs from the inception to end of economic life. The Levelized cost of energy or electricity (LCOE) is a model used to estimate the cost of electricity before the powerplant is constructed. The cost of building a nuclear power plant and any financing cost is the most important contributing factor to the cost of from nuclear power plants. Although modern nuclear power plants are generally large and expensive, their long project lifetime effectively reduces the cost of nuclear power can still be relatively low. Nuclear energy has generally been regarded by public opinion as a harmful energy resource. The growing concerns over global climate change and greenhouse gas emissions have changed this belief and nuclear is now considered a reputable green power source that can generate significant amounts of energy with low carbon emissions. Nuclear energy is currently a mature low-GHG emission energy resource that is ideal for use as baseload power. However, the share in global electricity generation has been declining globally but its share of global electricity generation has been declining since the year 1993 because of various barriers and risks. The life cycle GHG emissions from nuclear power are less than traditional fossil sources but assumptions and conditions under which they are deployed can have serious impact on the magnitude of life cycle GHG emissions compared to renewable technologies. The published median, interquartile range (IQR), and range for LWR life cycle GHG emission are 13, 23, and 220 grams of carbon dioxide equivalent per kilowatt-hour (g CO2-eq/kWh), respectively. Upon application of harmonizing methods to use consistent gross system boundaries and values important system parameters yielded 12, 17, and 110 g $CO_{2\text{-eq}}$/kWh, respectively. Based on ongoing improvements, median life cycle GHG emissions could be 9 to 110 g CO2-eq/kWh by 2050

Keywords
Nuclear energy; nuclear fission; nuclear fusion.

1. Introduction

Nuclear power is low-emission source of electricity, accounting for about 10% of global electricity generation. Nuclear energy can complement renewables in reducing emissions and contributing to electricity security as a dispatchable power source. Nuclear energy can also be used to produce low low-emission heat and hydrogen. There is need to get nuclear power on track with the Net Zero Emissions by 2050 Scenario. Lifetime extensions of existing nuclear plants has proved to be one of the most cost-effective sources of low-emission electricity. Other measures include promotion of small modular reactors, which can help expand the range of low-emission options and increase options to net zero power(IEA, 2022).

Nuclear power plants have been in operation for more than 50 years now, during which they have avoided 66 Gt of CO_2 emissions globally by replacing fossil fuel like coal, natural gas, and oil. Developed economies will generate 20% higher emissions over the past 50 years, led by the United States and European Union if nuclear power is abandoned. Emerging and developing markets like China and India have recently increased their nuclear power capacity leading a reduction in emissions by 9 Gt of emissions (IEA, 2022).

Nuclear power generation capacity reduced by about 3 GW globally in 2021 due to retirement of old power plants since new reactors could not compensate for over 8 GW of retirements. All new capacity in 2021 came from emerging markets and developing economies while Germany accounted for the majority permanent shutdowns (IEA, 2022). To achieve the Net Zero Scenario, nuclear power generation should expand by about 10-17 GW per year to 2030 to reduce fossil fuel consumption while at the same time increase the share of renewable sources of energy in power generation(Kabeyi & Olanrewaju, 2022a, 2022b). Measures like prioritising lifetime extensions in G7 will help bolster the low-emissions and make the most of new nuclear power generation capacity. Six large-scale nuclear reactors were commissioned in 2021 with a combined electricity generation capacity of 5.6 GW with most of the new capacity in China (IEA, 2022).

The net zero targets encourage innovation in nuclear power technologies, like use of small modular reactors (SMRs), which smaller than 300 MW per reactor, down to 10 MW. SMRs promise to provide more affordable, and easy and faster to construct compared to conventional large reactors with about 70 designs under development. SMRs can be built in factory and moved to final location, which reduces timelines and construction risks as well as and financing costs. As the share of wind and solar increases, SMRs promise to be key in the transition by meeting rising flexibility needs in the power system. SMRs can also be used for heat and hydrogen production(IEA, 2022).

SMRs success needs policy and regulatory reforms to streamline the licensing and regulatory frameworks. Lessons from the first commercial-scale projects, will help cut down the cost of new nuclear power plant projects. SMRs also require technological advancements for widespread use in decarbonised systems. The Generation III technologies, focusing on enhanced safety, have new concepts under construction expected to come online by 2030. Generation IV SMRs, include liquid metal-cooled, molten salt-cooled and gas-cooled designs, which are less advanced need more development. The ability to reach higher temperatures and potentially recycle used nuclear fuel makes SMRs attractive provided there is progress within required timelines. SMRs may be full commercialised by the mid-2030s, and add significant value to the in decarbonising power systems (IEA, 2022).

Most hydrogen is produced by steam reforming of natural gas or from coal gasification. The demand for large volumes of low-emission hydrogen to achieve Net Zero emissions generates new opportunities for nuclear power through many ways, but the most technologically advanced option is to couple nuclear reactors with electrolysers while other methods that create hydrogen directly from nuclear power without electrolysis are under development. In high-temperature thermochemical hydrogen production, heat is derived directly from the nuclear unit to split water into hydrogen and oxygen with system efficiency greater than 40%, which is higher than advanced electrolysis models which attain efficiency of 30%(IEA, 2022).

The Net Zero Scenario requires low-emission heat in district heating systems to increase significantly, since fossil fuels currently supply account for significant portion of heat used in district heating. Most current nuclear reactor designs are already well adapted to supply district heating and even on a smaller scale using SMRs which can be used in localised district heat production. Excess thermal energy from nuclear power plants can be injected into heating networks in a co-generation plant setup, which will significantly reduce the energy consumption used in heating(IEA, 2022).

Nuclear energy has ability to provide low-emission, dispatchable and flexible power to the electricity system. Through carbon pricing, an explicit value is placed on the low emissions benefits of nuclear power. Nuclear energy designs should adequately remunerate the capacity and ancillary services that nuclear energy is able to provide. In some countries, these costs are embedded in their marginal cost of electricity. Capacity mechanisms can be used to remunerate power generators for availing electricity generation capacity as applied in the US and some EU countries like France and the United Kingdom(IEA, 2022).

Energy security concerns, more so with relation to Russia's invasion of Ukraine have shown the vulnerability of relying on fossil fuels especially Germany which abandoned nuclear energy for gas. lifetime extension of existing nuclear reactors has shown positive impact on nuclear energy especially cost while innovative financing mechanisms, like Regulated Asset Base model in the United Kingdom, have proved to be useful policy measures toward net Zero carbon emissions304].

Between 2016-2020 annual investment in nuclear averaged over USD 35 billion per year spread across several regions. To be in line with Net Zero Scenario, investment in nuclear should be scaled upwards to over USD 100 billion in the late 2020s. This requires governments to reduce risks for nuclear power wherever possible(IEA, 2022). The various measures and recommendations need are.

i.) Strengthen policy frameworks to reduce risks in investing in low-emission **projects**, like nuclear power plants. Since financing costs represent a large share of total costs of nuclear power, risk reduction will reduce final costs to s to consumers throughout energy transitions.

ii.) Support innovative technologies like the SMR projects and hydrogen production through direct measures like the essential R&D capabilities, talent and the development of licensing frameworks.

iii.) There is need to review national and international decarbonisation pathways due to technological progress for nuclear power that include SMRs, and new applications in hard-to-abate energy sectors.

iv.) Facilitate efficient and effective safety regulations as well as appropriate waste management, and safety regulations for safe nuclear power generation. Regulators should skills and resources to review new projects and develop harmonised safety criteria for new designs. Licencing requirements should be clearly communicated to all parties.

v.) Accelerate the development and deployment of SMRs by identifying opportunities for SMR technologies to be cost effective investment and develop supply chains, to strengthen the SMR industries and promote earlier deployment.

vi.) Improve the supply chains and talent pipelines, building on any existing nuclear supply chains and cooperate with other industries relevant to the nuclear technologies like SMRs supply chains e.g., shipbuilding for modular construction.

vii.) Facilitate public engagement with all relevant stakeholders more so the local communities where nuclear technologies are expected to be deployed for acceptance(IEA, 2022). .

Commercialisation for new nuclear technologies, and reduction in costs can be accelerated by international collaboration. This can be achieved by coordinating the developing new designs and construction of commercial-scale projects to avoid duplication and hence avoid unnecessary costs and slowing down of innovation. Regulation and approval of new designs can significantly benefit from international collaboration. Faster implementation and lower project management costs will be achieved by collective review and approval of designs which shortens the time to market and reduce the access costs. This will facilitate standardisation of processes for new products and technologies like the SMRs which can be built at factory and transported to operational sites(IEA, 2022).

Nuclear power plants produce intense heat used to generate steam to run a steam turbine connected to a generator that produces electricity. Nuclear power plants are used as base load stations. Nuclear reactors are classified as large, medium, and small-sized nuclear reactors. There is a growing trend for development of small sized reactors away large nuclear reactors which have become less attractive. Small-sized nuclear reactors were originally used to facilitate the development and demonstration of early reactor technologies to develop operational experience for the nuclear power sector. Basic of reactors is concerned with reliability, safety, and passive safety systems. A brief review of the design and safety aspects of some small nuclear reactors have been discussed. [1]

In nuclear power plants, water is heated to produce steam which in return is used to spin steam turbines that generate electricity. The heat used in nuclear power plants is produced during nuclear fission of radioactive materials in nuclear fuel. During nuclear fission, atoms are split apart into subatomic particles releasing heat energy. The fission is controlled in the reactor of a nuclear power plant. Uranium fuel is contained in the reactor core of the power plants(US Energy Information Agency, 2022). Nuclear energy is released by the nucleus, which is the core of atoms, made up of protons and neutrons nuclear energy can be produced by produced fission where the nuclei of atoms split into several parts or fusion in which the nuclei fuse together. The energy release is harnessed to generate electricity through nuclear fission, as fusion is still under research and development stage(Association., 2023; Galindo, 2022).

Nuclear technology uses exploits the energy released by the splitting atoms of for heat and power generation. The technology was first used in the 1940s, and during the Second World War research initially in research focused in the production of bombs. The focus shifted in 1950s to peaceful use of nuclear fission, for controlled use in power generation. (Galindo, 2022).

There are more than 18,000 reactors globally dedicated to civil use operating in 32 countries worldwide. The beneficiaries are more due to increased use of regional transmission grids, e.g. Italy and Denmark, gets about 10% of their electricity from imported nuclear power(Galindo, 2022). The applications of nuclear technology are many and extend beyond low carbon energy to include medical diagnosis and treatment, space exploration and military applications.(Galindo, 2022).

2. Nuclear Energy

2.1. Nuclear Fissions

Uranium fuel for fuel reactors is formed into ceramic pellets which generally have same capacity equivalent to about 150 gallons of oil. The pellets are stacked end-to-end in 12-foot metal fuel rods. With a bundle of fuel rods that may contain hundreds of rods called a fuel assembly. A nuclear reactor core contains several fuel assemblies(US Energy Information Agency, 2022).

In nuclear power generation, heat generated in nuclear fission in the reactor core is used to heat and boil water into steam, which in turn is used to run a steam turbine coupled to an electric generator for power generation. The condensate is cooled in a cooling tower for recycling, together with fresh makeup water (US Energy Information Agency, 2022).

Radioactive materials have different isotopes for example hydrogen—^{1}H, ^{2}H, and ^{3}H. isotopes of uranium contain 143 neutrons (^{235}U) and 146 neutrons (^{238}U). Fission occurs or is induced when an atom neutron causing a breakup or fission of the nucleus into two fragments, each with a mass roughly one-half the mass of the original uranium nucleus. When a heavy nucleus undergoes fission two lighter nuclear fragments are formed, and release of two or three neutrons which trigger another event in a controlled manner using control rods which absorb neutron(Marion, 1974).

2.2. Nuclear Fusion

Nuclear fusion involves combination of two atomic nuclei to form a single heavier one with massive release of energy. This happens because the total mass of the resulting single nucleus is less than the mass of the two original nuclei hence the left over mass becomes energy based on Einstein's equation ($E=mc^2$), which states that mass and energy can be converted into each other(US Department of Energy, 2022). E is the energy in joules, m is the mass difference in kilograms, and c is the speed of light (approximately 300,000,000 or 3×10^8 m per second). Many elements in the periodic table can be used for fusion, but there is specific interest in deuterium-tritium (DT) fusion reaction which produces a neutron and a helium nucleus and releases much more energy than most fusion reactions(US Department of Energy, 2022).

The difference in the mass between the reactants and the products is manifested as energy release or absorption. The mass difference is due to the nuclear binding energy between the atomic nuclei before and after the fission or fission reaction. Active or main-sequence stars and other high-magnitude stars are powered by nuclear fusion which release huge amounts of energy . It has been established that fusion that produces atomic nuclei that is lighter than iron-56 or nickel-62 generally release energy since these elements have relatively small mass and a relatively large binding energy per nucleon. Fusion of nuclei that is lighter releases energy i.e. exothermic process, while the fusion of heavier nuclei results in energy retained by the product nucleons, leading to endothermic reaction. In nuclear fusion lighter elements are used like hydrogen and helium, which are generally more fusible but heavier elements like uranium, thorium and plutonium, are more fissionable. Through extreme astrophysical event of a supernova, enough energy can be produced to fuse nuclei into elements heavier than iron(US Department of Energy, 2022; Viswanathan, 2017).

Energy produced in fusion is also a result of an interplay of the very short-range attractive force binding the protons and neutrons together and the Coulomb force which results in the repulsion of the protons. The building nuclei from the lightest nuclei produces energy and called the fusion energy since nuclear forces are stronger than the Coulomb forces for atomic nuclei that is lighter than nickel and iron. Fusion is only possible when the nuclei fusing together are brought together in a confined volume (Viswanathan, 2017).

2.2.1. Fuels for Fusion

Fusion fuel is plentiful and easily accessible: deuterium can be extracted inexpensively from seawater, and tritium can potentially be produced from the reaction of fusion generated neutrons with naturally abundant lithium. These fuel supplies would last for millions of years. Future fusion reactors are also intrinsically safe and are not expected to produce high activity or long-lived nuclear waste. Furthermore, as the fusion process is difficult to start and maintain, there is no risk of a runaway reaction and meltdown; fusion can only occur under strict operational conditions, outside of which (in the case of an accident or system failure, for example), the plasma will naturally terminate, lose its energy very quickly and extinguish before any sustained damage is done to the reactor. Importantly, nuclear fusion — just like fission — does not emit carbon dioxide or other greenhouse gases into the atmosphere, so it could be a long-term source of low-carbon electricity from the second half of this century onwards.

2.2.2. Benefits and potential

Ever since the theory of nuclear fusion was understood in the 1930s, scientists — and increasingly also engineers — have been on a quest to recreate and harness it. That is because if nuclear fusion can be replicated on earth at an industrial scale, it could provide virtually limitless clean, safe, and affordable energy to meet the world's demand. Fusion could generate four times more energy per kilogram of fuel than fission (used in nuclear power plants) and nearly four million times more energy than burning oil or coal.Most of the fusion reactor concepts under development will use a mixture of deuterium and tritium — hydrogen atoms that contain extra neutrons. In theory, with just a few grams of these reactants, it is possible to produce a terajoule of energy, which is approximately the energy one person in a developed country needs over sixty years.

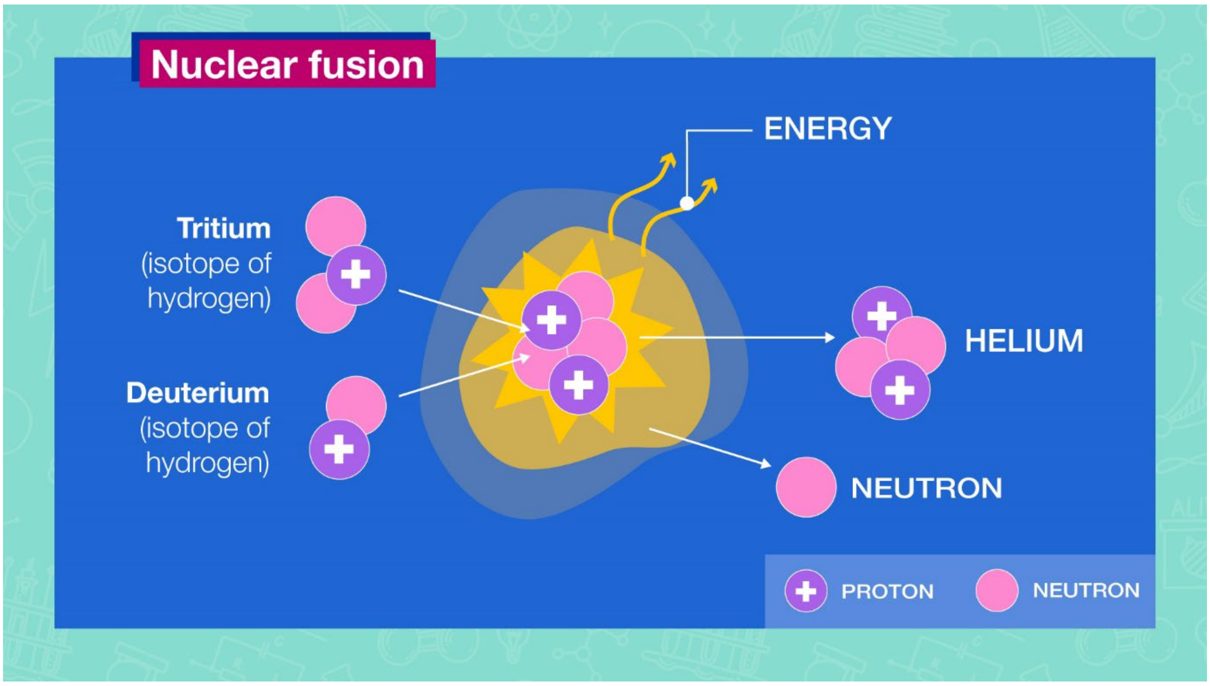

Figure 1. Nuclear fusion

While the sun's massive gravitational force naturally induces fusion, without that force a temperature even higher than in the sun is needed for the reaction to take place (Figure 1). On Earth, we need temperatures of over 100 million degrees Celsius to make deuterium and tritium fuse, while regulating pressure and magnetic forces at the same time, for a stable confinement of the plasma and to maintain the fusion reaction long enough to produce more energy than what was required to start the reaction. While conditions that are very close to those required in a fusion reactor are now routinely achieved in experiments, improved confinement properties and stability of the plasma are still needed to maintain the reaction and produce energy in a sustained manner. Scientists and engineers from all over the world continue to develop and test new materials and design new technologies to achieve net fusion energy.

2.2.3. The future

The future of nuclear fusion is uncertain. Fusion research began to make substantial progress in the last decade. This has culminated in recent breakthroughs in magnetic confinement technology, and work on laser and particle beam implosion is also progressing. Although such developments are encouraging and the potential is great, much work remains to be done and significant contributions from fusion are certainly very far in the future. From an environmental standpoint, many people hope nuclear fusion will be the long-term clean energy solution. However, it may not be totally free of as yet undefined environmental concern(Mathis et al., 1982).

Nuclear fusion and plasma physics research are carried out in more than 50 countries, and fusion reactions have been successfully produced in many experiments, albeit without so far generating more energy than what was required to start the reaction process. Experts have come up with different designs and magnet-based machines in which fusion takes place, like stellarators and tokamaks, but also approaches that rely on fuels. How long it will take for fusion energy to be successfully rolled out will depend on mobilizing resources through global partnerships and collaboration, and on how fast the industry will be able to develop, validate and qualify emerging fusion technologies. Another important issue is to develop in parallel the necessary nuclear infrastructure, such as the requirements, standards, and good practices, relevant to the realisation of this future energy source(Mathis et al., 1982).

2.2.4. Advantages of Nuclear Fusions

The next decades are crucially important to putting the world on a path of reduced greenhouse gas emissions. By the end of the century, demand for energy will have tripled under the combined pressure of population growth, increased urbanization and expanding access to electricity in developing countries. The fossil fuels that shaped 19th and 20th century civilization can only be relied on at the cost of greenhouse gases and pollution.

A new large-scale, sustainable, and carbon-free form of energy is urgently needed. The following advantages make fusion worth pursuing. Abundant energy: Fusing atoms together in a controlled way releases nearly four million times more energy than a chemical reaction such as the burning of coal, oil, or gas and four times as much as nuclear fission reactions (at equal mass). Fusion has the potential to provide the kind of baseload energy needed to provide electricity to our cities and our industries. Sustainability: Fusion in ITER will require two elements: deuterium and tritium. Deuterium can be distilled from all forms of water, while tritium will be produced during the fusion reaction as fusion neutrons interact with lithium. (Terrestrial reserves of lithium would permit the operation of fusion power plants for more than 1,000 years, while sea-based reserves of lithium would fulfil needs for millions of years.) A critical challenge is how to breed and recover tritium reliably in a fusion device. No CO_2: Fusion doesn't emit harmful substances like carbon dioxide or other greenhouse gases into the atmosphere. Its major by-product is helium: an inert, non-toxic gas. No long-lived radioactive waste: nuclear fusion reactors produce no high activity, long-lived nuclear waste. The activation of components in a fusion reactor is anticipated to be low enough for the materials to be recycled or reused within 100 years, depending on the materials used in the "first-wall" facing the plasma. Limited risk of proliferation: Fusion doesn't employ fissile materials like uranium and plutonium. (Radioactive tritium is neither a fissile nor a fissionable material.) There are no enriched materials in a fusion reactor like ITER that could be exploited to make nuclear weapons.

No risk of meltdown: A Fukushima-type nuclear accident is not possible in a tokamak fusion device. It is difficult enough to reach and maintain the precise conditions necessary for fusion—if any disturbance occurs, the plasma cools within seconds and the reaction stops. The quantity of fuel present in the vessel at any one time is enough for a few seconds only and there is no risk of a chain reaction. Cost: The power output of the kind of fusion reactor that is envisaged for the second half of this century would likely be like that of a fission reactor (i.e., between 1 and 1.7 gigawatts). The average cost per kilowatt of electricity cannot yet be extrapolated, however, as this would require the operational experience which will only be available after ITER has been operated for some years. As with many new technologies, costs will be more expensive at first, when the technology is new, and gradually less expensive as economies of scale bring the costs down.

The ideal future energy mix for the planet would be based on a variety of generation methods instead of a large reliance on one source. As a new source of carbon-free baseload electricity, producing no long-lived radioactive waste, fusion could make a positive contribution to the challenges of resource availability, reduced carbon emissions, and fission waste disposal and safety issues.

3. Lifecycle Assessment of Nuclear Power Plants

3.1. Levelized Cost of Nuclear Power Generation

The LCOE from a nuclear power plant in the United States in 2015 was estimated by Lazard to be between $97 per MWh and $136 per MWh.4 This was broadly like the cost of electricity from a coal-fired power plant (without carbon capture and storage) but more expensive than onshore wind power, utility solar power, or electricity from a natural gas combined cycle power plant. It is important to note that the nuclear cost estimate from Lazard does not include the cost of decommissioning which could have a significant effect on the actual cost of power. As with capital cost, the LCOE varies from country to country. IEA analysis suggests that at a similar discount rate (7%) the cost varies between $40 per MWh in South Korea and $101 per MWh in the United Kingdom; it was $37 per MWh and $48 per MWh for the two Chinese projects cited above(Breeze, 2017)

4. Nuclear Capacity

The first commercial nuclear power stations started operation in the 1950s. Nuclear energy now provides about 10% of the world's electricity from about 440 power reactors. Nuclear is the world's second largest source of low-carbon power (28% of the total in 2019). Over 50 countries utilize nuclear energy in about 220 research reactors. In addition to research, these reactors are used for the production of medical and industrial isotopes, as well as for training(Association., 2023)

As of July 1, 2022, 92 nuclear reactors were operating at 54 nuclear power plants in 28 states. Thirty-two of the plants have two reactors, and three plants have three reactors. Nuclear power plants have supplied about 20% of total annual U.S. electricity since 1990. Learn more about the industry. In 2020, 33 countries had commercial nuclear power plants, and in 17 of the countries, nuclear energy supplied at least 20% of their total annual electricity generation. The United States had the largest nuclear electricity generation capacity and generated more nuclear electricity than any other country. France, with the second-largest nuclear electricity generation capacity and second-highest nuclear electricity generation, had the largest share—about 69%—of total annual electricity generation from nuclear energy(US Energy Information Agency, 2022) (Figure 1).

Table 1. Top five nuclear electric generation capacity countries, 2020

Country	**Nuclear electricity generation capacity (million kilowatts)**	**Nuclear electricity generation (billion kilowatthours)**	**Nuclear share of country's total electricity generation**
United States	96.50	789.88	20%
France	61.37	379.50	69%
China	47.53	366.30	5%
Japan	31.68	43.00	5%
Russia	28.58	215.75	21%

Thirteen countries in 2020 produced at least one-quarter of their electricity from nuclear. France gets around 70% of its electricity from nuclear energy, while Ukraine, Slovakia, Belgium and Hungary get about half from nuclear (Table 1). Japan was used to relying on nuclear power for more than one-quarter of its electricity and is expected to return to somewhere near that level(Galindo, 2022)

4.1. Outlook

There is a clear need for new generating capacity around the world, both to replace old fossil fuel units, especially coal-fired ones, which emit a lot of carbon dioxide, and to meet increased demand for electricity in many countries. In 2019, 63% of electricity was generated from the burning of fossil fuels. Despite the strong support for, and growth in, intermittent renewable electricity sources in recent years, the fossil fuel contribution to power generation has not changed significantly in the last 15 years or so (66.5% in 2005)(Galindo, 2022).The OECD International Energy Agency publishes annual scenarios related to energy. In its *World Energy Outlook 2021*[1] there is an ambitious ‘Sustainable Development Scenario’ which is consistent with the provision of clean and reliable energy and a reduction of air pollution, among other aims. In this decarbonization scenario, electricity generation from nuclear increases by almost 75% by 2050 to 4714 TWh, and capacity grows to 669 GWe. The World Nuclear Association has put forward a more ambitious scenario than this – the Harmony programme proposes the addition of 1000 GWe of new nuclear capacity by 2050, to provide 25% of electricity then (about 10,000 TWh) from 1250 GWe of capacity (after allowing for retirements). Providing one-quarter of the world's electricity through nuclear would substantially reduce carbon dioxide emissions and improve air quality(Galindo, 2022).

4.2. Nuclear plant construction

About 100 power reactors with a total gross capacity of about 100,000 MWe are on order or planned, and over 300 more are proposed. Most reactors currently planned are in Asia, with fast-growing economies and rapidly rising electricity demand. Many countries with existing nuclear power programmes either have plans to, or are building, new power reactors. Every country worldwide that has operating nuclear power plants, or plants under construction, has a dedicated country profile in the Information Library. About 30 countries are considering, planning or starting nuclear power programmes (see information page on Emerging Nuclear Energy Countries) (Table 2).

Table 2. Power reactors under construction

Start		Reactor	Model	Gross MWe
2023	Bangladesh	Rooppur 1	VVER-1200	1200
2023	Belarus, BNPP	Ostrovets 2	VVER-1200	1194
2023	China, CNNC	Xiapu 1	CFR600	600
2023	Korea, KHNP	Shin Hanul 2	APR1400	1400
2023	Korea, KHNP	Shin Kori 5	APR1400	1400
2023	Turkey	Akkuyu 1	VVER-1200	1200

2023	UAE, ENEC	Barakah 4	APR1400	1400
2023	USA, Southern	Vogtle 3	AP1000	1250
2023	USA, Southern	Vogtle 4	AP1000	1250
2024	Bangladesh	Rooppur 2	VVER-1200	1200
2024	China, CGN	Fangchenggang 4	Hualong One	1180
2024	China, Guodian & CNNC	Zhangzhou 1	Hualong One	1212
2024	China, SPIC & Huaneng	Shidaowan 1	CAP1400	1500
2024	France, EDF	Flamanville 3	EPR	1650
2024	India, NPCIL	Kakrapar 4	PHWR-700	700
2024	India, NPCIL	Kalpakkam PFBR	FBR	500
2024	Iran	Bushehr 2	VVER-1000	1057
2024	Korea, KHNP	Shin Kori 6	APR1400	1400
2024	Slovakia, SE	Mochovce 4	VVER-440	471
2024	Turkey	Akkuyu 2	VVER-1200	1200
2025	China, CGN	Taipingling 1	Hualong One	1200
2025	China, Guodian & CNNC	Zhangzhou 2	Hualong One	1212
2025	China, SPIC & Huaneng	Shidaowan 2	CAP1400	1500
2025	India, NPCIL	Kudankulam 3	VVER-1000	1000
2025	India, NPCIL	Kudankulam 4	VVER-1000	1000
2025	Russia, Rosenergoatom	Kursk II-1	VVER-TOI	1255
2025	Russia, Rosenergoatom	Kursk II-2	VVER-TOI	1255
2025	Turkey	Akkuyu 3	VVER-1200	1200
2026	China, CGN	Cangnan/San'ao 1	Hualong One	1150
2026	China, CGN	Taipingling 2	Hualong One	1202
2026	China, CNNC	Changjiang SMR 1	ACP100	125
2026	China, CNNC	Tianwan 7	VVER-1200	1200
2026	China, CNNC	Xiapu 2	CFR600	600
2026	China, Huaneng & CNNC	Changjiang 3	Hualong One	1200
2026	India, NPCIL	Rajasthan 7	PHWR-700	700
2026	India, NPCIL	Rajasthan 8	PHWR-700	700
2026	Russia, Rosatom	BREST-OD-300	BREST-300	300
2026	Turkey	Akkuyu 4	VVER-1200	1200
2027	Argentina, CNEA	Carem	Carem25	29
2027	China, CGN	Cangnan/San'ao 2	Hualong One	1150
2027	China, CNNC	Sanmen 3	CAP1000	1250
2027	China, CNNC	Tianwan 8	VVER-1200	1200
2027	China, CNNC & Datang	Xudabao 3	VVER-1200	1200

2027	China, Huaneng & CNNC	Changjiang 4	Hualong One	1200
2027	China, SPIC	Haiyang 3	CAP1000	1250
2027	India, NPCIL	Kudankulam 5	VVER-1000	1000
2027	India, NPCIL	Kudankulam 6	VVER-1000	1000
2027	UK, EDF	Hinkley Point C1	EPR	1720
2028	Brazil, Eletrobrás	Angra 3	Pre-Konvoi	1405
2028	China, CGN	Lufeng 5	Hualong One	1200
2028	China, CNNC & Datang	Xudabao 4	VVER-1200	1200
2028	Egypt, NPPA	El Dabaa 1	VVER-1200	1200
2028	UK, EDF	Hinkley Point C2	EPR	1720
2030	Egypt, NPPA	El Dabaa 2	VVER-1200	1200

Latest announced/estimated year of grid connection.
Note: units where construction is currently suspended are omitted from the Table 2.

Increased capacity
Increased nuclear capacity in some countries is resulting from the uprating of existing plants. This is a highly cost-effective way of bringing on new capacity. Numerous power reactors in the USA, Switzerland, Spain, Finland, and Sweden, for example, have had their generating capacity increased.

In the USA, the Nuclear Regulatory Commission has approved about 165 uprates totalling over 7500 MWe since 1977, a few of them 'extended uprates' of up to 20%.

In Switzerland, all operating reactors have had uprates, increasing capacity by 13.4%.
Spain has had a programme to add 810 MWe (11%) to its nuclear capacity through upgrading its nine reactors by up to 13%. Most of the increase is already in place. For instance, the Almarez nuclear plant was boosted by 7.4% at a cost of $50 million.

Finland boosted the capacity of the original Olkiluoto plant by 29% to 1700 MWe. This plant started with two 660 MWe Swedish BWRs commissioned in 1978 and 1980. The Loviisa plant, with two VVER-440 reactors, has been uprated by 90 MWe (18%).

Sweden's utilities have uprated three plants. The Ringhals plant was uprated by about 305 MWe over 2006-14. Oskarshamn 3 was uprated by 21% to 1450 MWe at a cost of €313 million. Forsmark 2 had a 120 MWe uprate (12%) to 2013.

Plant lifetime extensions and retirements
Most nuclear power plants originally had a nominal design operating lifetime of 25 to 40 years, but engineering assessments have established that many can operate longer. By the end of 2016, the NRC had granted licence renewals to over 85 reactors, extending their operating lifetimes from 40 to 60 years. Such licence extensions at about the 30-year mark justify significant capital expenditure needed for the replacement of worn equipment and outdated control systems.

In France, there are rolling ten-year reviews of reactors. In 2009 the Nuclear Safety Authority (ASN) approved EDF's safety case for 40-year operation of its 900 MWe units, based on generic assessment of the 34 reactors. There are plans to take reactor lifetimes out to 60 years, involving substantial expenditure.

The Russian government is extending the operating lifetimes of most of the country's reactors from their original 30 years, for 15 years, or for 30 years in the case of the newer VVER-1000 units, with significant upgrades.

The technical and economic feasibility of replacing major reactor components, such as steam generators in PWRs, and pressure tubes in CANDU heavy water reactors, has been demonstrated. The possibility of component replacement and licence renewals extending the lifetimes of existing plants is very attractive to utilities, especially in view of the public acceptance difficulties involved in constructing replacement nuclear capacity.

On the other hand, economic, regulatory, and political considerations have led to the premature closure of some power reactors, particularly in the USA, where reactor numbers have fallen from a high of 110 to 92, as well as in parts of Europe and likely in Japan.
It should not be assumed that a reactor will close when its existing licence is due to expire, since operating licence extension is now common. However, new units coming online have been balanced by the retirement of old units in recent years. Over 2002-2021, 108 reactors were retired as 97 started operations. There are no firm projections for retirements over the next two decades, but the World Nuclear Association's 2021 edition of *The Nuclear Fuel Report* has 123 reactors closing by 2040 in its reference scenario, using conservative assumptions about licence renewal, and 308 coming online**.**

5. REACTORS

Nuclear reactors and their equipment contain and control the radioactive chain reactions, of uranium-235, to generate heat. Heat produced heats the reactor's cooling agent, often water, to produce steam which is channelled the steam turbines, coupled to an electric generator for power generation (Galindo, 2022). The nuclear reactors contain and control the nuclear chain reactions to release heat at a controlled rate (US Energy Information Agency, 2022).

5.1. Boiling-water nuclear reactors

In a boiling-water reactor, the reactor core heats water directly turning it to steam in the reactor vessel. The steam is then directed to the steam turbine generator for power generation (Figure 2).

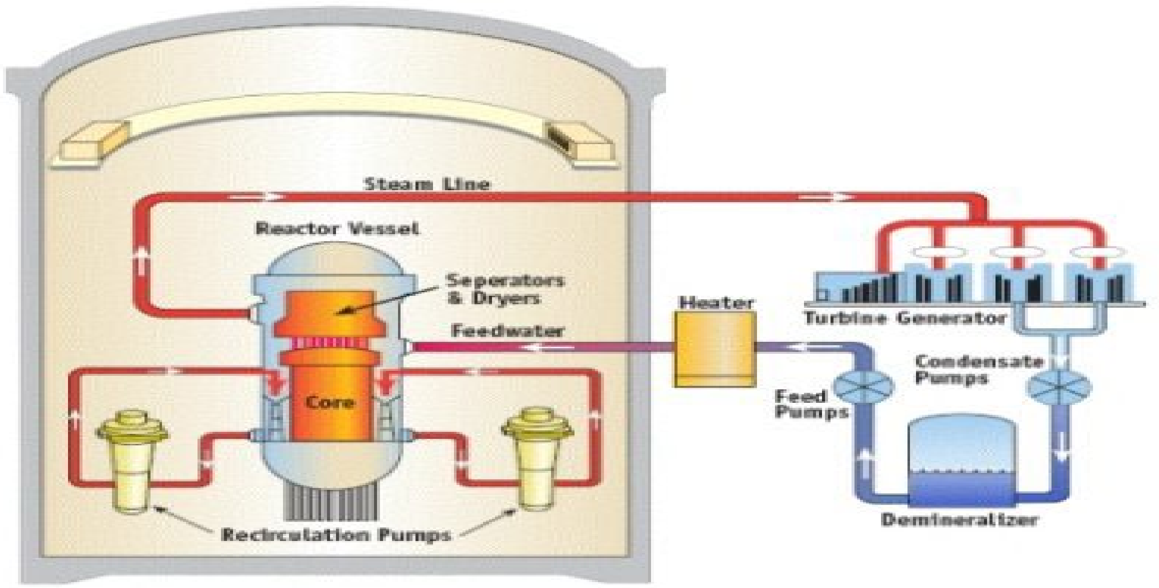

Figure 2. Diagram of a boiling-water nuclear reactor

5.2. Pressurized-water nuclear reactors

In a pressurized-water reactor, the reactor core heats water under pressure in a closed loop which prevents steaming. The hot pressurised water flows through tubes in a steam generator. Which is a giant cylinder filled with clean water (US Energy Information Agency, 2022) (Figure 3).
Source: U.S. Nuclear Regulatory Commission (public domain)

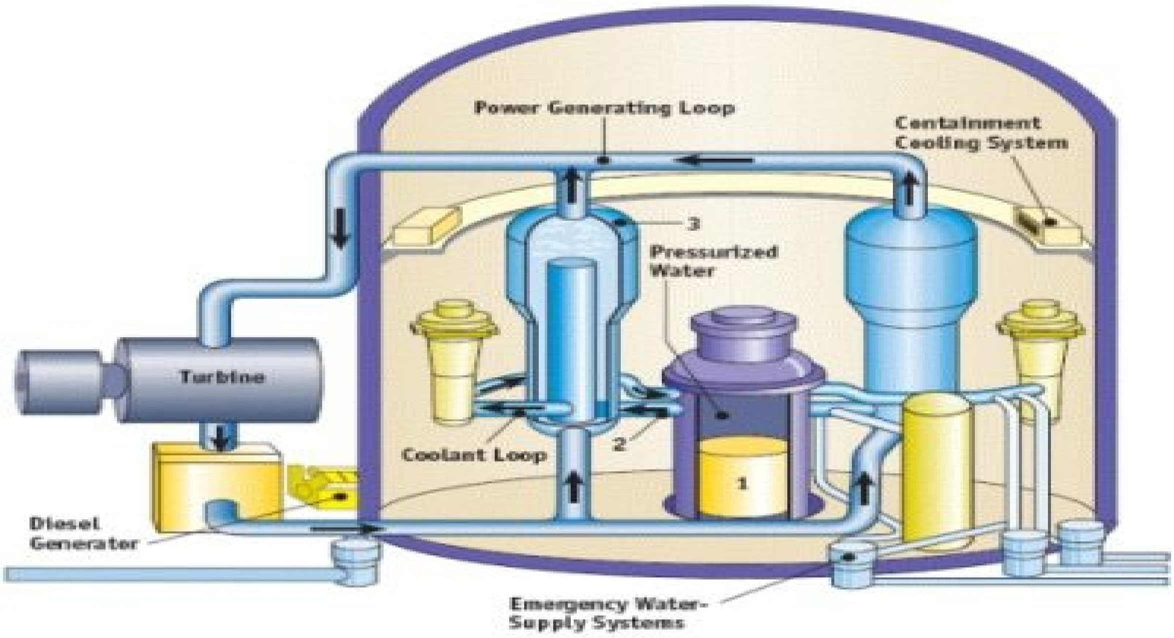

Figure 3. Diagram of a pressurized-water nuclear reactor
Source: U.S. Nuclear Regulatory Commission (public domain)

The pressurised water is recirculated through the reactor core for reheating and once heated goes to the steam generator to boil clean water for more steam production. Out 92 nuclear power reactors in the United States as of July 1, 2022, 61 or 66% are pressurized-water reactors(US Energy Information Agency, 2022). This demonstrates their popularity and wide use in power generation.

5.3. Small Modular Reactor (SMR)

The Small Modular Reactor (SMR) reactors that are smaller than conventional nuclear power plants which are generally above 1000 MW in capacity. The size and simplicity of the Small Modular Reactor (SMR) cut down time it takes to construct and commission a new nuclear power plant(Galindo, 2022).

5.4. Other Reactors

Besides commercial nuclear power plants, there are about 220 research reactors in over 50 countries, with more being developed for use in research and training, manufacture of medical and industrial isotopes. Reactors for marine propulsion are generally confined to the major navies for the last five decades, for powering submarines and large surface vessels. Globally, over 160 ships, mainly submarines, are driven by 200 nuclear reactors with over 13,000 reactor years of experience in marine reactors. Many have also been decommissioned by Russia and the USA from the Cold War era fleet (Association., 2023).

6. The Nuclear Fuel Cycle

Uranium is a radioactive metal found all-over the world and is the main fuel for nuclear power generation. Uranium has Uranium has two main isotopes: uranium-238 and uranium-235 with Uranium-238 being the most abundant in the world but cannot produce a fission chain reaction. On the other hand , Uranium-235 is used to produce energy by fission but constitutes less than 1 per cent of the world's uranium(Galindo, 2022).

To increase the chance of fission, the concentration of U-235 has to be increased through uranium enrichment process before it can be used effectively as nuclear fuel in power plants for between three to five years, though still radioactive it is disposed of following stringent guidelines to protect people and the environment. This used or spent fuel, can also be recycled into other types of fuel for use as new fuel in special nuclear power plants(Galindo, 2022).

7. Nuclear Waste

Radioactive waste makes up a small portion of all waste. It is the by-product of millions of medical procedures each year, industrial and agricultural applications that use radiation and nuclear reactors that generate around 11 % of global electricity. This animation explains how radioactive waste is managed to protect people and the environment from radiation now and in the future. The operation of nuclear power plants produces waste with varying levels of radioactivity. These are managed differently depending on their level of radioactivity and purpose. See the animation below to learn more about this topic(Galindo, 2022).

7.1. High level waste
7.2. Very low waste
7.3. Low level waste
7.4. Intermediate Waste

8. Nuclear Energy and Sustainable Development

Sustainable development is development that meets the needs of the present, without compromising the ability of future generations to meet their own. As a concept it is holistic, considering equity across countries and generations, and requiring the balancing of often-competing environmental, social, and economic factors. Until about 30 years ago, sustainability from the perspective of energy supply was thought of simply in terms of the availability of fuel relative to the rate of use. Today, in the context of the framework of sustainable development – and concerns about climate change and environmental degradation – the picture is more complex.

The relationship between energy consumption and human development is clear. Up to about 100 GJ per capita consumption – a level yet to be reached by 80% of the world's population – a country can fundamentally enhance the health, educational standards, and general wellbeing of its population by consuming more energy. Any transition towards a more equitable and sustainable future must therefore be predicated on delivering the benefits of access to modern, affordable, and reliable energy services to all. But doing so will increase overall energy demand: at present, the world's poorest 4 billion people consume just 5% of the amount of energy enjoyed by those living in developed economies. For that figure to rise to 15%, global energy consumption would increase by the equivalent of an additional United States' worth of demand.

The key question, therefore, is: how should that energy be supplied? At present, over 80% of primary energy consumption is from the burning of oil, gas and coal – unchanged since 1990. However, unregulated emissions from the combustion of fuels are causing climate change, environmental damage, and the premature death of an estimated 7 million people each year. The continued use of fossil fuels therefore has profound intra- and intergenerational social, economic, and environmental implications.

The resulting dual challenge – the need to reduce harmful emissions, whilst providing more energy to more people – positions the energy sector at the heart of achieving sustainable development.

There is no technology that is fully without risk to people or the environment. For example, whilst low-carbon sources of energy do not emit carbon dioxide at the point of use, they are responsible for emissions and waste during construction, manufacturing, and decommissioning. As such, any energy technology's compatibility with sustainable development objectives must be assessed in relative terms – in the light of the alternatives.

As the only proven, scalable and reliable low-carbon source of energy, nuclear power will be required to play a pivotal role if the world is to reduce its reliance on fossil fuels to address climate change and chronic air pollution. More broadly, however, the proposition of nuclear power as a sustainable energy source is fundamentally robust due to its innate energy density, and its internalization of health and environmental costs. Using nuclear energy has numerous sustainability advantages relative to alternative forms of generation. By expanding its use, modern and affordable energy can be provided to all who currently lack access, whilst reducing the human impact on the natural environment, and ensuring that the world's ability to meet its other sustainable development goals is not curtailed.

Defining Sustainable Development

A number of definitions have been put forward for sustainable development, but the most widely quoted is from the 1987 Brundtland Report[1]:*Sustainable development is development that meets the needs of the present, without compromising the ability of future generations to meet their own needs".*

Sustainable development is therefore the pathway to sustainability. For an activity, product or entity to be truly sustainable, it must achieve environmental, economic and social sustainability in balance: the three 'pillars'.

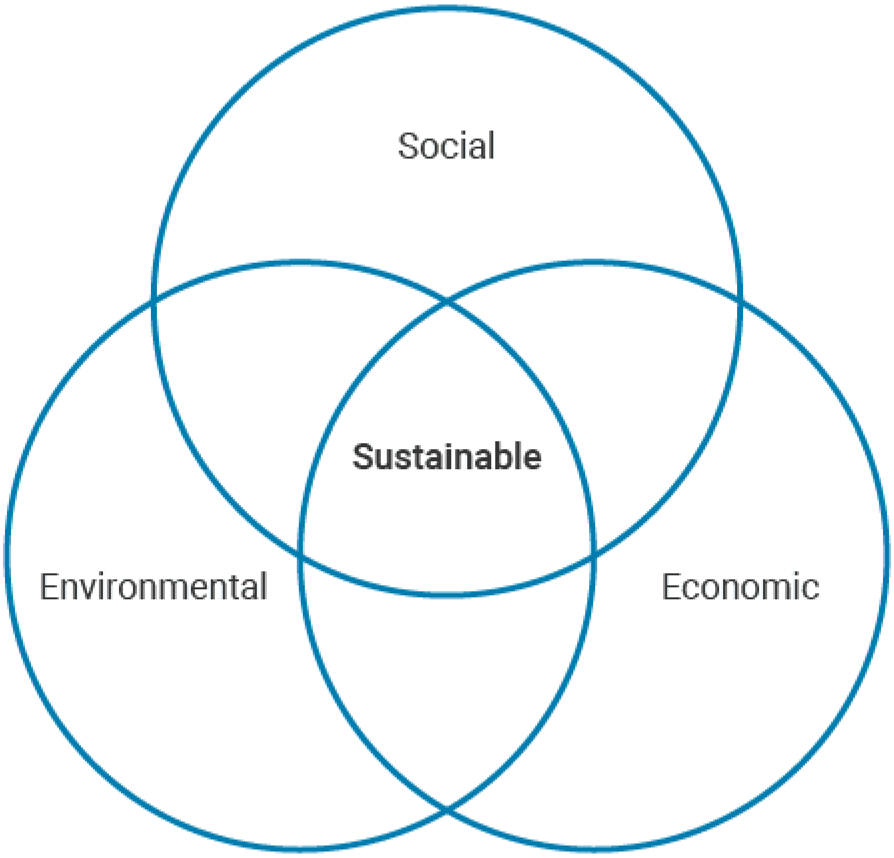

Figure 4. The three 'pillars' of sustainability

In 2015, the 193-member states of the United Nations (UN) adopted the 2030 Agenda for Sustainable Development – a plan of action for people, planet and prosperity (Figure 4), aligned to the three pillars of sustainability. To disaggregate the bold ambitions of the 2030 Agenda, the UN agreed 17 Sustainable Development Goals (SDGs) to be used to guide and gauge progress.

9. Nuclear And Climate Change

An uncontrolled nuclear reaction in a nuclear reactor could result in widespread contamination of air and water. The risk of this happening at nuclear power plants in the United States is small because of the diverse and redundant barriers and safety systems in place at nuclear power plants, the training, and skills of the reactor operators, testing and maintenance activities, and the regulatory requirements and oversight of the U.S. Nuclear Regulatory Commission. A large area surrounding a nuclear power plant is restricted and guarded by armed security teams. U.S. reactors also have containment vessels that are designed to withstand extreme weather events and earthquake.

Unlike fossil fuel-fired power plants, nuclear reactors do not produce air pollution or carbon dioxide while operating. However, the processes for mining and refining uranium ore and making reactor fuel all require large amounts of energy. Nuclear power plants also have large amounts of metal and concrete, which require large amounts of energy to manufacture. If fossil fuels are used for mining and refining uranium ore, or if fossil fuels are used when constructing the nuclear power plant, then the emissions from burning those fuels could be associated with the electricity that nuclear power plants generate.

A major environmental concern related to nuclear power is the creation of radioactive wastes such as uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes. These materials can remain radioactive and dangerous to human health for thousands of years. Radioactive wastes are subject to special regulations that govern their handling, transportation, storage, and disposal to protect human health and the environment. The U.S. Nuclear Regulatory Commission (NRC) regulates the operation of nuclear power plants(EIA, 2022).

Radioactive wastes are classified as low-level waste or high-level waste. The radioactivity of these wastes can range from a little higher than natural background levels, such as for uranium mill tailings, to the much higher radioactivity of used (spent) reactor fuel and parts of nuclear reactors. The radioactivity of nuclear waste decreases over time through a process called radioactive decay. The amount of time it takes for the radioactivity of radioactive material to decrease to half its original level is called the radioactive half-life. Radioactive waste with a short half-life is often stored temporarily before disposal to reduce potential radiation doses to workers who handle and transport the waste. This storage system also reduces the radiation levels at disposal sites(EIA, 2022). By volume, most of the waste related to the nuclear power industry has a relatively low level of radioactivity. Uranium mill tailings contain the radioactive element radium, which decays to produce the radioactive gas radon. Most uranium mill tailings are placed near the processing facility, or *mill*, where they come from. Uranium mill tailings are covered with a sealing barrier of material such as clay to prevent radon from escaping into the atmosphere. The sealing barrier is covered by a layer of soil, rocks, or other materials to prevent erosion of the sealing barrier.

The other types of low-level radioactive waste are the tools, protective clothing, wiping cloths, and other disposable items that become contaminated with small amounts of radioactive dust or particles at nuclear fuel processing facilities and nuclear power plants. These materials are subject to special regulations for their handling, storage, and disposal so they will not meet the outside environment(EIA, 2022).

High-level radioactive waste consists of *irradiated*, or *spent*, nuclear reactor fuel (fuel that is no longer useful for producing electricity). The spent reactor fuel is in a solid form, consisting of small fuel pellets in long metal tubes called rods. Spent reactor fuel assemblies are highly radioactive and, initially, must be stored in specially designed pools of water. The water cools the fuel and acts as a radiation shield. Spent reactor fuel assemblies can also be stored in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling. The United States does not currently have a permanent disposal facility for high-level nuclear waste(EIA, 2022).

When a nuclear reactor stops operating, it must be decommissioned. Decommissioning involves safely removing from service the reactor and all equipment that has become radioactive and reducing radioactivity to a level that permits other uses of the property. The U.S. Nuclear Regulatory Commission has strict rules governing nuclear power plant decommissioning that involve cleanup of radioactively contaminated power plant systems and structures and removing the radioactive fue(EIA, 2022)

The environmental pillar of sustainable development encompasses issues including air and water pollution, waste management, ecosystem management, and protection of natural resources, wildlife, and endangered species. Nuclear power is a low-carbon source of energy, because unlike coal, oil or gas power plants, nuclear power plants practically do not produce CO_2 during their operation. Nuclear reactors generate close to one-third of the world's carbon free electricity and are crucial in meeting climate change goals(Galindo, 2022).

The United Nations recognizes climate change as "the most systemic threat to humankind". As such, addressing it is generally considered the most significant and urgent sustainability challenge. Climate change is resulting from increasing concentrations of CO_2 in the Earth's atmosphere. Given that three-quarters of anthropogenic CO_2 emissions result from the burning of fossil fuels for energy, the main focus should be on deploying energy technologies that emit only small amounts of CO_2 per unit of energy.

On a life-cycle basis, nuclear power emits just a few grams of CO_2 equivalent per kWh of electricity produced. A median value of 12g CO_2 equivalent/kWh has been estimated for nuclear – similar to wind, and lower than all types of solar[5].

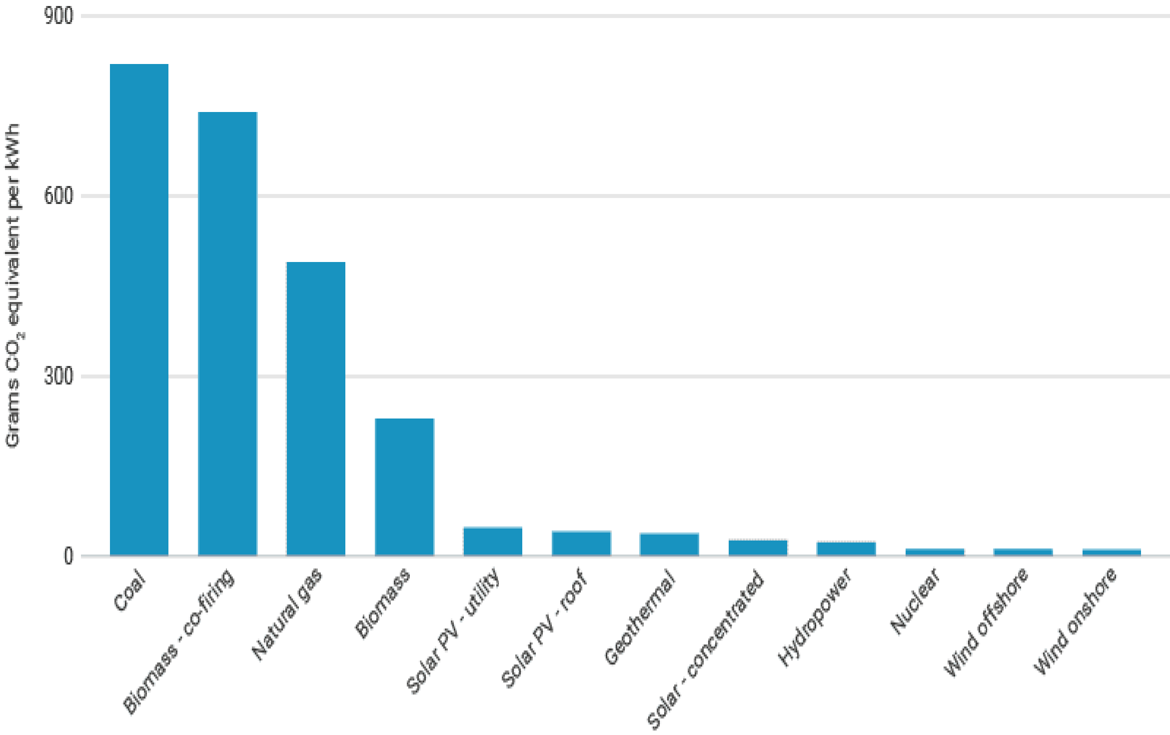

Figure 5. Average life-cycle CO_2 equivalent emissions (source: IPCC)

The main impacts of power production on ecosystems are eutrophication (*i.e.* increased concentrations of chemical nutrients (Figure 5), primarily nitrogen and phosphorus, that damage water quality by causing oxygen depletion) and acidification (*i.e.* increased concentrations of acidic chemicals – caused by the absorption of atmospheric CO_2 – that damage water quality, harming shellfish and coral, and leading to excessive algal growth).

Among power producing technologies, fossil fuels have by far the greatest potential to cause both acidification and eutrophication. CO_2 released into the atmosphere during the combustion of fossil fuels dissolves into the oceans, increasing their acidity; and the mining, extraction, transport, waste treatment and emissions associated with fossil fuel use contribute to their high eutrophication potential. By contrast, both the acidification and eutrophication potential of nuclear power are estimated to be among the lowest of all available generation technologies.

9.1. Land and water use

Land and water usage are key criteria for assessing the sustainability of different power production technologies. The power sector competes for limited resources with other important sectors such as agriculture, industry and housing, and the emergence of a new concept known as the water-food-energy nexus reflects the growing appreciation of the interconnectedness of policy decisions in these three areas.

Nuclear power plants produce huge amounts of low-carbon power and require less land to do so than any other energy source. The UN expects two-thirds of people to be living in urban areas by 2050 – an additional 2.5 billion individuals – where land is at a premium. Coupled with the need to preserve land to prevent loss of biodiversity, it is likely that nuclear energy's unique land-use advantages will prove increasingly determinative in the future.

9.2. The social pillar

Human health – air pollution

Air pollution arising from the use of carbon-based fuels for energy is one of the biggest threats to human welfare. The World Health Organization estimates that about 7 million people die prematurely each year as a result of air pollution exposure.

Nuclear power plants emit virtually no air pollutants during operation, and because they are reliable and can be deployed on a large scale, they can directly replace fossil fuel plant. NASA's Goddard Institute for Space Studies and Columbia University's Earth Institute estimated that the use of nuclear power prevented over 1.8 million air pollution-related deaths between 1971 and 2009.

There are numerous non-power uses of nuclear technology that contribute to fulfilment of human 'needs'. For example: the provision of nuclear medicine; helping to control the spread of infectious diseases; and securing reliable supplies of clean water, sanitation, and food.

Human health – radiation
Radiation is a well-understood process, with natural sources accounting for most of the radiation people receive each year. Doses received average 2.4 mSv/yr, but vary widely by location, driven by factors such as underlying geology and altitude. The highest known level of background radiation affecting a substantial population is in the states of Kerala and Madras in India where some 140,000 people receive doses which average over 15 mSv/yr from gamma radiation, in addition to a similar dose from radon. Comparable levels occur in Brazil and Sudan, with average exposures up to about 40 mSv/yr to many people. Lifetime doses from natural radiation range up to several thousand millisieverts. However, there is no evidence of increased cancers or other health problems arising from these high natural levels.

20 mSv/yr is the current average allowed limit for nuclear industry employees and uranium miners during normal operation. The millions of nuclear workers that have been monitored closely for 50 years have no higher cancer mortality than the general population but have had up to ten times the average dose.

Nuclear power is the only technology that systematically measures and accounts for radioactive emissions. However, exposure to above-background radiation is not exclusive to nuclear power-related activities. UNSCEAR has estimated that both occupational and public exposures from electricity generation are higher for workers in the coal industry, for example.

Employment
Nuclear power plants can operate for over 60 years, creating long-lasting, high-paying jobs for people from a range of fields and educational backgrounds. Undertaking a nuclear power programme therefore represents a long-term investment in human capital.

Investment in capital-intensive projects tends to spill over into other industries and economic sectors. A modern gigawatt-scale nuclear power plant employs 500-1000 workers directly. But throughout both its construction and operation, it requires a complex supporting supply chain (*e.g.,* construction, manufacturing and consultancy services), creating attractive indirect and induced employment opportunities.

9.3. The economic pillar
Resource adequacy, preservation & opportunity cost
Uranium has no significant use other than nuclear energy production. Producing electricity with uranium extends the overall resource base available for human use, provides greater diversity of choice and allows the use of other resources, such as hydrocarbons, where they are most effective *e.g.* for transportation or petrochemicals(World Nuclear Association, 2022).

Uranium is plentiful and is distributed among a wide range of geopolitically diverse countries. The distribution of uranium reduces the risk of market disruptions of the nature experienced during historical oil and gas crises(World Nuclear Association, 2022).
Resource efficiency and material throughput

The focus on power supply options defined as 'renewable' over the past several decades reflects the importance attached to the preservation of finite resources. Renewable sources of energy are those generated from natural processes that are continuously replenished. Renewable technologies, therefore, are defined as those that are not fuelled by a finite resource(World Nuclear Association, 2022).

Intergenerational equity is a key principle of sustainable development, and so the purported advantage of renewable energy options – that they do not diminish finite fuel resources for future generations – is valuable. However, fuel supply is just one aspect of the material requirements for power generation. All means of generating electricity require infrastructure that consumes finite resources, with the major material inputs by volume outside of fuel supply typically concrete and metals(Figure 6) (*e.g.,* aluminium, cooper, steel). Estimates for the use of key bulk materials and copper per TWh for different technologies have been produced by former environmental organization Bright New World[9], based on a literature review of studies on this topic(World Nuclear Association, 2022).

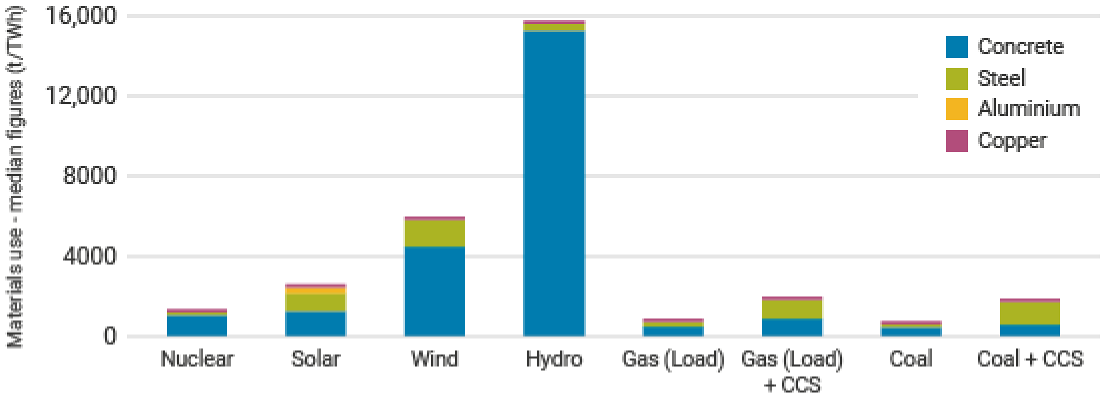

Figure 6. Major materials for different generating technologies, tonnes per TWh

Table 3. Major materials for different generating technologies, tonnes per TWh

	Nuclear PWR	Solar	Wind	Hydro	Gas (load following)	Gas (load following) + CCS	Coal	Coal + CCS
Concrete	1060	1220	4470	15,320	390	820	450	520
Steel	130	940	1450	330	320	970	160	1170
Aluminium	0.3	287.5	17.4	8.7	5.7	21.4	1.6	37.4
Copper	2.5	68.0	39.1	4.8	5.4	8.8	3.0	11.8
Capacity f.	85%	28%	35%	50%	30%	30%	85%	85%
Lifespan	60	30	30	100	60	60	60	60

Table 3 and Figure 7 show major materials for different generating technologies, tonnes per TWh (source: Bright New World)

The aim of reducing material inputs is a central concept of sustainable development. Using material in the production, transport and implementation of power producing technologies will consume energy in the form of fossil fuels, and as such the metric of material throughput is important in consideration of energy efficiency as well as life-cycle carbon emissions. But more broadly, resource efficiency is a key aim. Consumption of primary materials is expected to more than double by 2050. Using nuclear energy to generate electricity is one means by which resource demand can be reduced to more sustainable levels(World Nuclear Association, 2022).

Affordability

Affordability is a key component of SDG 7. The benefits of access to modern energy are profound, but the aspiration of ensuring access for all can only be realised if it is affordable.

The relative affordability of electricity supply options is a function of generation costs as well as the costs they impose on the system. Generation costs are typically reported using the levelized cost of electricity generation (LCOE) metric, which is a measure of the ratio of the total costs of a generic plant (capital and operating), to the total amount of electricity expected to be generated over that plant’s lifetime. LCOE as a metric is relatively simple and transparent, and so is widely referenced. However, its ability to assess overall costs to society are limited. In deregulated markets, revenues are uncertain over a generator’s lifetime making the metric less pertinent; and the metric does not attempt to capture the markedly different system costs of technologies(World Nuclear Association, 2022).

System costs have always existed, but the growth in variable renewable energy sources has promoted the topic in recent years. System costs include required outlays for distribution and transmission, and most importantly, backup for the inherent variability of some renewable energy. System costs are difficult to assess, as they depend on the characteristics of the system in question, the time frame considered, location and numerous other factors. Whilst there is uncertainty, estimates are consistent in that system costs for variable energy sources are significant, increase non-linearly with growing shares of electricity generation, and are an order of magnitude higher than for dispatchable technologies(World Nuclear Association, 2022)

The costs of the system are ultimately borne by society, and so, given the increasing use of variable renewable energy, it is important that system costs are internalized to ensure that policy decisions can be properly directed towards maximizing affordability. Negative effects beyond the system itself (*i.e.* negative externalities) related to the provision of electricity are increasingly being recognized as significant and complicate the picture further. Negative externalities related to electricity generation – most notably the emissions of greenhouse gases and other pollutants – represent a social cost that may impact the true affordability of different electricity supply options. It is well documented that the social and economic costs of climate change and air pollution are significant. In order to better-understand the socially optimal level of externalities (relative to production) it is imperative that the relative costs of different supply options include a reasonable estimate of their impacts on emissions and the climate(World Nuclear Association, 2022).

Nuclear energy is cost-competitive based on a simple LCOE comparison, particularly at low discount rates. Its unique attributes of providing predictable, reliable supply that is low-carbon means that inclusion of system costs and negative externalities both markedly improve the relative affordability of nuclear energy(World Nuclear Association, 2022) (Figure 7).

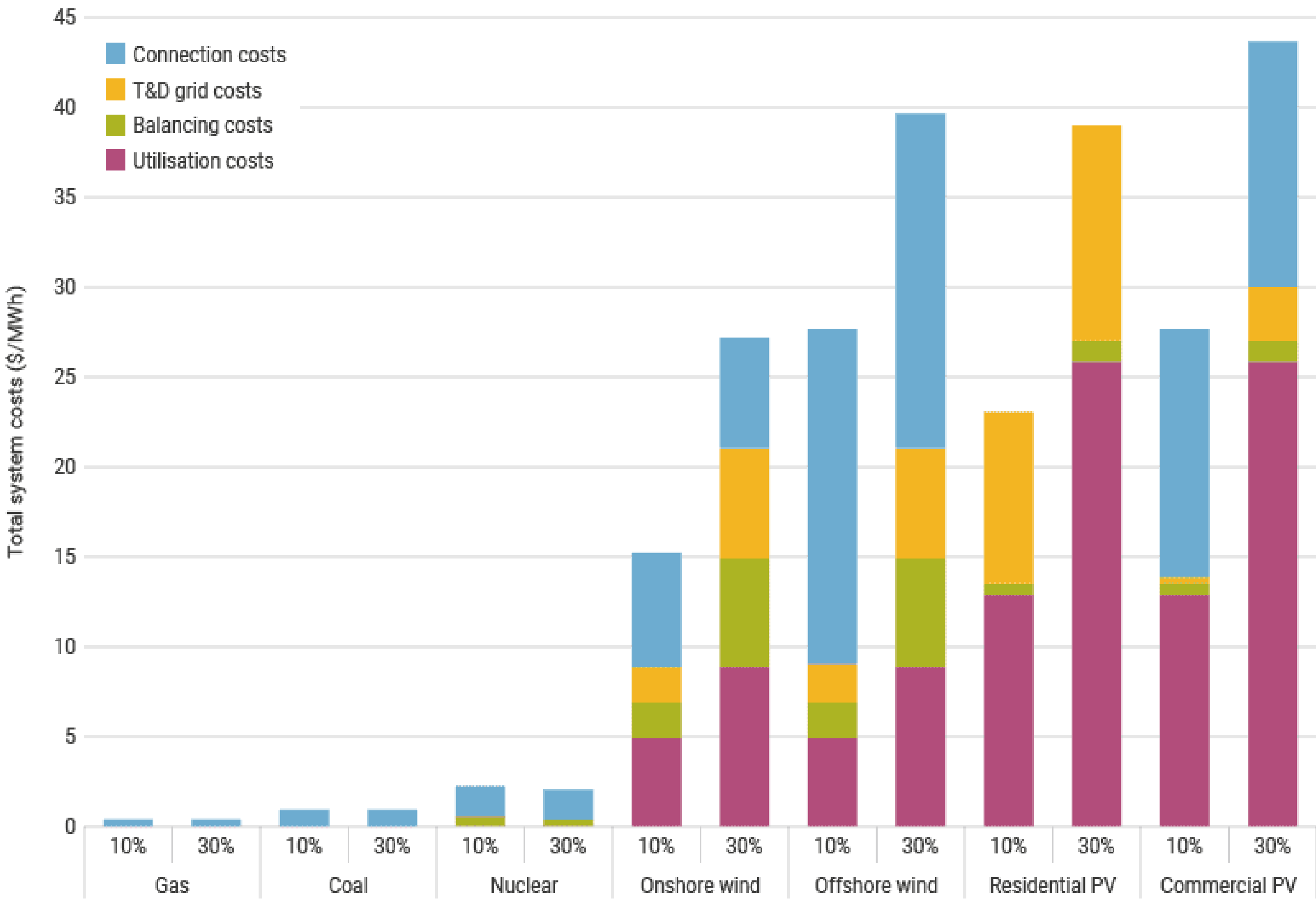

Figure 7. Grid-level system costs for dispatchable and renewable technologies (source: OECD Nuclear Energy Agency, 2018)

Notes & references

a. The Human Development Index (HDI) is a United Nations Development Programme statistical tool to measure a country's level of social and economic development. The social and economic dimensions of a country are based on the health of its people, their level of education attainment and their standard of living. A country scores a higher HDI when the lifespan of its people is longer, the education level is higher, and the gross national income per capita is higher(World Nuclear Association, 2022).

10. Results And Discussion

Nuclear power plants produce intense heat used to generate steam to run a steam turbines connected to a generator that produces electricity. Nuclear power plants are used as base load stations. Nuclear reactors are classified as large, medium, and small-sized nuclear reactors. There is a growing trend for development of small sized reactors away large nuclear reactors which have become less attractive. Small-sized nuclear reactors were originally used to facilitate the development and demonstration of early reactor technologies to develop operational experience for the nuclear power sector. Basic of reactors is concerned with reliability, safety, and passive safety systems. A brief review of the design and safety aspects of some small nuclear reactors have been discussed. (Khan et al., 2020) he economic viability of a power plant is dependent on the cost of the electricity generated which is influenced by a wide range of factors and inputs from the inception to end of economic life. The Levelized cost of energy or electricity (LCOE) is a model used to estimate the cost of electricity before the powerplant is constructed. The cost of building a nuclear power plant and any financing cost is the most important contributing factor to the cost of from nuclear power plants. Although modern nuclear power plants are generally large and expensive, their long project lifetime effectively reduces the cost of nuclear power can still be relatively low. Nuclear energy has generally been regarded by public opinion as a harmful energy resource. The growing concerns over global climate change and greenhouse gas emissions have changed this belief and nuclear is now considered a reputable green power source that can generate significant amounts of energy with low carbon emissions. Nuclear energy is currently a mature low-GHG emission energy resource that is ideal for use as baseload power. However, the share in global electricity generation has been declining globally but its share of global electricity generation has been declining since the year 1993 because of various barriers and risks. The life cycle GHG emissions from nuclear power are less than traditional fossil sources but assumptions and conditions under which they are deployed can have serious impact on the magnitude of life cycle GHG emissions compared to renewable technologies. The published median, interquartile range (IQR), and range for LWR life cycle GHG emission are 13, 23, and 220 grams of carbon dioxide equivalent per kilowatt-hour (g CO2-eq/kWh), respectively. Upon application of harmonizing methods to use consistent gross system boundaries and values important system parameters yielded 12, 17, and 110 g $CO_{2\text{-eq}}$/kWh, respectively. Based on ongoing improvements, median life cycle GHG emissions could be 9 to 110 g CO2-eq/kWh by 2050

11. Conclusions

The cost of building a nuclear power plant and any financing cost is the most important contributing factor to the cost of from nuclear power plants. Although modern nuclear power plants are generally large and expensive, their long project lifetime effectively reduces the cost of nuclear power can still be relatively low. The economic viability of a power plant is dependent on the cost of the electricity generated which is influenced by a wide range of factors and inputs from the inception to end of economic life. The Levelized cost of energy or electricity (LCOE) is a model used to estimate the cost of electricity before the powerplant is constructed. The cost of building a nuclear power plant and any financing cost is the most important contributing factor to the cost of from nuclear power plants. Although modern nuclear power plants are generally large and expensive, their long project lifetime effectively reduces the cost of nuclear power can still be relatively low. Nuclear energy has generally been regarded by public opinion as a harmful energy resource. The growing concerns over global climate change and greenhouse gas emissions have changed this belief and nuclear is now considered a reputable green power source that can generate significant amounts of energy with low carbon emissions.

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Biographies

Moses Jeremiah Barasa Kabeyi is currently a doctoral researcher in the department of Industrial Engineering at Durban University of Technology. He earned his B.Eng. degree in Mechanical and Production Engineering and MSc. in Mechanical and Production Engineering from Moi University, in Kenya, and an MA in Project planning and Management from University of Nairobi, Kenya. He also has a Diplomas in Project management, Diploma in Business management and a Diploma in Management of non-governmental organizations (NGOs) from The Kenya Institute of Management. He has worked in various factories including sugar manufacturing at Nzoia Sugar Company Ltd, pulp and paper at Pan African Paper Mills EA Ltd, and power generation at the Kenya Electricity Generating Company (KenGen) in Kenya, in an industrial career of 16 years before moving into teaching. He has taught in various universities in Kenya including University of Nairobi, Technical University of Mombasa, and Egerton University and currently on study leave. His research interests are power generation, fuels and combustion, internal combustion engines and project management and sustainability. He is registered with the Engineers Board of Kenya (EBK) and Institution of Engineers of Kenya (IEK) and has published several journal papers and conference papers.

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa