The Viability of Nuclear Energy in Africa: A Technical, Economic, and Political Review

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Abstract

The announcement at COP28 in December, 2023, of a multilateral agreement to triple nuclear energy production by 2050 was a significant milestone in the advancement of the nuclear industry. It demonstrated a global acknowledgement that nuclear energy is vital to the attainment of climate goals set forth earlier in the Paris Agreement of 2015. It also signaled a paradigm shift in the perception of the safety and viability of nuclear power on a global scale.

This research addresses reasons why nuclear energy is now being embraced by the global community. It delves into the sources of historic stigma associated with nuclear energy, advances in processes and technology to enhance the safety of nuclear, the viability of technology writ large, and assesses whether nuclear development is appropriate for emerging markets, particularly on the African continent.

This thesis takes the hypothetical case study of Djibouti since the nation exhibits both positive and negative potential when it comes to nuclear development. My research methods included technical resources, articles, peer-reviewed papers, and interviews with individuals who have a vested interest in the infrastructure development of sub-Saharan countries in Africa.

Keywords: nuclear energy, nuclear power, energy transition, Africa, African energy, COP28, clean energy, decarbonization

Author’s Biographical Sketch

Benjamin Miller serves as a Commander in the United States Navy. After more than 22 years in the nuclear submarine force, he accepted the diplomatic position of Senior Navy Liaison to the Marine Nationale in France. He has served two tours onboard the *USS Georgia* as the Reactor Control Assistant, and later as the Weapons Officer; he went on to be the Executive Officer of the *USS Jacksonville*. In between tours at sea, he served as an instructor of reactor and steam plant chemistry and radiological controls as well as a submarine tactics and warfare instructor before serving at the Pentagon and l’Hexagone Balard in Paris.

He holds a B.S. in Mechanical Engineering from the University of Utah and an M.A. in Military Operational Art and Science from the U.S. Air Command and Staff College. He is currently pursuing an ALM in International Relations from Harvard Extension School.

In 2022, Benjamin launched a startup company called Indigo Nuclear to provide trained and licensed nuclear operations and training teams to emerging markets seeking to develop their own civil nuclear energy program. His company is primarily focused on off-grid production in the U.S., as well as on facilitating communities in Africa in their pursuit of clean, reliable energy that supports sustainable growth.

Acknowledgements

I'd like to acknowledge the contributions of Dr. Michael Miner and Dr. Doug Bond at Harvard University. Without their insight and perspective, my research would have likely been manifested in the form of a meme or, perhaps, a Tik Tok video. Their patience and guidance are greatly appreciated. I would also like to thank my wife, who embarked on a graduate program of her own in a show of solidarity. Her marks greatly exceeded mine and she ensured I was acutely aware of this for the duration of my studies. She is my motivation and most ardent supporter in all things, but particularly in endeavors that seem far-fetched and highly aspirational. Simply put, I am able to achieve more with her at my side. Lastly, my research has paralleled the development of my company, Indigo Nuclear. In this pursuit, I have had discussions with some brilliant minds in the nuclear, business, and diplomatic fields. I am indebted to Enobat Agboraw, David Arinze, Max Masispa, Michael Mekbib, the great people at the Nuclear Business Platform, and the OECD. Additionally, I am grateful for the feedback from the potential investors who expressed their misgivings about nuclear energy development in Africa – some more colorfully than others. It is their concern that prompted me to conduct this research.

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Glossary of Terms[1]

123 Agreements – Negotiated by the U.S. State Department with concurrence from the U.S. Department of Energy and National Nuclear Security Administration, 123 Agreements are formed between the United States and other nations as part of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). 123 Agreements advance U.S. *nonproliferation* principles by requiring partner countries to adhere to requirements of non-proliferation in exchange for partnership in areas such as technical exchanges, scientific research, and other forms of cooperation around nuclear energy. Partner countries are codified in the Atomic Energy Act, Section 123.

Atomic Energy – Energy released through nuclear interactions. The heat generated as a product of either fission or fusion is harnessed as a heat source for power generation.

Atomic Energy Act – Established the Atomic Energy Commission (AEC) to promote the utilization of atomic energy for peaceful purposes. Following its abolition, the roles of the AEC were largely taken over by the Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE).

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[1] The definitions included in this section are derived from multiple sources, including:
International Atomic Energy Agency, https://inis.iaea.org/search/thesaurus.aspx
International Monetary Fund, https://www.imf.org/en/About/Terminology
Nuclear Energy Agency, https://www.oecd-nea.org/general/acronyms/
Nuclear Energy Institute, https://www.nuclearinst.com/write/MediaUploads/Resources/Burges_Salmon_Glossary_of_Nuclear_Terms_-_July_2014_(FINAL_VERSION).pdf
Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/basic-ref/glossary.html
U.S. Department of Energy, https://www.energy.gov/lpo/glossary-terms

Capacity Factor (CF) – Percentage of time a power plant is operating at maximum power.

Centrifuge enrichment – Utilizing rotating cylinders, gasified uranium is separated by relative atomic weight. Uranium-239 and uranium-238 is removed from the more readily-fissile uranium-235. The remaining percentage of the lighter uranium-235 in the end product determines the sample's enrichment.

Coolant – The medium used to remove heat from nuclear fuel. For the reactors discussed in this paper, water is the preferred coolant.

Core – The term used to describe a nuclear reactor assembly up to, but not including, the coolant piping and secondary systems. Usually defined by components within the reactor vessel.

Critical/Criticality – The state of a core of a nuclear reactor where the amount of neutrons released through fission reactions are exactly balanced by the number of neutrons being absorbed. A critical reactor is one that maintains a constant power output.

Daughter products - Isotopes that are formed from the radioactive decay of an element.

Decarbonization – The shift away from energy sources that emit carbon and other greenhouse gases in favor of low, to no-carbon sources such as wind, solar, hydroelectric, and nuclear.

Department of Energy (DOE) – U.S. governmental agency with the mission to advance the national, economic, and energy security for the United States. Additionally, it promotes scientific and technological innovation while overseeing the environmental cleanup of the national nuclear weapons complex.

Effective Load-Carrying Capacity (ELCC) – The baseline power output of a power plant, taking into account fluctuations in output and capacity factor.

Enrichment – The process through which the content of uranium-235 within a given sample is increased by percentage volume. The term also describes the content of uranium-235 relative to the mass of the sample.

Fast neutron – A high-energy neutron released as a result of fission. Fast neutrons are generally less likely to cause subsequent fission reactions in the presence of nuclear fuel.

Fission – The splitting of a heavy, unstable nucleus such as uranium-235 into two *daughter* nuclei. This process is a product of absorbing a low-energy, thermal neutron and releases neutrons, fission products, and a large amount of energy.

Fission product – Atomic fragments left after a large atomic nucleus undergoes nuclear fission.

Fuel / Nuclear fuel – For purposes of this thesis, fuel describes the sample of enriched uranium that provides the fissile material necessary to release a controlled amount of energy or heat.

Grid – The layout of an electrical distribution system.

Highly enriched uranium (HEU) – Uranium enriched to more than 20 percent uranium-235, used in naval reactor fuel and in nuclear weapons. Commercial reactors typically use 3-5 percent, low enriched uranium.

International Atomic Energy Agency (IAEA) – The culmination of President Eisenhower's "Atoms for Peace" address to the United Nations General Assembly in 1953. The IAEA is the world's center for cooperation in the nuclear field to promote the safe and peaceful use of nuclear technologies.

Isotope – Atoms of the same element that have an equal number of protons but a different number of neutrons. Properties such as atomic stability can vary based on these variations and, as such, some isotopes of a given element are more fissile than others.

Levelized Cost of Energy (LCOE) – A metric that describes the lifetime costs of an energy generator divided by energy production. It is the most common way to plan investment and budgeting for power sources.

Low enriched uranium (LEU) – Uranium enriched to less than 20 percent uranium-235, but greater than the 0.7% that is naturally occurring.

Megawatt (MW) – A unit of electrical power equal to one million watts. Output of most power plants is measured in Megawatts.

Megawatt-hour (MWh) – A measure of electricity equal to one Megawatt expended for one hour.

Microreactor – An advanced, highly portable nuclear reactor with a typical power capacity of less than 20 MW per unit.

Moderator – Material that can slow down neutrons from fast (less likely to cause fission) to thermal (more likely to cause fission). For the reactors being considered in this thesis, the moderator used in the core is water.

Nuclear Nonproliferation Treaty (NPT) – International agreement designed to stop the spread of nuclear weapons by restricting the trade of all nuclear technology and materials to signatory nations who, in turn, agree to full compliance with international safeguards.

Nuclear Regulatory Commission (NRC) – U.S. agency responsible for ensuring that activities associated with the operation of nuclear power and the use of radioactive materials in other applications are conducted with adequate protection of public health, safety, and national security.

Radiation – Transmission of energy in the form of particles or electromagnetic waves.

Radioactive decay – The spontaneous emission of nuclear particles and/or electromagnetic waves from an instable radioactive isotope in order to achieve a more stable state.

Small Modular Reactor (SMR) – Advanced nuclear reactors that have a power capacity of up to 200 MW per unit.

Uranium – A naturally occurring metal that exists in abundance in the earth's crust that is the primary fuel used in commercial nuclear reactors.

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Chapter I.

Introduction

The team that brings clean and abundant energy to the world will benefit humanity more than all of history's saints, heroes, prophets, martyrs, and laureates combined.

— Steven Pinker

When French President, Emmanuel Macron unveiled a multilateral commitment to triple global nuclear energy production at the UN Climate Change Conference (COP28) in Dubai, it signaled a wider acceptance and appreciation that the development of nuclear power is vital to achieving climate goals established at the Paris Agreement in established in 2015 (see Appendix). This aggressive aspiration would mean that approximately one-third of the world's current electricity demand would come from a nuclear source (Nordhaus, 2023). The relatively sudden shift in attitude toward nuclear power is somewhat surprising considering the stigma nuclear has endured for decades. My research will illuminate the reasons for this paradigm shift by delving into the fundamentals of nuclear energy and how advanced technology and designs have made the industry safer and more economical. I will also evaluate nuclear energy as a technology to determine if it is truly a viable source of energy suitable for the multilateral commitment expressed at COP28. Finally, in light of disparate technological advances between developed countries and the global south, I will evaluate whether nuclear power is a tenable option for African countries looking to establish clean reliable energy production on a scale supportive of their projected growth.

Nuclear energy as a technology is a surprisingly simple concept to understand. It is nothing more than turning water into steam and sending it through a turbine to generate electricity. In this regard, it is nearly identical in principle to other types of power plants such as coal, oil, and natural gas. The differences lie in the heat source and the byproducts of energy generation. It is for this reason that nuclear reactors can be constructed on the same site as retired conventional power plants. The existing grid connections, real estate, infrastructure, and even turbine equipment can be reused for nuclear applications, thus minimizing stranded assets and mitigating cost (Van der Ploeg & Rezai, 2020).[2]

Obstacles remain in terms of public opinion, despite the multilateral solidarity expressed at COP28. Nuclear accidents over the past several decades have tapped into fears of the public and have prompted countless anti-nuclear demonstrations around the world. I will evaluate the most infamous of these accidents and define the process and design improvements the nuclear industry has developed to ensure that the likelihood of recurrence is minimized.

My background is in nuclear power and its applications in the U.S. Navy. As such, despite my efforts to the contrary, my personal bias toward nuclear as a technology may be evident in my findings. It is with an open mind, however, that I address the

[2] An energy strategy that shifts away from the incumbent power source risks incurring significant cost in the form of "stranded assets." That is, if a nation or utility constructs several coal plants and they are energy policy dictates they must transition away from fossil fuels prior to the end of life of the plant in question, they are left with a significant investment that is effectively stranded in place. Reusing existing plants to construct nuclear reactors minimizes the economic impact of stranded assets and is a concept championed by several American companies including Terra Praxis and TerraPower, which is founded by Bill Gates and is developing a proof-of-concept plant in the State of Wyoming.

viability of nuclear development across Africa. Political instability, the risk of nuclear proliferation, regulatory controls, economics, and even climate and seismic concerns all cast doubt on whether many African countries could legitimately pursue a civil nuclear energy program. There are currently more than 15 countries across the African continent that are working with the International Atomic Energy Agency (IAEA) to develop nuclear programs. However, this collaboration does not necessarily equate to successful nuclear development and, for the reasons listed above, many of these efforts are likely to languish at some stage of incompletion.

I selected Djibouti as a case study to evaluate the viability of nuclear development. Djibouti is not one of the aforementioned countries actively engaged with the IAEA. Djibouti's land area and population are small, and its GDP places the country in a lower- to middle-income country. Djibouti enjoys a fairly stable political landscape, but finds itself located geographically between several volatile nations from which potential security threats might emerge. In short, Djibouti is a country with an established political base and growth potential, but it still faces hurdles that challenge nuclear energy development across the continent.

Chapter II.

Nuclear in a Nutshell

As context for the rest of my research, I provide here a somewhat simplified rundown of what nuclear energy is and how it works. For those readers who are not technically inclined, or are already knowledgeable about nuclear energy, or simply have no interest, feel free to skip to the next section. I have also provided a Glossary of Terms should there be unfamiliar verbiage.

The term “nuclear” is often intimidating. Nuclear energy production is certainly complicated, but it is not complex. In fact, as an officer in the U.S. Navy tasked with teaching the operation of our nuclear power plants to non-nuclear-trained sailors, I found I was able to do it adequately by drawing a picture on a paper scrap or paper towel. For purposes of academic credibility, I proceed here in more depth.

First, it is important to understand that nuclear energy is actually steam energy. That is, “nuclear” refers only to the heat source that generates steam. It is the same concept as coal plants, geothermal plants, or even the steam locomotives seen in old black-and-white photos. The steam that is generated is piped with enough pressure to spin a turbine, which is attached to a generator, which creates an electrical current. If the desired output is motion instead of electrical current (as with a locomotive), the turbine can be coupled to a drivetrain that spins wheels or a propellor at a desired speed. That is it. You are ready to operate a nuclear submarine.

While there are several different reactor designs, this over-simplified synopsis is the overarching purpose and function of power-generating nuclear plants. In order to understand the risks, benefits, and ultimately the viability of nuclear energy in new markets, however, a little more detail is required.

A modern nuclear reactor is typically comprised of fuel elements, some sort of "neutron absorber," a *moderator* that facilitates nuclear interactions, and a *coolant* contained in a *core* that is housed in a *reactor vessel.* Controlled nuclear *fission* occurs within the fuel, which emits kinetic and thermal energy in the form of sub-atomic particle emissions and heat. This process repeats itself within the fuel, and the chain reactions are controlled by the neutron absorber and the moderator. This heat is transferred to the coolant (for our purposes deionized water), which is circulated at high temperature and pressure through the core.

In a pressurized-water reactor design (see Figure 1), this high-temperature and high-pressure water is then pumped to a steam generator, which is simply a heat exchanger that transfers the heat from the coolant to water being circulated on the other side of the heat exchange surface. Think of an air conditioning unit, a refrigerator, or the radiator in a car. The coolant never comes in contact with the water on the other side of the heat exchanger. For this reason, the coolant in the reactor is typically referred to as *primary coolant* while the water on the other side is called *secondary coolant.* The secondary coolant flashes to steam and is used to spin turbines which, as mentioned, generates electrical current or is translated into mechanical power (Montgomery & Graham, 2017). Once the steam passes through the turbines, it is condensed and cooled and recirculated to the steam generator to repeat the process and provide continuous cooling to the primary coolant, which, in turn, cools the reactor. In a boiling-water reactor design (see Figure 2), the secondary coolant is eliminated, the primary coolant flashes to steam and turns the turbine directly before being condensed, cooled, and recirculated.

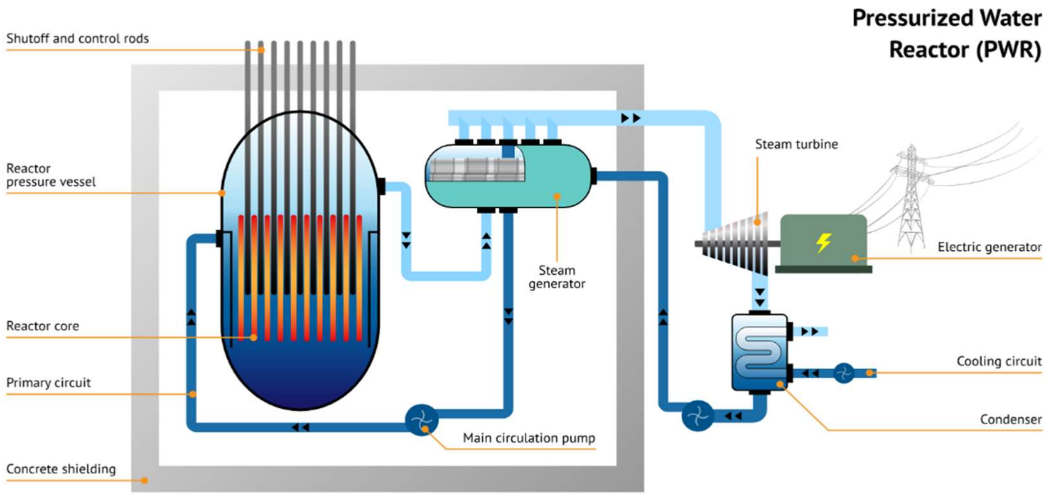

Figure 1: Pressurized Water Reactor Diagram

Source: Energy Encyclopedia

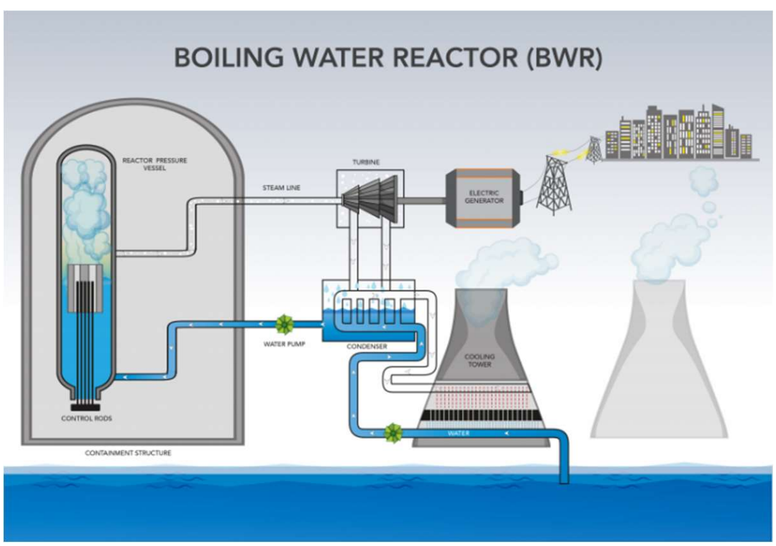

Figure 2: Boiling Water Reactor Diagram

Source: Department of Energy

I will discuss these components further. First, nuclear fission is the process of an atom splitting into two smaller atoms. This is occurs naturally but can be facilitated through a number of processes. Atoms have a number of neutrons and protons within their nucleus. The number of protons defines the element and is expressed through its atomic number on the periodic table. The number of neutrons, however, can vary. The number of neutrons will change the mass of the atom, but not the chemical properties.

Atoms of a certain element with different numbers of neutrons are called *isotopes.* Some isotopes can be inherently less stable than others, that is, they are more prone to fission than others. These isotopes emit sub-atomic particles when they split, so they are typically referred to as *radioisotopes* (Galindo, 2022). Within a nuclear reactor, neutrons are introduced to the nuclear fuel that is comprised of unstable isotopes. The neutron prefers to "stick" to the atom, which imparts energy to the isotope and makes it less stable, causing the isotope to split. This process releases *fission products* in the form of sub-atomic particles, heat, and other high-energy neutrons, which continue on to cause more fission within the fuel. This chain continues until there is an intervention or until the fuel burns out completely.

An intervention is possible within a reactor through the aforementioned absorber. The absorber is constructed of a material that is able to absorb high amounts of neutrons while maintaining stability, like a neutron sponge in the reactor. The degree to which the absorber interfaces directly with the fuel determines how many neutrons are absorbed, and thus the rate of fission within the core. Designs vary, but for illustrative purposes, think of several "rods" of absorber that can be raised or lowered within a honeycomb of fuel. The more honeycomb cells that are filled with these "control rods," the less fission occurs (NRC, 2023).

Nuclear fuel is most often comprised of an isotope of uranium. Uranium-238 (U-238) is by far the most prevalent, naturally occurring isotope. Uranium-235 (U-235), however, is the preferred isotope for nuclear fuel due to its high mass, inherent instability, and therefore its propensity for nuclear fission in the presence of a neutron flux. U-235 comprises only about 0.1% of a given sample of mined uranium, and in order to manufacture nuclear fuel with a sufficient amount of U-235, it needs to be refined. This is most efficiently done by gasifying the raw uranium and sending it through a series of *centrifuges* that separate the U-235 from other isotopes of uranium. The vast majority of commercial nuclear fuel is only 3% to 5% U-235 (NTI, 2023) and is considered *low-enriched uranium,* but this concentration is sufficient to generate enough power to light a city. This fuel is then manufactured into the requisite structure for the reactor application. In contrast, in order to develop a nuclear weapon, the uranium needs to be *highly enriched,* which is a U-235 content of greater than 20%.

The moderator is a material or substance that is designed to slow neutrons. Fission of U-235 generates high-energy neutrons that allow the nuclear reactions to continue within the core. The collision of high-energy neutrons with U-235 tend not to facilitate fission, however, as the reaction is more prevalent when the neutron is absorbed, or sticks to the nucleus of the atom. A high-energy, *fast neutron* imparts energy to the atom but does not lend to the instability; thus the probability of fission, as much as a slower, lower-energy *thermal neutron.* The moderator is comprised of a substance with a low atomic mass such that when it collides with a fast neutron, it efficiently absorbs the kinetic energy from the fast neutron and slows it such that the neutron is more likely to cause fission in the fuel. In the majority of commercial reactors, water doubles as both the moderator and the primary coolant. This simplifies the processing of the moderator during maintenance and refueling as well as lowers the overall cost of operation.

The vast majority of modern reactors that use water as the moderator are designed to have a negative, dominant coefficient of reactivity. This is not insignificant. Should reactor power and temperature increase, steam could form in the core which is far less efficient of a moderator than liquid water. As a result, the number of thermal neutrons in the core decreases, the rate of fission decreases, reactor power lowers, and temperature will thus decrease. This design characteristic lends to the stability of nuclear reactors. I will discuss the importance of this later in the discussion of Chernobyl.

Last, but certainly not least, is the role of the primary coolant within the core. Again, in most commercial reactors, water serves as both the coolant and the moderator. As one would expect, the ability to cool the reactor is vital in ensuring its safe operation (Galindo, 2023). The loss of coolant flow is the proverbial death knell for nuclear reactors. This means, from a design standpoint, several redundant systems, as well as backup and emergency sources of cooling are integrated into commercial nuclear design. Even with these safeguards in place, a loss of coolant flow resulting in the fuel becoming "uncovered" can result in the rapid overheating of the fuel elements and the ultimate meltdown of the reactor itself.[3]

[3] The Nuclear Regulatory Commission, U.S. Department of Energy, and the International Atomic Energy Agency all provide extensive information on the fundamentals of atomic energy and the function of a notional nuclear reactor. These are all excellent resources for further research and understanding.

Chapter III.

A Brief History of Public Opinion on Nuclear Energy

The current world view of nuclear and renewable energy sources can largely be attributed to a handful of world events that shaped the trajectory, not only of technological development but of the political and public appetite and, in more recent years, fervor for these types of energy production. I provide this brief synopsis as context for my research.

However, first I must emphasize that "nuclear" and "renewables" should not be conflated. In fact, renewable energy sources, such as wind, solar, and hydro, have taken distinctly different paths than has nuclear. The global push toward "green" energy prioritizes renewables while largely excluding discussions on nuclear energy, despite there being resurgent public approval of nuclear power in the United States and abroad (Leppert & Kennedy, 2023). Despite the increase in favor, nuclear still lags far behind solar and wind power in public perception. The World Bank and International Monetary Fund still will not touch nuclear investment (Nordquist & Merrifield, 2023), and even the United States' initiative "Power Africa" has little to no interest in funding nuclear projects.[4]

[4] These positions pre-date the multilateral declaration at COP28. While there is an expectation these organizations will alter their respective views toward nuclear energy, the fact that they have not, in an official capacity as of the time of this writing, is illustrative of the lag experienced between policy announcements and the mechanisms through which the policy is facilitated.

So why have these decarbonized energy sources taken such disparate paths? As Ralph Schoellhammer noted in his report for MCC Brussels: “The toxic image of nuclear energy in popular culture reinforces negative public sentiments toward nuclear—but it doesn’t resemble the truth” (Schoellhammer, 2023). The answer to the disparate views on nuclear versus renewable energies lies in their respective origins, media coverage of the technologies, and public education, the last of which would help the casual observer to discern fact from fiction and proof from perception.

First let’s look at the ugly origins of nuclear energy. On August 6, 1945, the United States dropped an atomic bomb on Hiroshima, killing hundreds of thousands of Japanese people. Three days later, the U.S. dropped a second bomb on Nagasaki. After World War II, as the global community began to process the horrors of nuclear weapons, the term “nuclear” evoked a sense of fear and trepidation, particularly in the American public. Despite this, nuclear power was heavily researched as an efficient source of energy in the United States and abroad.

The first commercial nuclear power station was connected to the national power grid in Windscale, England, in August 1956; the first American plant commenced operations the following year. Both were heralded initially as the beginning of the “new atomic age”—but they were not without their critics (Brown, 2003). The advent of nuclear power as a viable alternative to fossil fuels was polarizing. On one side, the risks associated with the technology were tantamount in the continuing atomic bombs; on the other, the lack of energy diversity and an ever-increasing reliance on fossil fuels to supply the burgeoning demand for energy production seemed likely to place the United States and others on a path to war over oil reserves and production. Detractors of nuclear technology have heavily influenced the world view of nuclear energy, and conflation of nuclear reactors and nuclear weapons is common, even with today's growing public understanding; there is a stigma that today's industry experts are still trying to overcome.

The global push for alternative sources of energy can be traced largely to the energy crisis of 1973. On October 13 that year, President Richard Nixon authorized Operation Nickel Grass, an effort to airlift military equipment and supplies to Israel in order to counter Soviet support for Egypt and Syria, which had launched a joint attack a week earlier. While Israel was able to repel the attack (dubbed the Yom Kippur War), and sign a ceasefire on October 25, the ramifications of U.S. logistical support for Israel rippled across the international political and economic landscape. Almost immediately, the Organization of Arab Petroleum Exporting Countries (OAPEC) countered with an oil embargo on the United States and The Netherlands (Wallace, 2021). The embargo not only triggered an oil shortage in the U.S., but largely shaped foreign policy between Washington and the Middle East for decades.

The sudden shortage of fuel in the United States spurred the Nixon Administration to recognize how vulnerable the U.S. was to Middle East policies on production, supply, and pricing of oil in the international market. The U.S. responded with a concerted investment in domestic oil production and alternative energy sources, in order to generate a more resilient, self-sufficient American economy (Fiorino, 2022). This prompted a precipitous drop in the cost of solar energy production (see Figure 3) and a significant increase in the quantity of global nuclear power production over the next decade (see Figure 4). Despite these trends, the Western view of renewable energy was optimistic, even as the development of nuclear was still mired in the increasingly influential anti-nuclear movement of the 1970s and 1980s (Daubert & Moran, 1985).

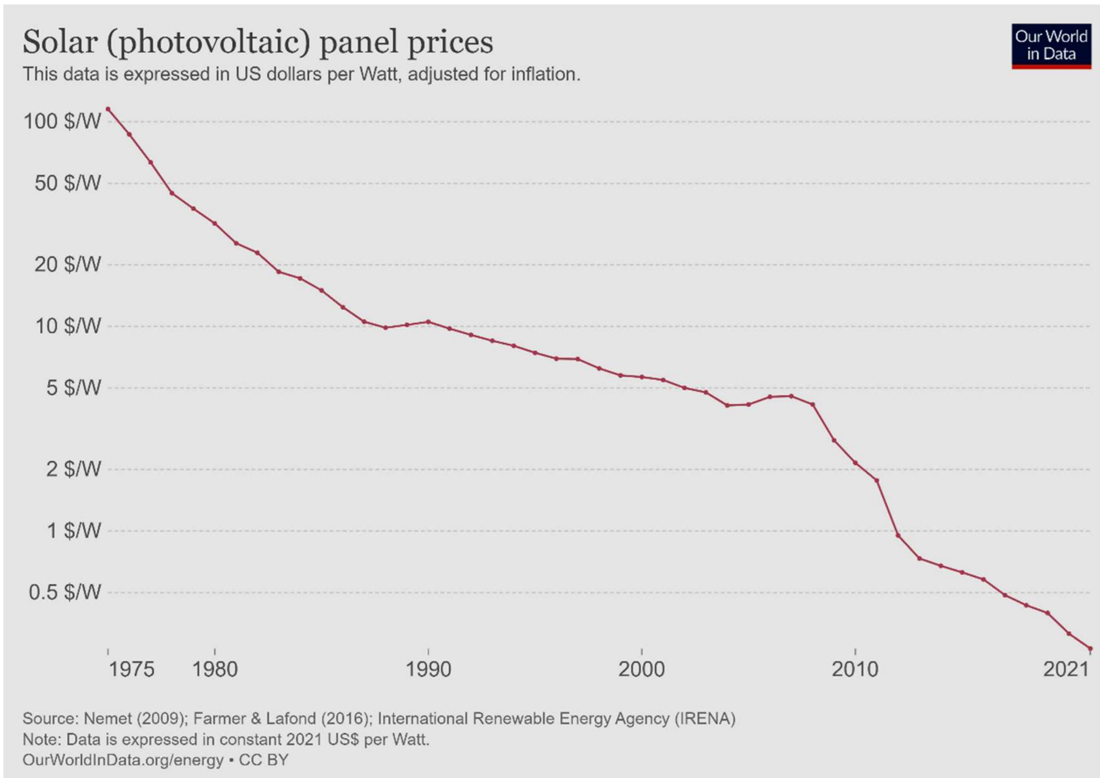

Figure 3: Cost of Solar Panels Over Time.

Source: www.OurWorldinData.org

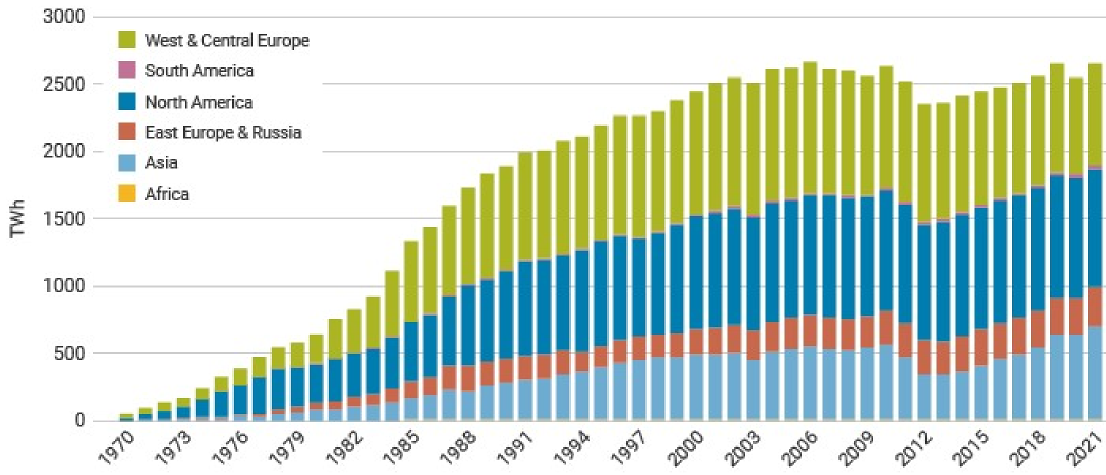

Figure 4: Share of Nuclear Energy Production.

Source: www.World-Nuclear.Org

There have been three nuclear incidents that could be considered seminal events relative to the hazards of nuclear energy. The partial meltdown of Three Mile Island outside of Harrisburg, Pennsylvania, brought the risks of nuclear reactors to the front of the American conscience; the horrific images following the aftermath of the accident at Chernobyl seven years later presented the possibility of a hazard that was unacceptable to much of the world. Finally, the accident at Fukushima Daiichi Nuclear Power Plant following an earthquake and tsunami in Japan served as a stark reminder of the risks inherent with nuclear power. Chernobyl, Three Mile Island, and Fukushima each fueled trepidation followed by resistance to further nuclear development. While all three incidents were significant, in reality none was as apocalyptic as prevailing public opinion suggested. In fact, even including these events, nuclear is still one of the safest and cleanest forms of power generation (see Figure 5).

Each mishap was heavily scrutinized and studied, resulting in improvements in procedure and design that made nuclear power generation safer, But this is rarely mentioned in portrayals of these events and even less frequently remembered by the public. There is a cognitive disconnect between public perceptions of nuclear energy and the relevant safety statistics. The work of Daniel Kahneman may provide some insight as to why this is the case. His theory on "negativity bias" is based on human propensity to focus on and retain negative stimuli rather than positive (Kahneman, 2011). This is not a conscious decision, per se, as brain scans on test subjects indicate a different, physiological response to negative imagery. In short, humans are hardwired to form opinions based on negative associations more so than positive ones.

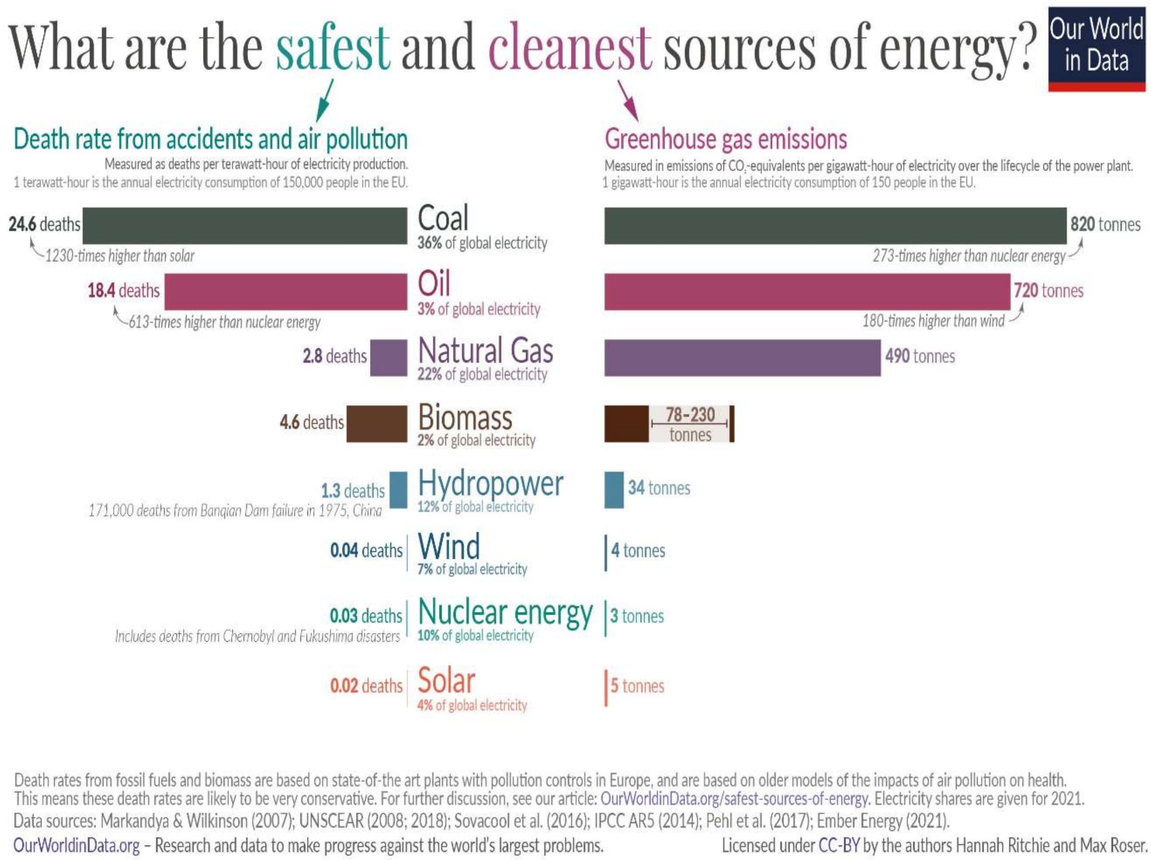

Figure 5: Safety and Greenhouse Gas Emissions, by Energy Source.

Source: www.OurWorldinData.org

With this in mind, Kahneman suggests that an effective method for overcoming this bias is to gather more information on the topic so as to shift one's thinking from the subconscious to the conscious. To this end, I will briefly discuss each incident in more detail.

Three Mile Island

On March 28, 1979, one of two reactors at the Three Mile Island facility experienced a partial meltdown due to the loss of cooling water flow to the steam generators. The loss of flow triggered an automatic shutdown of the reactor. As a result, pressure increased, which prompted a relief valve to open, allowing steam to escape the primary system and lowering pressure. A mechanical failure of the relief valve caused it to stick open, despite the fact that staff received indications the valve had shut. As steam continued to escape, cooling water levels dropped to dangerous levels and the core overheated (NRC, 2023).

Numerous independent surveys and studies were conducted in the aftermath of the accident at Three Mile Island. They revealed that despite damage to the reactor, the incident had little to no effect on the health of the surrounding population or environment. No injuries or adverse health impacts were ever attributed to Three Mile Island. A detailed evaluation of events leading to the partial meltdown was conducted which resulted in closer oversight, more rigorous licensing and regulation of reactor staff, and mandatory upgrades to reactor safety design, equipment, and training. These requirements remain in place today.

Chernobyl

The accident at Chernobyl stands as the most severe nuclear accident in history, both in terms of radiation released and loss of human life. The reactor design and purpose were unique in that, in lieu of water, the reactor used graphite as a moderator. Further, in addition to thermal output the core was designed to yield weapons-grade plutonium for the Soviet nuclear weapons program (Colvin, 2011). Another design peculiarity in the Chernobyl reactors was a “positive void coefficient” (WNA, 2022)—more on this in a bit.

On April 25, 1986, the staff at the Chernobyl 4 power plant prepared to perform a test of how long electric power would continue to be generated following a loss of main electric supply. This test required the staff to disable automatic shutdown features and other indications designed to ensure safe operation of the plant. The test itself was inherently dangerous in that it placed the reactor in an unstable condition with reduced safety systems in place. While conducting the test, the staff conducted the atypical reactor shutdown by inserting fuel rods into coolant with a much larger difference in temperature than a routine operation. The thermal shock to the fuel rods caused them to fracture which, in turn, rapidly produced high levels of steam and pressure. The pressure blew the cover plate of the reactor vessel loose, creating an open system that prompted all the coolant in the core to immediately flash to steam. This escaping steam caused a massive steam explosion, opening the afflicted reactor to the atmosphere and releasing high amounts of fission products. The blast killed two Chernobyl staff and the resulting fires took hundreds of firefighters ten days to extinguish.

Succinctly, the accident was due to poor design, poorly trained operators, and the lack of a culture of safety (Montgomery & Graham, 2017). The test was poorly designed, deliberately cutting out automatic safety features and indications. The staff was ill-trained and reacted poorly to indications of danger. Perhaps the most significant contributor, however, was a design that allowed reactivity (and thus reactor power) to increase as steam became more prominent in the core. That is to say, as temperature in the reactor increased, so did the reactor power. This is what is known as a "positive void coefficient," and in the reactor at Chernobyl it was this factor that dominated the uncontrolled reaction that caused the initial explosion and subsequent meltdown.

This is worth noting because, due to this design flaw, an unprecedented collaboration between the Soviets and the United States occurred to ensure that these critical engineering flaws would be eliminated from nuclear reactor design. Today, there is not a single pressurized water or boiling water nuclear reactor operating in the world that is at risk of a dominant, positive reactivity coefficient (CNSC, 2015). Nuclear reactors are inherently stable today, in that as coolant temperature increases, reactivity and reactor power decreases.

There is no question the disaster at Chernobyl was tragic and the effects of the resulting contamination are still present in modern-day exclusion zone surrounding the accident site (Atkinson, 2023). The World Nuclear Association reports, in addition to the two operators killed in the explosion, 28 additional responders died within weeks from acute radiation syndrome. An estimated 5,000 cases of thyroid cancer are attributed to the fission product release, and roughly 350,000 people were evacuated as a result of the accident (WNA, 2022).

As horrific as the events of April 25 were, however, it is important to consider the root causes of the incident, including the historical context, and the safety-focused mitigations that are now utilized as a result. When assessing the viability of nuclear energy as a technology and as an industry, one must separate the subjective from the objective. In this case, despite this terrible accident, nuclear power is still one of the safest forms of electricity generation.

Fukushima

The nuclear accident in Fukushima on the island of Honshu, Japan, differs from those at Three Mile Island and Chernobyl. The events in Japan were triggered by the strongest earthquake ever recorded in the region followed by a massive tsunami that claimed more than 18,000 Japanese lives. There are similarities, however, in that poor regulatory oversight contributed to a decreased margin of safety that ultimately resulted in disaster (Montgomery & Graham, 2017).

On March 11, 2011, a magnitude 7.4+ earthquake caused the island of Honshu to instantly shift approximately 2.4 meters (7 feet 10 inches) to the east. The quake caused a 40-meter (131 feet) tsunami extending flood waters 10 kilometers (32.8 feet) inland. The plant itself survived the earthquake and the initial flooding. Additionally, the reactors at the Daiishi plant shut down automatically as designed. The tsunami, however, brought mud-choked saltwater over seawalls and rendered the emergency power and pumps for the Number One reactor's emergency cooling system inoperable. Without emergency cooling flow, the shut-down reactor continued to produce heat that began to boil off existing water in the core. The fuel elements in the core overheated, and the reactor melted down. Within the containment building of reactor Number One, hydrogen concentrated to explosive levels and, upon restoration of electrical power to the reactor, a spark caused the building to explode. Reactors 2, 3, and 4 suffered similar fates in the coming days, each resulting in the release of irradiated material into the environment. Unlike Chernobyl, the reactor's core was never exposed to the environment (Montgomery & Graham, 2017).

The safety mechanisms and design characteristics of the Daiichi plant worked—to some extent. The seawalls that were breached, the placement of emergency generators, and the resilience of emergency cooling equipment to seawater and debris were all found to be sufficient for a wave incursion of much smaller magnitude. In short, engineers simply did not think a 131-foot wave was possible. The Fukushima Daiichi plant was constructed in the early 1960s and was one of the largest and oldest plants in operation in Japan. According to the IAEA, vulnerability assessments of the Fukushima Daiichi nuclear power plant had never been conducted during its lifetime, since there were no regulatory requirements in Japan to do so (IAEA, 2014). This led experts to believe that despite the massive earthquake and devastating tsunami, the accident at Fukushima could have been avoided.

In the aftermath, the Japanese government conceded more could have been done to ensure the safety of the Daiichi plant, and since the incident the government has implemented mandatory stress tests be completed on all nuclear reactors in Japan prior to restarting, similar to requirements in place in the European Union. Such tests will help ensure the mechanical and structural integrity of the reactor components and associated systems (WNA, 2023).

I include this brief discussion of these seminal incidents to illustrate that the reluctance of the general public to embrace nuclear power has some merit. The stigma surrounding the technology is one that industry experts have sought to overcome for decades, with limited efficacy. But with the global need for reliable, non-carbon energy solutions, public opinion is shifting (Leppert & Kennedy, 2023). Nuclear power generation is predicated on a strict culture of safety and procedural compliance. A culture that is constantly being revisited, revised, and reinforced in order to continue the transition to greater acceptance of nuclear, it is critical for the industry to acknowledge the negative bias in most people, and to educate communities on the pros—and yes, the cons—of nuclear power.

Chapter IV.

Carbon and Consistency: The Reliability of Nuclear Power

The COP28 conference in Dubai convened in November 2023 amid much anticipation that the U.S., U.K., and others would announce their commitment to triple nuclear output by 2050. Such an announcement would mark a significant shift in global opinion on the role of nuclear energy in climate goals and global decarbonization. Even the most fervent advocates of renewable energy sources like solar and wind concede that the goal of global warming no higher than 1.5°C, set forth in 2015 with the Paris Climate Agreement, was unattainable with renewables alone. Simply put, the world's current and projected need for energy is too great for solar and wind technology to be the only supply. This point was unfortunately illustrated in the case of Germany during the first months of the Russia-Ukraine conflict.

A Case Study of Germany

In 2010, Germany announced an initiative to phase out nuclear and coal plants in favor of renewable energy production. The goal would be to continue industrial and economic growth while achieving carbon neutrality by 2050. Under this plan, dubbed *Energiewende* (Energy Transition), nuclear power would be retired by 2022, and fossil-fuel-based energy production would gradually be replaced by solar and wind (Appunn, Haas, & Wettengel, 2021). The resulting policies and investment were celebrated, and German lawmakers were heralded as being at the leading edge of the global, environmental movement (Schreurs, 2016). Numerous charts and graphs suggested Germany's policies were a shining example of a how an industrialized nation could decarbonize while maintaining their economy (see, for example, Figure 6).

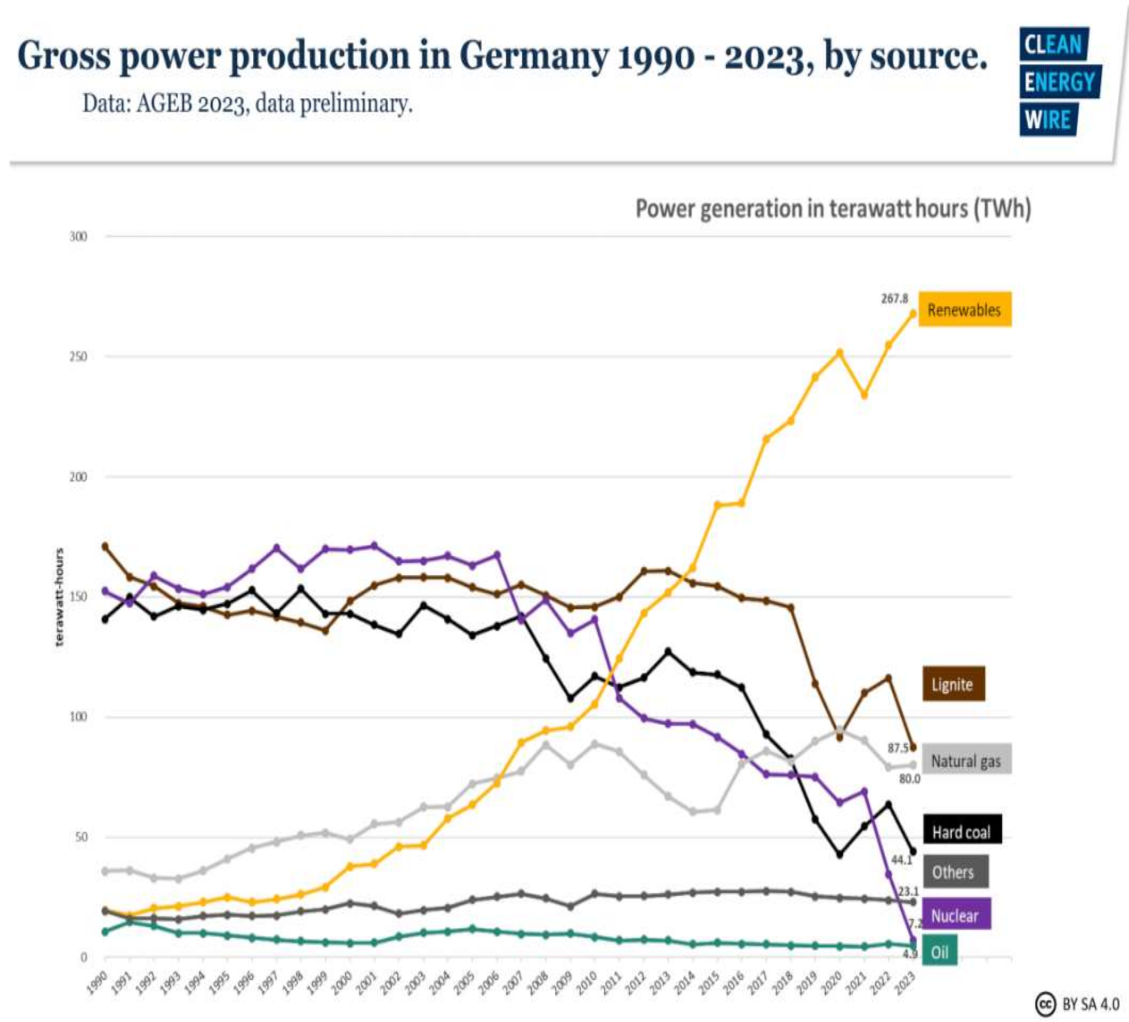

Figure 6: Gross Domestic Power Production in Germany.

Source: www.bdew.de

Figure 6 tells a compelling story about how an industrial power could effectively shift its energy landscape away from fossil fuels. Of course, this graph does not tell the whole story. It shows the amount of domestically produced energy in Germany since 1990. According to the International Trade Administration, domestic production accounted for roughly 16% of Germany's energy consumption in 2022. That means more than 80% of Germany's energy consumption was sourced by imported resources, primarily mineral oil, natural gas, and coal (ITA, 2023).[5] While *Energiewende* looks great on paper, the net result was an industrialized nation adopting a policy that exposed the country to significant external market risk.

Russia's invasion of Ukraine in February 2022 was a worst-case scenario for Germany's energy strategy. More than one-third of Germany's imported mineral oil and more than half of its coal and natural gas imports came from Russia prior to the start of the war (Labunski, 2023). When Western-imposed sanctions on Russian exports of petroleum products were agreed upon by the European Council in May 2022, Germany and several other states were forced to reassess their respective abilities to generate the requisite energy during the peak months in the upcoming winter. Despite bolstering their domestic, renewable energy production, Germany recognized that without the fossil fuels supplied by Russia in conjunction with the closure of several nuclear and coal-fired power plants, Germany could very well be facing an energy crisis within the year. This concern was exacerbated by demonstrated inconsistencies in energy output from the solar and wind sectors due to meteorological fluctuations (Drücke, et al., 2021).

Through a combination of energy subsidies, re-opening of coal plants, extension of nuclear plants slated to close, rapid development of liquid natural gas refinement

[5] The International Energy Agency (IEA) recently unveiled an addition to its website that provides data and synopses of partner nations' energy insights. It is a free and open resource with extensive information on energy production, consumption, and emissions. https:www.iea.org/

capabilities, and industry protective policies, Germany was able to provide energy security to the general public and to its economy. Despite its efforts, energy prices spiked over 34% and inflation jumped by nearly 8%. This scenario proved to be a cautionary tale of being overly dependent on a single country's imports in an industry as foundational as energy. While achieving climate goals is undoubtedly important, the significance of reliable, domestic, energy production cannot be overlooked when transitioning to a decarbonized yet robust economy.

The Nuclear Solution

Nuclear energy provides reliable baseload power while holding a number of advantages over both fossil fuels and renewable sources such as solar and wind. Low carbon emissions, land usage, scalability, reliability, and cost make advanced nuclear reactors not only viable but critical to the world's transition from fossil fuels, and I discuss each of these factors below. This is not to say it is a panacea per se, but rather recognition that these advantages prove nuclear to be an integral piece of a holistic and diversified energy strategy.

Carbon Emissions

When considering carbon emissions, it is important to assess the full life-cycle of energy production. This includes not only emissions produced during plant operation, but carbon emitted during extraction of raw materials, production of components, construction of a plant or facility, maintenance, and decommissioning.

With this in mind, the United Nations Intergovernmental Panel on Climate Change published the relative, full-cycle carbon emission intensity for the most common sources of energy. As one would expect, hydropower yielded the least, while coal and oil produced the most (Berggren, 2023).

- Hydropower: ~ 4g CO_2e/kWh
- Wind: ~11g CO_2e/kWh
- Nuclear: ~12g CO_2e/kWh
- Solar: ~ 41g CO_2e/kWh
- Natural Gas: 290-930g CO_2e/kWh
- Oil: 510-1170g CO_2e/kWh
- Coal: 740-1689g CO_2e/kWh

What may be surprising is that nuclear is nearly identical to wind power emissions and significantly less than solar. It may be apparent that wind and solar do not produce carbon emissions while generating power, so how can these figures be accurate? The answer lies in the life span of the associated equipment, amount of materials needed to be extracted to produce the equipment, and the amount of waste generated when decommissioning the equipment.

Energy Density

In order to properly compare the cost and emissions of energy production between different sources, it is important to consider the "energy density" of the fuel. Energy density refers to the amount of energy that can be produced by one kilogram of fuel material. Table 1 below breaks down the comparison.

Table 1: Energy Density of Common Sources of Fuel.

FUEL	TYPE	ENERGY DENSITY (MJ/kg)
Firewood	Biomass	16
Coal	Fossil fuel	24
Crude Oil	Fossil fuel	44
Diesel	Fossil fuel	45
Gasoline	Fossil fuel	46
Liquefied Natural Gas	Fossil fuel	55
Uranium-235 (enriched to 3.5%)	Nuclear fuel	3,900,000

Source: www.visualcapitalist.com

To put these numbers in context, it would take more than 162 metric tons of coal, or 41,000 gallons of liquefied natural gas, to yield the same amount of energy as one kilogram of enriched uranium (Bhutada, 2023). The emissions generated from extraction and transport of a large volume of fossil fuels far exceeds that of an equivalent amount of uranium ore. Energy density also plays a direct role in land use, and how often each type of energy production plant needs to be replaced or refueled.

Land-Use Intensity

Land-use intensity describes the area required to produce a given power output. The energy density of uranium and the efficiency with which nuclear fission produces power sets it apart from traditional renewable sources of energy such as wind and solar.

In Figure 7, nuclear has a low land-use intensity as well as low greenhouse gas emissions per TWh of energy produced. On the vast expanses of the central U.S. plains,

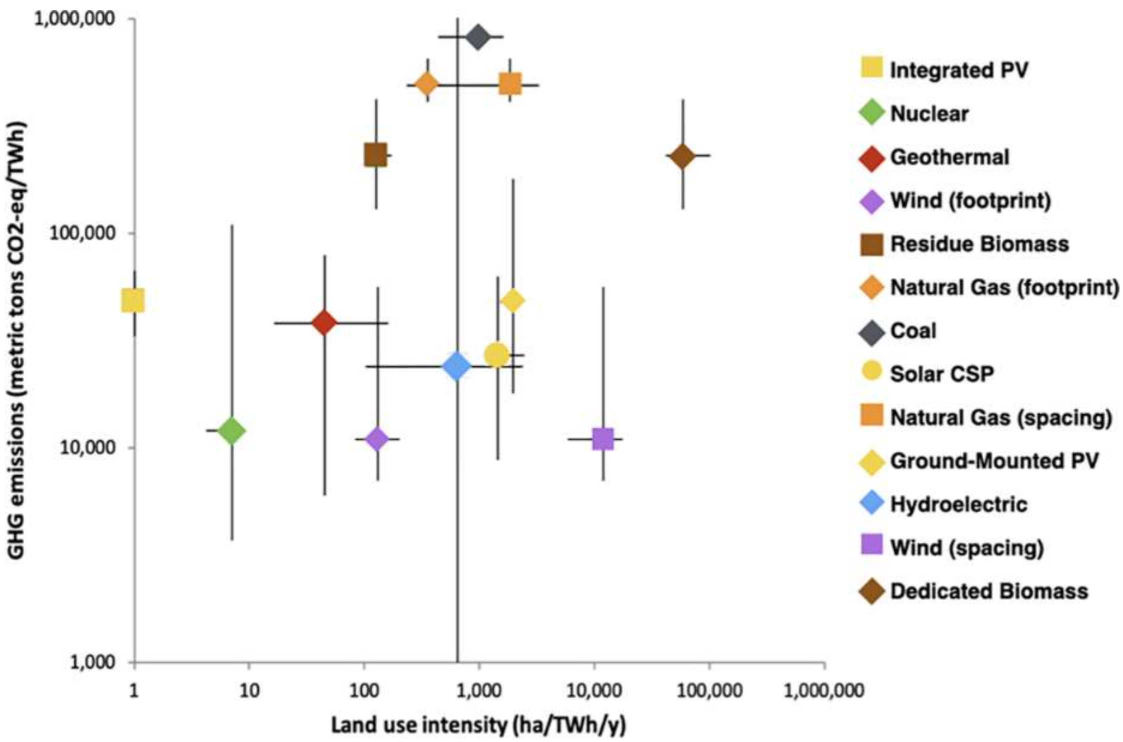

Figure 7: Relationship Between Land Use Intensity of Electricity (Ha/Twh/Y) and Lifecycle Greenhouse Gas Emissions (Metric Tons CO2e/Twh) on a Log Scale.

Source: www.thebreakthrough.org

where acreage is abundant and relatively cheap, this may not be a significant concern, but as smaller, emerging markets assess the viability of energy development, occupied space and the associated cost become a major consideration (Webster-Herber, 2004).

Facility Life Span

Because of the energy density of uranium and the relatively low maintenance requirements of nuclear power plants, the typical life span of nuclear plants exceeds that of fossil fuel plants, solar, and wind facilities. This has a direct impact on the cost and amount of carbon emitted for resource extraction and transport as well as the emissions linked to construction and decommissioning of the plant. Nuclear reactors have an average expected life span of 50+ years while typical photovoltaic cells are estimated at roughly 30 years, and a wind farm even less than that (English & Donovan, 2020). Additionally, the time associated with the replacement of renewable energy equipment reduces the time electricity is actually being produced. This is a metric referred to as the *capacity factor* of an energy source, and it has significant implications when comparing different types of energy production.

Capacity Factor

The *capacity factor* (CF) of a power plant is defined as its power output, divided by its generation capacity. This takes into account outages for maintenance, refueling, etc., as well as fluctuations in power output due to meteorological effects. It is used to describe the reliability of an energy source to produce consistent, baseload power. The concept is key in determining the size and output of a plant relative to the power demand of the load it is servicing. To this end, the output of the plant to be built must be, at a minimum, Power Demand divided by the Capacity Factor. For example, if a municipality consumes a peak of 800MW of electricity, a power plant with a CF of 50% must have a generation capacity of at least 1600MW in order to avoid power disruptions. The U.S. Department of Energy published a chart (see Figure 8) comparing capacity factors in 2021, which indicates nuclear has a CF of nearly 93%. This is the highest of any energy source and is more than triple the CF of solar.

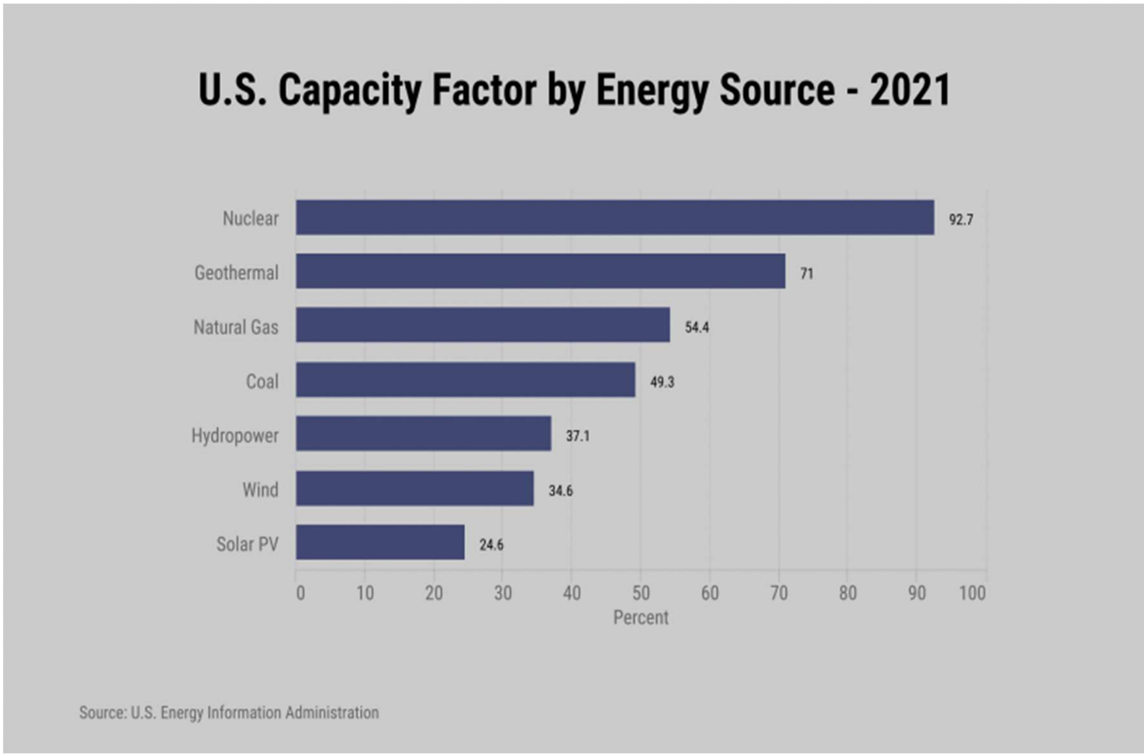

Figure 8: U.S. Capacity Factor by Energy Source.

Source: U.S. Energy Information Administration. www.energy.gov/ne/articles/what-generation-capcity

In the example of the 800MW peak-load municipality, a nuclear plant with a generation capacity of at least 860.2MW must be built. Conversely, should solar power be used exclusively to supply electricity to the same town, a plant with a maximum capacity of 3,252MW must be built. That would require an area the equivalent of roughly 17,000 American football fields, does not include support or energy storage facilities, nor does it include integration costs associated with renewables. As one would expect, a plant of this size and capacity drastically increases cost and presents challenges to markets that are economically and/or land-constrained.

Levelized Cost of Energy

Cost calculations of energy production can get complicated. Upfront investment, operating expenses, fuel procurement, capacity factors, and other variables all play into the calculation of the *levelized cost of energy* (LCOE), a metric that is commonly used to define the economics of electricity generation (Comello & Reichelstein, 2017). The LCOE of different power sources are often compared in order to determine the economic viability and cost-effectiveness of an energy project. While LCOE is a simple means by which to compare power-generation systems of varying life spans, sources, and project size, it has proven to be an inadequate measure of the true cost of energy production for sources with highly-variable outputs and low-capacity factors. Specifically, LCOE significantly underestimates the actual of expense of renewable energy sources such as solar and wind (Uekerdt, et al., 2013).

Solar and wind are referred to as *variable renewable energy* (VRE) sources because their respective outputs are dependent on environmental factors. For instance, a solar plant's output is hampered during cloudy conditions as wind farms are limited when there is little to no wind. As a result, renewable power plants need to be engineered such that their *engineered load-carrying capacity* meets the energy needs of the loads it is servicing. Additionally, costly energy storage systems are required in order to mitigate the fluctuations in output. If this still proves to be inadequate, other sources of energy supplying the load need to be scaled and adjusted as part of a hybrid energy strategy to provide consistent, baseload power. These costs are not incorporated into a standard LCOE calculation, and they can significantly alter the economic viability of a renewable energy project. These factors are summarized by the term, *integration costs,* and they describe the additional expenses incurred to actually utilize the power generated in a comprehensive energy strategy.

Integration costs become more important as VRE is more heavily leveraged in a system, primarily due to the increased requisite energy storage capacity (Uekerdt, et al., 2013). Consistent, high-CF generation sources, such as liquefied natural gas and nuclear, inherently avoid significant integration costs due to their reliability in providing baseload power regardless of environmental conditions. The inability of LCOE calculations to account for the inconsistent economic variables between renewable and non-renewable energy sources makes it an inadequate metric by which to make a proper assessment.

A simplified estimate of integration costs can be made using a figure called the *levelized cost of storage* (LCOS). This figure is calculated similarly to LCOE, but incorporates only the energy storage equipment associated with VREs. When incorporating the LCOS into economic assessments, nuclear becomes a cost-competitive option for supplying reliable baseload energy.

This is not meant to be an indictment of renewable energy or fossil fuels. Quite the opposite, in fact. In order to develop a diversified, resilient, and reliable energy strategy, policy makers and utilities need to recognize the benefits and drawbacks of each source of energy. Despite the historical stigma associated with nuclear power, advanced reactors have proven to be safe, reliable, and cost effective while using less land and producing less waste than both fossil fuels and most renewables. This is why the global community is recognizing a significant increase in nuclear energy as being an essential part of meeting climate goals, and also why world leaders came together with such solidarity to pledge the advancement of nuclear at the COP28 in Dubai.

The question becomes: is nuclear advancement a privilege of wealthy countries exclusively, or can emerging markets reap the benefits of nuclear as well? Moreover, does implementing nuclear energy in certain parts of the world guarantee disaster?

Chapter V.

The Role of Nuclear in African Markets: An Energy Dilemma

Two short points tell the story of how the African continent is on the precipice of either resurgence and growth or abject poverty:

1. There are currently between 600 and 700 million people on the continent with little or no access to electricity (Murshed & Ozturk, 2023), and
2. The African population is projected to nearly double by 2050 (Stanley, 2023).

The implications of these two data points are alarming. Without a major shift in political stability, economic policy, and domestic and foreign investment, African countries could find themselves on the cusp of disastrous poverty and civil unrest.

Political Stability

When discussing African business opportunities with Western investors, the "elephant in the room" is always the political turmoil in countries throughout the continent. I personally have received responses ranging from "interesting, but not compelling" to colorful, illustrative language decidedly inappropriate for an academic paper. It is not surprising if one considers that most of the Western news stories out of Africa tell tales of war and corruption. This is not necessarily an inaccurate or erroneous or perception. In its 2023 annual report showing the Fragile States Index (see Figure 9), the Fund for Peace assessed Africa to be the most volatile continent based on their data (Haken, et al., 2023). The assignment of risk is based on the identification of internal and external pressures that could push a state to unrest and failure.

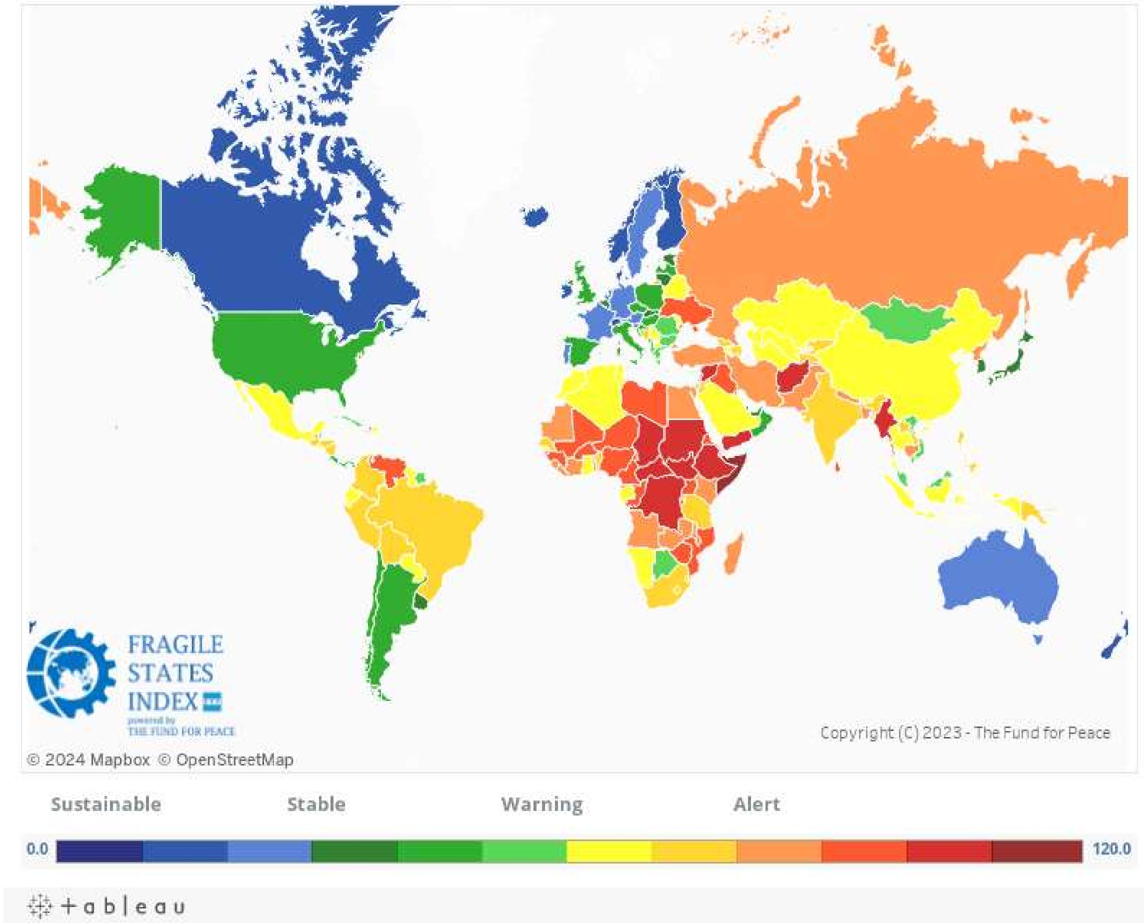

Figure 9: Fragile States Index.

Source: www.fragilestatesindex.org

Figures 10 and 11 identify countries facing active conflicts and demonstrations. The data show a strong correlation between civil unrest, food insecurity, and political corruption.

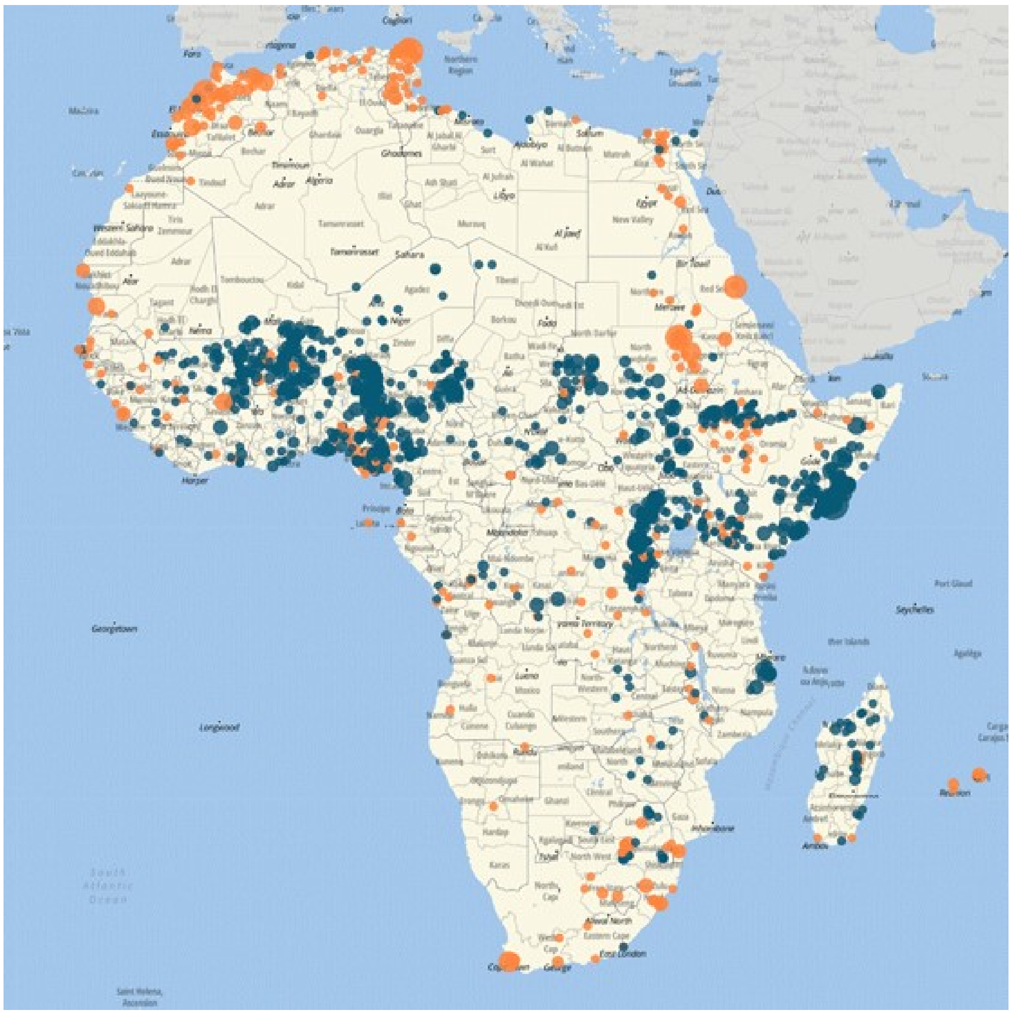

Figure 10: Active Conflicts and Demonstrations, July 2023.

Source: www.acleddata.com

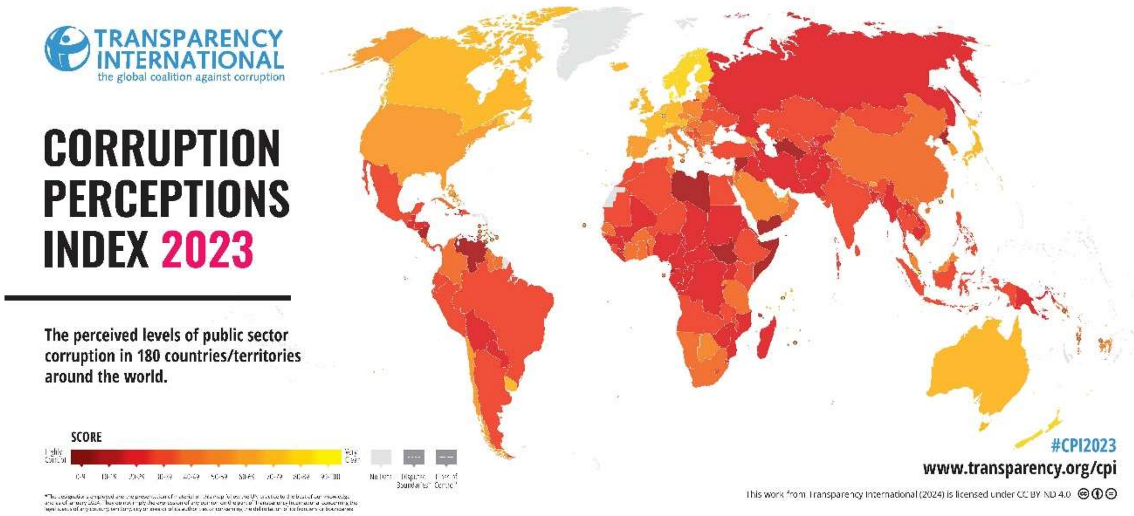

Figure 11: Corruption Perceptions Index 2023.

Source: www.transparency.org/cpi

The figures above do not portray an optimistic picture of political stability on the African continent. Civil unrest, conflict, and perceived corruption make it an unappealing market for outside investment of any kind, much less investment in something as high-value and high-risk as a nuclear power plant. Concerns over terrorist threats, regime changes, public-sector corruption, and risks of weaponization of expended fuel make significant foreign investment in African nuclear energy an extremely difficult sell. And if that picture is not bleak enough, there is more.

A Question of Debt

The development of energy infrastructure to support Africa's burgeoning population will require substantial investment from both the public and private sectors. However, according to international debt statistics from the World Bank, public debt in African countries has doubled since 2010 (World Bank, 2023). The International

Monetary Fund currently considers 22 low-income African countries to be on the verge of debt distress. This means those countries will have to make hard choices between paying their respective creditors or paying their obligations to their own people (Akeredolu, 2023). As of 2021, ten African countries have a debt-to-GDP ratio in excess of 75% (see Table 2). Typically, when a country's debt ratio is high, their economic growth suffers. This tends to be a more pronounced correlation in low-income nations. Additionally, a country's credit rating is negatively impacted by higher debt ratios. This increases the cost of the debt the country will incur and dissuades risk-averse lenders from investing in that country.

Table 2: 10 Highest Debt-to-GDP Ratios in Africa (December, 2022).

Rank	Country	Debt-to-GDP ratio
1.	Eritrea	164%
2.	Cape Verde	127%
3.	Mozambique	101%
4.	Republic of the Congo	99.57%
5.	Sierra Leone	98.8%
6.	Ghana	88.8%
7.	Egypt	87.2%
8.	Gambia	80.8%
9.	Senegal	75%
10.	Morocco	71.6%

Source: Business Insider Africa

As part of its Belt and Road Initiative (BRI), China has increased its lending for infrastructure development across Africa. It is now the single largest creditor on the continent with debt holdings of roughly 12% (ADF, 2023). In 2020, the World Bank named seven African countries as being *en extremis* due in large part to the volume of Chinese financing (Okafor, 2023).

Standard & Poor's regards bonds rated BBB– or better as "investment grade." Of all the countries on the African continent, only Mauritius (BBB–) and Botswana (BBB+) meet the necessary criteria. The trend is not positive, either. The United Nations Economic Commission for Africa reported the Big Three credit reporting agencies (Moody's, S&P, Fitch) downgraded the sovereign credit ratings of Egypt, Ghana, Kenya, Nigeria, and Tunisia in the second quarter of FY2023 alone (Nkhalamba, et al., 2023). Currently, in order to be able to invest in their own infrastructure development, most African countries need to rely on the willingness of creditors, including China, to restructure their debt (Akeredolu, 2023).

Viability of Investment

As mentioned, the majority of African countries do not present an attractive investment opportunity. Even if a country were able to pay the higher interest demanded by a riskier loan, the chance of losing the entire investment due to case of regime change or default tends to dissuade most private investors. As one potential investor told me, "I wouldn't touch Africa with a ten-foot pole. Neither would any investor I know." It would seem, then, that the African continent is destined for decline.

Hope is not lost, however. There are attainable, albeit challenging, features of the market that are attractive to foreign direct investment (FDI). In its report, "Rethinking Regional Attractiveness in the New Global Environment," the Organization for Economic Cooperation and Development (OECD) outlined possible key factors and provide a roadmap to help investors identify investment targets that contribute to a region's development goals. The OECD 2023 reports emphasizes the importance of quality physical and digital infrastructure, attractiveness of a region to talent and human resources, sustainability of a development project, internal and external stability, and the existence of special economic zones that facilitate supply and economic mobility in and out of the region.

Last, and perhaps most important, investors need to believe in the cause. In response to the surge of green initiatives, for example, the report cites an increase of investment in renewable energy as a share of total energy investments, from 10% in 2004 to roughly 90% by 2021 across OECD economies (OECD, 2023). Demonstrating these features is easier said than done, however, particularly when overcoming decades of stigma. But an emerging market can show due diligence and intent when prioritizing their domestic investment to promote these attributes. Additionally, when considering the challenges of energy access and population growth, African countries stand poised to be the next great investment frontier.

Despite the risk, an investment in African energy could facilitate the shift away from relatively low-grossing extractive industries such as mining, and usher in the development of a manufacturing base that would provide jobs and income to the local population. Clean, reliable nuclear power at scale can be used not only to provide residential electricity, but also to lay the groundwork for manufacturing and tech industries. Additionally, thermal energy used in conjunction with electrical output can be used for a variety of industrial applications, including desalination and other clean water projects that would provide climate resilience for populations residing in drought-prone areas. The investment becomes more attractive when an investor believes they can effect real change and improve the lives of millions of people.

The challenge of overcoming obstacles and enticing affordable investment in time to develop the infrastructure necessary to meet the needs of Africa's growing population still remains, and the prospect of a humanitarian investment is rarely prioritized over returns. A country's investment in an energy strategy that produces reliable, decarbonized electricity, with nuclear as its cornerstone, is a clear message to foreign investors that policy makers are serious about developing sound, foundational infrastructure for economic and industrial growth.

Energy development, however, cannot be presented as a high-return investment in its own right. The reliability and scalability of a nation's power production and grid must be showcased as an impetus to secondary and tertiary investment opportunities such as non-extractive industrial growth, water desalination, and potentially, the establishment and growth of a robust tech industry on the African continent.

African Progress in Nuclear Energy

As of this writing, only South Africa operates a commercial nuclear power plant on the continent. However, there are several other countries that also recognize the benefits of nuclear energy and are actively cooperating with the International Atomic

Energy Association (IAEA) and suppliers to develop their respective civil nuclear energy programs. Egypt, Ghana, Morocco, and Uganda, for instance, are on track to complete construction of their first reactors by 2030, with other African nations at various stages of development behind them.

The African Commission on Nuclear Energy (AFCONE) was established in 2009 as the organization that would oversee the terms of the African Nuclear Weapon-Free Zone Treaty. Since that time, AFCONE's Executive Secretary, Enobot Agboraw, has been one of the most fervent supporters of nuclear energy development on the African continent. In a workshop hosted by the Nuclear Energy Agency in June 2023, he emphasized the importance and immediate need for energy infrastructure investment and development, particularly in sub-Saharan Africa. While the efforts of individual African countries have yielded some progress, he pointed out that a more unified, multilateral approach toward development is critical for the timely and economically viable establishment of nuclear energy programs. His recommended approach is comprised of three multilateral efforts:

1. Standardized training, operations, and regulation across the continent, aligned with the standards of the IAEA.
2. A multilateral acquisition strategy utilizing a single supplier in order to drive down construction and development costs by buying in bulk.
3. Development of a robust, cross-border power grid infrastructure to facilitate continuous and reliable electricity supply while also fostering regional cooperation.

While this collaborative approach is logical and optimistic, the reality is that there is a race among African countries to be the first to develop their respective nuclear energy programs. This perceived competition lends itself to a more piecemeal pursuit that ignores the efficiencies inherent in Agboraw's plan.[6]

There is still optimism that nascent nuclear energy programs will remain on track but all of the above-mentioned leading countries, with the exception of Uganda, are in the top 10 in terms of debt-to-GDP ratio. Egypt, in fact, recently awarded a $25 billion contract to Russian energy giant, Rosatom, for a 4.8GW nuclear plant (Kincer & Lovering, 2023). That single contract represents 6% of the country's GDP. The immediate need to realize progress has prompted African nations to pursue agreements with Russia and China in order to streamline the approval process.

The United States is aggressively pursuing partnerships in Africa but has more stringent approval criteria. Entering into an agreement with a foreign country requires a recommendations from the U.S. Department of State, Department of Energy, National Nuclear Security Agency, and Nuclear Regulatory Commission. Each recommendation is presented to the U.S. Congress, then an amendment to Section 123 of the Atomic Energy Act is generated, and a 123 Agreement is signed by the U.S. and the partner nation. All this moves at the typical pace of bureaucracy and creates delays that African countries see as untenable. In many cases, a partnership with Russia or China becomes the only viable option.

[6] Enobot Agboraw's strategic proposal was presented at the conference, Nuclear Energy in Africa: Policy Options to Enhance Safe and Secure Deployment workshop, hosted by the OECD and DNEA, in Paris, France. Elaboration on his points was gleaned through several discussions between Mr. Agboraw and the thesis author.

Chapter VI.

Djibouti: A Hypothetical Case Study

Djibouti provides an interesting hypothetical case for studying the viability of nuclear energy. It is a small, lightly populated country that lies just south of the Bab al Mandeb, where the Gulf of Aden meets the Red Sea (see Figure 12). This is one of the busiest straits in the world in terms of maritime shipping, fishing traffic, and military vessels. Due to its location, it is strategically important and, as a result, the U.S., France, Italy Japan, and China all have military installations in Djibouti.

Figure 12: Foreign Military Installations in Djibouti.

Source: Deutsche Welle (DW)

From an energy standpoint, Djibouti is effectively a clean slate in that it produces 126MW of total power, all of which comes from thermal energy. Only about 57MW can be supplied reliably, however. As a result, only 55% of the urban population and less than 5% of the rural population have access to electricity (USAID, 2023). Military installations operate primarily by using diesel generators installed on-site. While USAID assesses Djibouti as having significant potential for development in the energy sector, the country is pre-decisional when it comes to nuclear development and, as such, has no agreement with the International Atomic Energy Agency.

Politics

The Republic of Djibouti enjoys relatively high political stability. Its leader, President Ismail Omar Guelleh, has been in office since 1999 and won his fifth term in office with 97% of the popular vote. This landslide win, however, is attributed to rival political parties boycotting the election due to a lack of transparency in the election process. Civil tensions are generally peaceful and are motivated by socioeconomic conditions (CIA, 2024).

Economy

Djibouti's GDP is roughly $5.4 billion with a growth rate of some 6% per year. With a population of just over one million people, it ranks as a low-to-middle income country. The country's debt-to-GDP ratio is a modest 42% (IMF, 2024). Primary industries are agriculture, services, and shipping. There is nearly 30% unemployment as of 2022 (World Bank, 2022). The Corruption Perceptions Index is relatively high, with

Djibouti ranking 130 out of 180 countries and territories assessed (Transparency.org, 2023).

Climate and Geography

The climate in Djibouti is extremely dry and its primary source of fresh water is from underground water tables fed by rainwater. The Gulf of Aden has a high salt content and an inland lake of 20 square kilometers is one of the saltiest inland lakes in the world (USAID, 2020). During the summer months, the average temperature typically ranges between 85F and 105F; in the winter, temperature hover between 70F and 83F.

Seismic activity is moderate, with 15 earthquakes detected since 1990. The Tadjoura rift, located between Arabia and Somalia and dominated by a boundary fault zone to the north, is the source of seismic activity (Daoud, et al., 2011). All recorded earthquakes were between 4.0 and 5.4 on the Richter scale, and no deaths, injuries, or significant damage were reported.

Other Considerations

Djibouti lies between Eritrea, Somaliland, and across the Bab el Mandeb from Yemen (see Figure 13). Despite this potentially volatile location, violent crime rates are low, and the country is politically stable. However, a Western military presence in Djibouti makes threats from Houthis and Al Shabab relatively high.

Figure 13: Horn of Africa, with Levels of Political Instability.

Source: Secret Service Agency of Ethiopia Central Ethiopia intelligence Agency

Of further consideration, the warm climate and lack of fresh-water resources means the heat exchangers on a nuclear power plant will operate at lower efficiency, thus requiring a larger, engineered output design. A reactor's cooling water and moderator will need to be desalinated, deionized, and likely cooled prior to use in a plant. This will incur significant added operating and integration costs.

Assessment

Nuclear development in Djibouti has moderate potential for success. The country's energy needs are appropriate for a small modular reactor (i.e., less than 300MW), and the design of that size could be scaled up should the need arise.

From a geopolitical standpoint, the stability of the country and the low rate of violent crime make it a viable location for nuclear development. However, additional risk must be considered due to active terrorist organizations in surrounding countries.

Economically, nuclear development will require major outside investment. A small modular reactor and supporting facilities will likely cost $2 billion to $3 billion, with potential overages for desalination and chilling facilities. Thus, as a standalone investment the plant will not be economically viable. Developing desalination facilities that can service the plant as well as surrounding areas would benefit the region. Also, increasing the population's access to reliable baseload energy makes Djibouti a more attractive market for foreign direct investment. It could facilitate diversification of the country's economy, thus lowering its unemployment rate and bolstering its GDP.

Chapter VII.

Assumptions, the Western Perspective, and Conclusion

This research has admittedly been conducted through a Western lens, making several assumptions on reactor type, cooling medium, funding mechanisms, etc. For the sake of constraining the discussion, I assumed nuclear development in emerging markets would be accomplished using small, modular, pressurized water, nuclear reactors. However, this may not necessarily be the case, as Rosatom—to whom Egypt awarded its contract—specializes in large, legacy reactors. I have also assumed that financing for these projects would be a combination of public and private funding. I have chosen not to delve into possible contributions for nuclear development from multilateral organizations such as the World Bank or the International Monetary Fund.

Additionally, I have advocated for nuclear development irrespective of cultural disruptions the technology might present. In my conversation with David Arinze, a member of the Nigerian Economic Summit Group, he told me about his efforts to develop off-grid renewable energy solutions for communities that never had access to electricity. His team lobbied for, funded, and constructed a small solar plant for a small village and things were progressing well until a dry spell hit. Thereafter, at the behest of a local official, the locals destroyed the solar panels with hammers so as to not offend Surya, God of the Sun. Surely, they thought, the rains would come once these panels were destroyed. When David finished his story and voiced his disappointment and frustration, I understood that any development in emerging markets represents a seismic shift, not only economically but culturally as well. These massive changes need to be predicated on and supported by education and true grassroots efforts to ensure that the local population understands the project and its implications—in their terms and at their level. If there is no public acceptance, the project will not succeed, regardless of the benefit it might provide.

Nuclear energy as a technology is complex, but not complicated, that is, the physics of nuclear fission can be difficult to understand, but harnessing the energy produced and generating electricity is as simple as boiling water in a steam kettle. Still, the stigma associated with it is deep-rooted and has resulted in a decline in the use of nuclear energy for decades. With the realization that continued, unabated consumption of fossil fuels is not sustainable for Earth's population or its climate, the world shifted focus toward alternative sources of energy in the form of renewables such as wind and solar. This prompted an explosion of investment and yielded massive development of these types of energy production globally.

Unfortunately, this was not enough to meet global climate goals so the world community was forced to analyze other low-emission sources of reliable power. Advanced nuclear reactor designs are safer, smaller, more cost-effective, and are scalable for smaller applications. As a result, they have been widely embraced as an integral piece of the global decarbonized energy strategy. The multilateral agreement agreed upon at COP28 is evidence of shifting views toward the criticality of nuclear energy development. This collaboration suggests the need for significant investment on the part of developed countries to develop nuclear energy in emerging markets in order to mitigate the glut in carbon emissions that have accompanied developing industrial bases and economies.

As my research suggests, however, in the current political economy, nuclear energy is simply not a viable option for all regions, regardless of advances in technology and a region's imminent projected power needs. Finances, perceived public and private corruption, a lack of political security, and public acceptance are primary obstacles facing many markets, especially for emerging markets in Africa.

Africa, as a continent, has its own stigma to overcome—as much as nuclear power does. But when analyzing the viability of nuclear energy in African nations, one must be careful not to treat the continent as a single, homogenous entity. Africa is comprised of 54 distinct countries and economies with myriad cultures, political systems, and traditions. Each project proposal is an opportunity, and must be analyzed on its own merit in order to gauge its potential for success (NBP, 2023).

Additionally, regulatory and acquisition strategies, led by the African Union and administered by AFCONE, would not only mitigate the risks associated with the piecemeal development strategies of individual African countries, but would also generate efficiencies that would streamline international approval and drive down development costs for the continent writ large. If global leaders are serious about tripling nuclear output by 2050, and if the global wealth gap between developed countries and the global south is to be mitigated, the prospect of nuclear development on the African continent must be addressed.

Appendix

Full Text of the Multilateral Nuclear Declaration of COP28

Declaration to Triple Nuclear Energy
02 December 2023

Recognizing the key role of nuclear energy in achieving global net-zero greenhouse gas emissions /carbon neutrality by or around mid-century and in keeping a 1.5°C limit on temperature rise within reach and achieving Sustainable Development Goal 7;

Recognizing the importance of the applications of nuclear science and technology that contribute to monitoring climate change and tackling its impacts, and emphasizing the work of the International Atomic Energy Agency (IAEA) in this regard;

Recognizing that nuclear energy is already the second-largest source of clean dispatchable baseload power, with benefits for energy security;

Recognizing that analyses from the OECD Nuclear Energy Agency and World Nuclear Association show that global installed nuclear energy capacity must triple by 2050 in order to reach global net-zero emissions by the same year;

Recognizing that analysis from the Intergovernmental Panel on Climate Change shows nuclear energy approximately tripling its global installed electrical capacity from 2020 to 2050 in the average 1.5°C scenario;

Recognizing that analysis from the International Energy Agency shows nuclear power more than doubling from 2020 to 2050 in global net-zero emissions by 2050 scenarios and shows that decreasing nuclear power would make reaching net zero more difficult and costly;

Recognizing that new nuclear technologies could occupy a small land footprint and can be sited where needed, partner well with renewable energy sources, and have additional flexibilities that support decarbonization beyond the power sector, including hard-to-abate industrial sectors;

Recognizing the IAEA's activities in supporting its Member States, upon request, to include nuclear power in their national energy planning in a sustainable way that adheres to the highest standards of safety, security, and safeguards and its "Atoms4NetZero" initiative as an opportunity for stakeholders to exchange expertise;

Recognizing the importance of financing for the additional nuclear power capacity needed to keep a 1.5°C limit on temperature rise within reach;

Recognizing the need for high-level political engagement to spur further action on nuclear power;

Participants in This Pledge:

Commit to work together to advance a global aspirational goal of tripling nuclear energy capacity from 2020 by 2050, recognizing the different domestic circumstances of each Participant;

Commit to take domestic actions to ensure nuclear power plants are operated responsibly and in line with the highest standards of safety, sustainability, security, and non-proliferation, and that fuel waste is responsibly managed for the long term;

Commit to mobilize investments in nuclear power, including through innovative financing mechanisms;

Invite shareholders of the World Bank, international financial institutions, and regional development banks to encourage the inclusion of nuclear energy in their organizations' energy lending policies as needed, and to actively support nuclear power when they have such a mandate, and *encourage* regional bodies that have the mandate to do so to consider providing financial support to nuclear energy;

Commit to supporting the development and construction of nuclear reactors, such as small modular and other advanced reactors for power generation as well as wider industrial applications for decarbonization, such as for hydrogen or synthetic fuels production;

Recognize the importance of promoting resilient supply chains, including of fuel, for safe and secure technologies used by nuclear power plants over their full life cycles;

Recognize the importance, where technically feasible and economically efficient, of extending the lifetimes of nuclear power plants that operate in line with the highest standards of safety, sustainability, security, and non-proliferation, as appropriate;

Commit to supporting responsible nations looking to explore new civil nuclear deployment under the highest standards of safety, sustainability, security, and non-proliferation;

Welcome and encourage complementary commitments from the private sector, non-governmental organizations, development banks, and financial institutions;

Resolve to review progress towards these commitments on an annual basis on the margins of the COP;

Call on other countries to join this declaration.

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