The Environmental Impact of Nuclear Power

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Abstract:

The current carbon dioxide emissions from electricity production contribute to global climate change. These emissions can be greatly reduced using alternate energy sources, such as nuclear power, to produce electricity. The life-cycle emissions from a nuclear power plant have been estimated through many methods including direct emission data from the sources. This paper attempts to combine multiple life-cycle analyses into a coherent average of carbon dioxide emissions and compare the average to that of coal, the current leading technology in electricity production. This analysis finds nuclear power to be a virtually carbon dioxide emission free when compared to coal, thus making nuclear power a viable low carbon energy source.

Introduction:

Nuclear power has long been seen as a clean energy source. In a world ever more affected by global climate change this is becoming increasingly important. Nuclear power is viewed as a clean source as it does not directly produce any carbon dioxide emissions in the production of electricity. For this reason, nuclear power has been proposed as a way to decrease the global carbon dioxide emissions while maintaining the standard of living.

The western world has long had the ability to produce electricity by nuclear fission and is currently looking to increase the amount of energy produced by nuclear fission. At present, the outlook, as to whether the industry is going to emerge as a low carbon source or if other methods of lowering carbon dioxide emissions will more prevalent, is unclear. There are companies that are banking on the industry emerging as the leader. Two companies, Areva and Japan Steel Works, have invested millions into new forges to construct the large components needed in a nuclear power plant {{6 Besmann,Theodore M. 2010}}.

The western world is not the only area that is looking into the use of nuclear power to reduce carbon dioxide emissions. In Iran, the Bushehr Nuclear Power Plant is estimated to reduce the carbon emissions by up to 3% {{9 Kargari,Nargess 2011}}. The Atomic Energy Organization of Iran is currently exploring the possibilities of increasing the electrical output from nuclear power plants to 20 Giggawatts {{9 Kargari,Nargess 2011}}.

The arguments are deeply entrenched on both fronts on whether nuclear power is a viable way to decrease carbon dioxide emissions. This paper is an analysis of the true environmental impact of the construction and maintenance of a nuclear power plant. All impacts will be compared to the values from a coal power plant as it is the dominate source of energy throughout the world.

Open Nuclear Fuel Cycle:

The United States currently uses what is termed an open fuel cycle. This is in reference to the fuel needing to be constantly replaced as it is only used once and then stored as waste. The cycle simply runs from mining to storage of waste.

The open fuel cycle is a once through progression of steps. First, after the raw ore has been mined, it must be milled into a form in which it can be enriched. The raw ore is first crushed and screened to separate out the “yellowcake” uranium oxide. The ore is termed yellowcake due to its fine powder type consistency and bright yellow color. The yellowcake is then converted to uranium hexafluoride or “hex”. The gaseous hex can then be enriched for use in light water reactors.

The hex that was produced by conversion contains approximately 0.7% U235; but the current light water reactors require at least an enrichment of 3.5% U235 {{5 Sovacool,Benjamin K. 2008}}. At present there are two common ways to enrich the hex: gaseous diffusion or gas centrifuges. Gaseous diffusion forces the gaseous hex through approximately 1400 membranes to separate the U235 from the more common U238 {{5 Sovacool,Benjamin K. 2008}}.The diffusion works due to U235 being lighter and thus has an easier time getting through the membranes. Gaseous centrifuges work on a similar principle; the gaseous hex is separated by weight in a massive cascade of gas centrifuges. These two methods produce approximately 90% of the enriched uranium used throughout the world, with the remaining 10% coming from the recycling of nuclear weapons {{5 Sovacool,Benjamin K. 2008}}.

After the hex has been enriched, it is chemically altered to uranium dioxide. The uranium dioxide is then processed into small cylindrical pellets that will be stacked into a fuel rod. The column of pellets is encased in a zirconium alloy pipe to become a fuel rod. The rod is then used in the light water reactor to produce energy.

The fuel rods are then inserted to into a reactor for the burn-up stage. The burn-up of uranium fuel happens in either boiling water or pressurized water reactors. Regardless of the reactor design, the purpose is the same- to produce high pressure steam that will be used to turn a turbine which creates electrical power. The uranium slowly degrades through nuclear reactions and must be replaced for the plant reactor to continue to produce energy.

When the fuel rods are first removed after use from a reactor, they are moved to temporary storage. This normally is simply a large pool of water. The water acts as both a radiation barrier as well as a coolant. The water level must be observed but for the most part these pools are left alone while the spent fuel cools for later permanent storage.

The ultimate end of the open fuel cycle is disposal of the waste products of radioactive decay. At present a permanent long term storage structure has not been built in the United States. All current proposals revolve around a permanent geological disposal site in which the spent fuel would remain undisturbed for the billions of years it takes for the waste to decay to a safe material.

Closed Nuclear Fuel Cycle:

There are other possible manners in which the fuel cycle can be operated. The closed fuel cycle has been implemented in countries such as France both to limit the waste from nuclear power and to prolong the amount of energy extracted from a piece of fuel.

Open and closed fuel cycles very in only a handful of ways. Both cycles start with the mining of uranium ore that must be milled, converted, and fabricated into fuel rods. The first difference in the two cycles is what happens when the rods are removed.

In the open cycle the fuel is removed and then stored temporarily until ultimate disposal. In the closed cycle the fuel is also stored and cooled in a spent fuel pool, but is then removed to be reprocessed. The reprocessing removes the usable uranium and plutonium from the waste. The recovered uranium is then combined into the enrichment process to be used again. The plutonium can be combined with uranium and other byproducts to produce a mixed oxide fuel, MOX, to be used in MOX reactors. At present this is not used on a commercial scale; it is only used in research.

Environmental Impact of Mining and Milling:

The mining of uranium, like any mining operation, has inherent carbon dioxide emissions. Mining uranium produces a greater amount of carbon dioxide per unit mass mined than other metals due to the low concentrations of the ore over the surface of the earth. Uranium is more common than most metals; however, it is in very low concentrations, 0.18% - 2.29% even in Australia, one of the most uranium rich countries in the world. The two areas with the richest ores, Cigar Lake and McArthur River, are in Canada. Cigar Lake has an ore deposit with a purity of approximately 18.3% whereas McArthur River has a purity of approximately 14.3% {{12 Mudd,Gavin M. 2008}}. The mining of uranium ore can be done either through surface mining or through subterranean mining. These combined operations include open pit mines, traditional underground mines, in situ leach mining and heap leaching.

Uranium can be mined in a manner similar to coal, when the concentration of uranium ore is high enough to be economical. When the ore is near the surface, the mining company will make a large cutting into the terrain; open pit mining, which will then be used to harvest the raw material from which the uranium ore is extracted. Open pit mines emissions vary widely based on the concentration of the uranium ore.

The Rössing open pit mine in Namibia, west Africa, produces approximately 45.7 tons of carbon dioxide per ton of uranium oxide U_3O_8 with a purity of 0.034-0.041% {{12 Mudd,Gavin M. 2008}}. The Ranger Mine in Australia has a much higher purity (0.28-0.42%) but produces 14.1 tons of carbon dioxide per ton of uranium oxide {{12 Mudd,Gavin M. 2008}}. Cluff Lake with the highest purity of the three at 2.71%, produced the fewest emissions per unit of mass mined; 12.1 tons carbon dioxide per ton of uranium oxide. In all listed cases the emissions are for the combined mining and milling into pure yellowcake as both mining operations have an adjacent mill included in the emission values. The conversion to hex aspect of milling is not included in these emissions.

The mining process is similar when the ore is deep in the earth's crust. However, in underground mining only the earth containing the uranium ore needs to be extracted, so there is less earth moved. This makes the underground option more environmentally friendly; however, the working conditions in underground mines are also slightly more dangerous.

Underground mining operations are not normally exclusively uranium mines. Olympic Lake in Australia is a combination copper, silver, gold, and uranium mine. As such the official data shows the carbon dioxide emissions from the entire complex not strictly for the uranium mining. The estimate emissions associated with the uranium mining and milling of pure yellowcake at Olympic Lake is 50.4 tons of carbon dioxide per ton of uranium oxide with a purity of between 0.064% and 0.114% {{12 Mudd,Gavin M. 2008}}.

Australia and Canada are some of the few countries that use traditional mining techniques, as the purity of the ore in these countries is high enough for these processes to be economically feasible, whereas most countries lack the purity of either countries' deposits. Most countries must use one of the other following methods.

In situ leach mining removes small deposits of uranium that are widely dispersed though loose soil or sand. The process of in situ leach mining is simple. Oxygenated water that is slightly acidic or alkaline is pumped into the ground. The water is then pumped back out of the ground to be processed, having picked up small particles of uranium that will then be precipitated out for collection and further processing. This process is largely used in countries such as the United States where the uranium ore purity is low.

The emissions from in situ mining are lower than the other mining operations. The Beverley mine in Australia has a purity of only 0.18% but only produces 10.3 tons of carbon dioxide per ton of uranium oxide produced {{12 Mudd,Gavin M. 2008}}. This is less than the emissions from the highest purity open-pit mines, however it is unclear if these values include the milling of the uranium.

Heap leaching is a method that can be used in conjunction with either open pit mines or underground mines. Heap leaching is similar to in situ leach mining, except the process does not require that the soil be loose. Leaching out the uranium involves moving the raw material to an impermeable surface (to prevent loss of product), treating it with either an acidic or alkaline solution, and collecting it to be processed for uranium precipitates.

Heap leaching can also take place in large tanks. The Rössing mine batch loads the mined ore into large processing tanks. The tanks agitate the slurry of crushed ore containing rock and sulfuric acid {{15 Rössing Uranium Limited 2011}}. This slurry is then processed in the same manner as all heap leaching. There are no estimates for this process as it normally only used only in conjunction with another method of mining.

Environmental Impact of Conversion and Enrichment:

From the mine mill, the yellowcake is exported to countries such as the United States and France for conversation and enrichment. Conversation is largely a series of chemical reactions and thus takes little energy to happen and emits very little carbon dioxide. Conversion is estimated to produce only 0.2 grams of carbon dioxide per kilowatt-hour of electricity produced, accounting for approximately 0.9% of the total carbon dioxide produced by the life-cycle of a nuclear power plant in both the open and closed cycles {{1 Hondo,Hiroki 2005}}.

While the conversion to hex for enrichment does not emit much carbon dioxide, the actual enrichment process does. Both gaseous diffusion and gas centrifuges require a great deal of electricity to run. In the United States, where 70% of the electricity is produced by coal fired power plants, this means a huge amount of carbon dioxide is produced indirectly. Assuming that 67% of a sample is enriched in the United States and 22% enriched in France, both using gaseous diffusion, with the remaining enriched in Japan, the Netherlands, and the United Kingdom using gas centrifuges, approximately 15 grams of carbon dioxide will be produced per kilowatt-hour generated by the nuclear power plant accounting for 61.9% of the total emitted {{1 Hondo,Hiroki 2005}}.

Environmental Impact of Nuclear Burn-Up:

Unlike in a coal fired power plant, no carbon dioxide is produced directly during the production of electricity in a nuclear power plant. During the time a fuel rod is in the reactor, no carbon dioxide is released. It is a common misconception that the plumes of steam emitted from a reactor's cooling towers are either smoke or radioactive, neither of which is true. The steam that is released is simply that - steam. The steam was not exposed to the reactor core and thus is not radioactive.

While the steam release has no direct environmental impact on humans, it causes the same environmental damage that a coal fired power plant does in terms of affecting the cooling water source. Federal law in the United States control the increase in temperature from the inlet to outlet, however even a small change in temperature causes a change in the water source. While this is an environmental impact, it is not necessarily a problematic impact, and can be controlled easily within the confines of federal law.

Environmental Impact of Storage of Nuclear Waste:

When the used uranium (spent fuel) is removed from the reactor, it is moved to a spent fuel cooling pool. The fuel will remain in this state for 10 years before moving to either long-term temporary storage or to a reprocessing plant {{5 Sovacool,Benjamin K. 2008}}. There is very little environmental impact due to the storage in cooling pools as they are mostly automatically maintained; however the fuel that is not to be reprocessed is moved to dry storage.

The dry storage of the spent fuel moves the fuel into steel lined concrete drums that are then filled with helium to keep everything inert {{5 Sovacool,Benjamin K. 2008}}. The fuel continues to produce heat while in storage thus necessitating the drums to have cooling fins and not be packed together tightly{{5 Sovacool,Benjamin K. 2008}}. This manner of the storage of the spent fuel makes up a significant percent of the total carbon dioxide emissions of the life cycle (2.9%){{1 Hondo,Hiroki 2005}}. This can be reduced by reprocessing the fuel.

Reprocessing the fuel decreases the carbon dioxide emissions by 1.9% directly, but only by 0.8% when factoring in the entire disposal of waste, low level waste for both methods, and high level waste for the reprocessing method{{1 Hondo,Hiroki 2005}}. The final disposal of waste's environmental impact cannot be estimated with any reliability as there is currently neither a permanent disposal site nor protocol.

Environmental Impact of Nuclear Power Plant Construction:

Construction of a new nuclear power plant is a major undertaking from a legal, environmental, or capital standpoint. At present the United States Nuclear Regulatory Commission (NRC) is developing new licensing protocols to allow for a more streamlined licensing process. The environmental impact is that of the construction of a new industrial complex; the size of this complex directly determines the capital investment needed.

In 1989 the NRC established the new licensing protocol, which is still considered only under development as it has not yet been used to license a new plant. This new process supersedes the two-step licensing process, a construction permit and an operation license, with a combined license for construction and operation. This process includes: a safety review of the design of the reactor, an environmental impact study, and an anti-trust review. Each review is a major undertaking in terms of time and committed resources. After all reviews are completed, a public hearing allows for input from the public as well as a defense from the utility seeking construction. The licensing process takes an average of three years to complete, based on data from the two-step process for a construction permit. While there is not a direct environmental impact due to the length of the licensing process, the time spent is more time where the United States is using primarily coal to produce electricity.

The environmental review completed by the NRC looks at the environmental impact of the plant after completion. This is valuable, however, it mostly focuses on the radiological environmental impacts. The construction of a nuclear power plant on average requires between 32,000 and 66,000 tons of steel, 44 miles of piping, and 300 miles of electrical wiring {{16 Nuclear Energy Institute 2009; 5 Sovacool,Benjamin K. 2008}}. The manufacturing of each component has an environmental impact associated with it. The combined impact of these components is approximately 2.8 grams of carbon dioxide released per kilowatt-hour making up 11.7% of the total emissions from the life of a nuclear power plant {{1 Hondo,Hiroki 2005}}.

Comparison of Environmental Impact from Nuclear and Coal Fired Power Plants:

As with any fuel cycle, the first step is always procurement of the necessary raw material, in the case of a nuclear fuel cycle, mining of the uranium ore. In a fossil fuel cycle there is not a large amount of greenhouse gas released in mining compared to the final output; however in the nuclear fuel cycle mining is one of the steps with the largest number of emissions. In a coal fired power plant mining releases an estimated 9.7 grams of carbon dioxide per kilowatt-hour generated compared to the estimated 1.1 gram per kilowatt-hour estimated for uranium mining and milling. In the nuclear case this amounts to 4.5% of the carbon dioxide release compared to 1.0% in the case of coal {{1 Hondo,Hiroki 2005}}.

The construction of a coal fired power is much shorter process and is completed much more quickly. This is not to say that the emissions are less just because it is quicker; quite the opposite in fact. The estimated carbon dioxide emissions from the construction of a coal fired power plant are 3.6 grams per kilowatt-hour {{1 Hondo,Hiroki 2005}}. In the construction of a nuclear power plant the estimates are 2.8 grams of carbon dioxide per kilowatt-hour {{1 Hondo,Hiroki 2005}}.

The environmental impact from a coal fired power plant in operation is like the emissions from construction in that they are higher than nuclear; however unlike construction they are magnitudes larger. In the electrical generation stage in a nuclear power plant 3.2 grams of carbon dioxide are produced per kilowatt-hour; there are no direct emissions during this stage however the operation of the plant requires an outside electrical source {{1 Hondo,Hiroki 2005}}. In the generation stage of a coal fired power plant 6.7 grams of carbon dioxide are produce per kilowatt-hour {{1 Hondo,Hiroki 2005}}. This number does not seem to show a significant difference between the two plants because it does not include the carbon dioxide emissions from the actual combustion of coal. When the carbon dioxide produced by the combustion of coal is taken into account, 886.8 grams carbon dioxide per kilowatt-hour, the total of 893.5 grams of carbon dioxide per kilowatt-hour shows the true difference in carbon dioxide emissions {{1 Hondo,Hiroki 2005}}.

Coal produces more carbon dioxide per kilowatt-hour in every category except one. In a nuclear power plant there is the need to store and maintain spent fuel. In a coal fired power plant there is the need to contain and dispose of the ash that is produced. The disposal of the ash is not at all significant to the amount of carbon dioxide released. The estimated emissions are less than 0.1 grams per kilowatt-hour {{1 Hondo,Hiroki 2005}}. Nuclear power plants have the issue of maintaining the spent fuel, which requires energy. In the current (open) system there is an estimated 0.8 grams of carbon dioxide emitted per kilowatt-hour produced to store the fuel {{1 Hondo,Hiroki 2005}}. In the closed cycle this is decreased to 0.5 grams per kilowatt-hour {{1 Hondo,Hiroki 2005}}. While in this area coal is the better option, the emissions are very small and thus there is not ground to truly argue over the change.

Conclusions:

There are several studies published, in both trade and peer-edited journals, that show that nuclear power is both a viable and highly recommended method to decrease carbon dioxide emissions, however, there are some drawbacks not directly related to the environmental impact from the nuclear power plant. The lack of a permanent depositary for the spent fuel has left many people questioning the industry. The lack of the depository can be linked to the public's fear of radiation, however even without it the fear remains. In that manner coal is the much better option as it is perceived by the public to be safer.

In a strictly environmental approach, the obvious choice would be to convert more of the current base-load generation of electricity to nuclear power as it releases very little carbon dioxide throughout its lifecycle. The total release of carbon dioxide (24.2 grams per kilowatt-hour in the open cycle) is approximately 3% of that of the lifecycle of coal power plant (886.8 grams per kilowatt-hour) {{1 Hondo,Hiroki 2005}}.

Overall the choice is still vague, given the capital investment needed, however, the case can be strongly made that nuclear power the best single solution to decrease the output of carbon dioxide from electricity production. As a means to lower carbon dioxide emissions while maintaining the current standard of living nuclear is the best single choice.

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