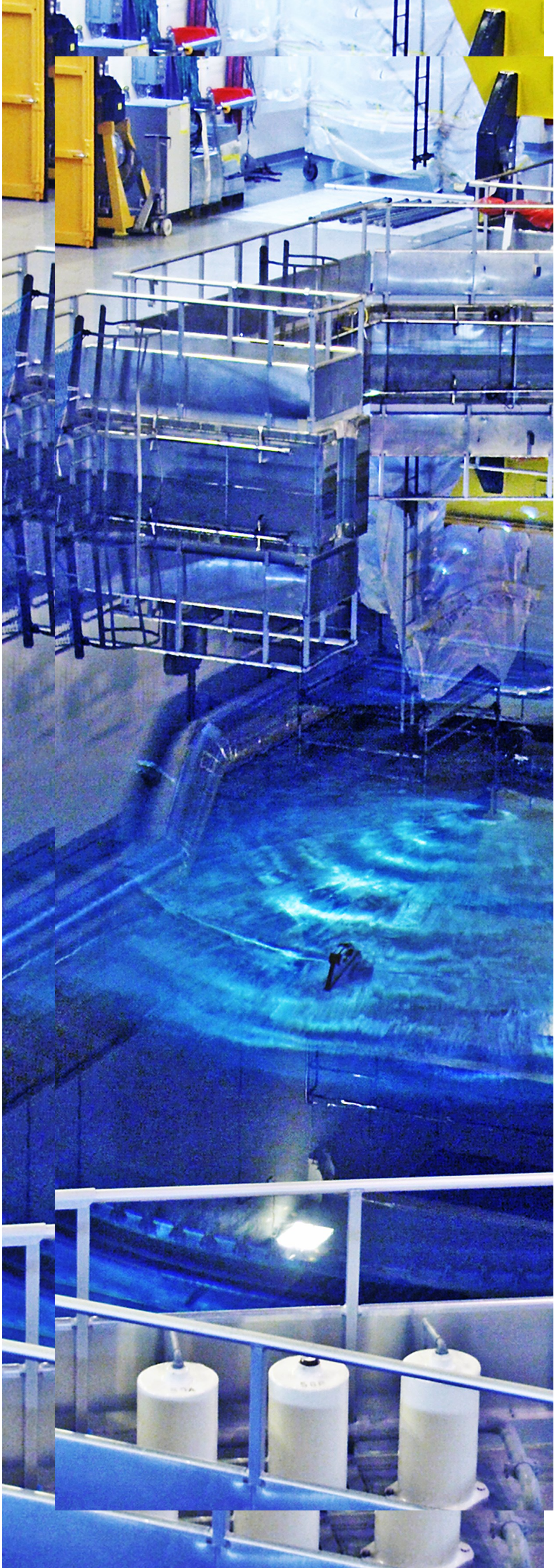

environnementalisme réaliste

projet gaia project

realistic environmentalism

Electricity Generation: Nuclear Fission

The Gaia Project
270 Rookwood Avenue
Fredericton, NB
E3B 2M2

1 (506) 442-9030
www.thegaiaproject.ca
contact@thegaiaproject.ca

Electricity Generation: Nuclear Fission
An overview of electricity generation by Nuclear Fission.

The Gaia Project is a charitable organization whose mission is to empower informed decisions about energy and its impact on the environment. We are dedicated to providing project-based learning opportunities in the areas of energy, environment and sustainable engineering.

We develop projects, provide professional development, technical support and ongoing project support for teachers and students throughout New Brunswick. Our projects aim to incorporate three key principles, which symbolise our focus on realistic environmentalism:

1. **Data-Informed Decisions** – We want students to be able to explain why, and quantify the effect of each decision they made along the way to their final solution.
2. **Economic Assessments** – We expect students to be able to assess the cost effectiveness of their solutions, and be able to optimize their projects with limited budgets.
3. **Environmental Impact and Lifecycle Assessments** – We need students to take a holistic view to their projects. This means looking at their projects from cradle to grave, as opposed to just examining the use phase, and acknowledging that greenhouse gas reduction is not the only environmental issue at stake.

For more information, please visit www.thegaiaproject.ca

The Gaia Project
270 Rookwood Avenue
Fredericton, NB
E3B 2M2
Canada

1 (506) 442-9030
contact@thegaiaproject.ca

The development of this series of documents was supported by the following funding partners:
- The McCain Foundation
- NB Power
- National Science and Engineering Research Council's PromoScience Program
- New Brunswick Department of Environment and Local Government's Environmental Trust Fund Program
- Government of Canada's Canada Summer Job Program

Front Cover Credits

Introduction

We often don't think about where the electricity we use in our lives comes from. The industry and infrastructure behind the production and delivery of electricity into our lives is vast and complex and each component can have social, economic, and environmental consequences.

This document will explore the processes, costs and environmental impacts associated with generating electricity from nuclear energy. It is part of a series of documents designed to simplify the complex electricity generation industry and covers fossil fuels, water power, solar power, wind energy, nuclear energy, biomass, tidal sources, and geothermal energy all in an international, Canadian, and New Brunswick context.

For details concerning each type of electricity generation, please consult the appropriate generation document and the **Generation Technology Comparison Table.** This document series is designed for teachers, upper level high school students, and curious members of the public wishing to know more about how electricity is generated in New Brunswick. This series is not designed to isolate the "best" or "worst" technologies; rather, its purpose is to facilitate the comparison between the available electricity generation options with *the goal of providing clarity and a foundation for energy literacy*. Information has been collected in these documents to allow the reader to draw their own conclusions about energy and how it relates to society.

At the Gaia Project we believe that different individuals face different challenges when trying to reduce their impact and the first step to recognizing these challenges is through access to unbiased information. This is central to our principle of realistic environmentalism, an approach that recognizes the social, technological, environmental, and economic aspects of any solution identified to our energy problems.

Nuclear fission is the process of splitting the nucleus of an atom into smaller parts. This process releases free neutrons and photons, as well as a huge amount of energy that can be used for electricity generation.

History

The early 20^{th} century saw the discovery of the process of nuclear fission. Between 1919 and the 1930s, scientists were discovering the parts of the atom's structure. In 1919, Ernest Rutherford discovered protons – positively charged particles located in the nucleus of the atom, an achievement he later won a Nobel Prize for. Electrons – negatively charged particles – make up the other portion of the atom by orbiting around its center.

The complete picture, however, wasn't yet clear because elements could weigh differently based on the sample. In 1932, James Chadwick helped resolve this by discovering the neutron – a subatomic particle without charge. Neutrons are found in the atom's nucleus along with protons.

The number of protons and electrons are always the same for any given element, but the number of neutrons can differ. **Isotopes** are different forms of elements that can have differing numbers of neutrons and therefore different atomic masses. Isotopes became the key to producing large amounts of energy from nuclear fission (the explanation as to why can be found in the Process section below).

The possibility to harness energy from splitting atoms seemed immense, and the first particle accelerators were designed to work towards achieving this. Early particle accelerators fired protons at nuclei, though these protons were repelled by the positively-charged nuclei. Enrico Fermi (also a Nobel Prize winner for his work in nuclear physics) tried a different approach and successfully shot neutrons at atoms to split them. This was successful because atoms didn't repel neutrons—neutrons have no net charge. The process of nuclear fission was officially discovered in 1938 when Otto Hahn (again, a Nobel Prize winner) and Fritz Strassman used this process to split uranium. Strassman was Hahn's student and some debate still exists as to whether credit should go to Lise Meitner also, who was one of Hahn's other students working on the project.

Nuclear fission has been controversial since its discovery. While the tremendous amounts of energy produced by this reaction can be used to generate electricity and be used for other peaceful activities, it has also been used for the development of the atomic bomb.

Alongside the development of nuclear science for use in weaponry was the possibility of fission providing electricity. On December 20, 1951 electricity was first generated by a nuclear reactor in Idaho, producing about 100 kW. In 1954, the Obninsk Nuclear Power Plant in the former USSR came online and was the first nuclear power plant to produce electricity for a power grid, generating around 5MW, a 50-fold increase from the reactor in Idaho[1].

Process

As previously discussed, nuclear fission is the process of splitting an atom by bombarding it with neutrons - a process that releases a great deal of energy. When a neutron strikes a nuclei and breaks it apart, two (or more) new atoms are created, these are called fission products (**Figure 1**).

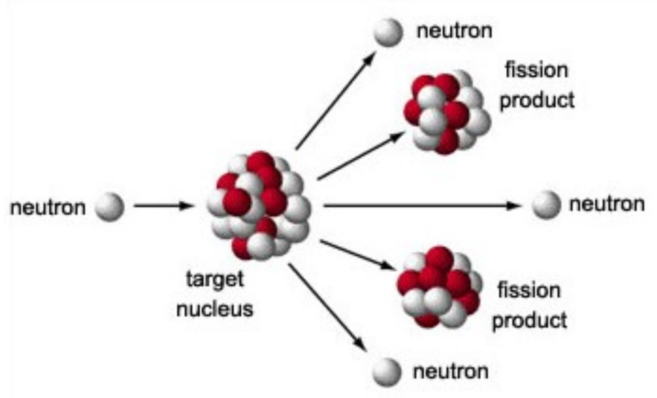

Figure 1. Nuclear fission cascade. Via: http://www.atomicarchive.com/Fission/Fission1.shtml

The sum of the masses of these new atoms is minutely smaller than the mass of the original atom. The reason for this was discovered by Einstein, and is explained by and lives on through the very famous equation: $E = mc^2$. Einstein proposed that energy and mass were the same thing, and that energy (E) had mass (m) and that mass had energy.

The 'c' in the equation stands for the speed of light, which at 300,000,000 m/s is the key to the whole nuclear process. It means that a very small amount of mass contains a massive amount of energy since the mass is multiplied by $300{,}000{,}000^2$ or 9×10^{16} m^2/s^2.

The tiny difference between the masses of the atom beforehand and the sum of its products was actually energy. It was energy that held the atom together – that bonded the particles in the nucleus. When the atom is broken apart, that energy is released – and since energy has mass, that mass is missing from the final

U-235 + 1 Neutron → Ba-127 + Kr-97 + 2 Neutrons

products. Consider the fission of Uranium 235 below (the letter is the element abbreviation and the number following it is its molecular weight):

The total number of protons and neutrons

235.0439 + 1.00867 → 136.9061 + 96.9212 +2(1.00867)

across the reaction is conserved, however, when the masses of the products and the reactants are considered (units not necessarily important):

It can be seen from simple addition on both sides that there is a mass difference of 0.2082. This mass has been converted into energy according to $E = mc^2$. The energy released is roughly 8.6×10^{-18} kWh, which is a tiny amount but quickly adds up considering the number of reactions occurring in a reactor (1 gram of Uranium has about 2.6×10^{21} atoms of U-235). The energy itself is released as heat.

A nuclear reaction is based on the idea of a chain reaction. When some matter is bombarded with neutrons, and break up, the newly freed neutrons are likely to strike another nucleus and break it up – causing a chain reaction (cascade).

The difference between a nuclear explosion and a nuclear reactor is that the chain reaction in the first is uncontrolled (meaning it expands rapidly), while in the second it is controlled (meaning it is designed to maintain the same level, or slow down over time).

The heat from the nuclear reaction is used to create steam in exactly the same way as fossil fuels are used to create steam. Outside of the nuclear reaction, the process for electricity generation is virtually identical to a coal-fired power plant.

Fuels

Nuclear reactors use Uranium as a fuel. In nature, Uranium is comprised of 99.27% U-238 (bearing 92 protons and 146 neutrons) and 0.72% U-235 (with 92 protons and 143 neutrons). Uranium 235 is a naturally fissile (easily split) element; if bombarded with neutrons, it can sustain a nuclear chain reaction. In nuclear power generation, the splitting of U-235 provides the bulk of the heat for electricity generation. U-238 and the **daughter products** of U-235 also play a role in the production of heat in nuclear reactors as they are then bombarded by neutrons (and other particles) released from the decay of U-235 that can cause them to break apart.

Uranium as found in the earth's crust must undergo a variety a chemical processes in order to be incorporated into a nuclear reactors' fuel bundle (**Figure 2**).

Figure 2. Uranium fuel pellets and a Zirconium fuel bundle. Via: http://www.virginmedia.com/digital/science/pictures/nuclear-fuel-cycle.php?ssid=7

As the radioactive element of interest, U-235, is only present as 0.7% of present Uranium many reactors require enriching the U-235 content to between 3-5% by mass. The technology to enrich Uranium is controversial because it can be used to produce weapons-grade (90% U-

235) Uranium. Some reactors can use natural Uranium as fuel (see the section on *Types of Nuclear Reactors*).

Some people will argue that nuclear fuel is in short supply globally, with estimates suggesting less than 100 years of supply currently available[2]. These estimates are usually given as the amount that is **economically recoverable** at the current price, so generally these numbers have to be viewed cautiously. Generally, as demand increases and supply decreases, the price will go up. As the price goes up, miners look at their mine and determine that with the new higher prices they can afford to go after areas of the mine that were more costly to extract either because the concentration was lower or were hard to access. The amount of the resource that is economically recoverable has increased. So as price increases, so generally do the estimates of recoverable reserves. This is a vastly different number to the actual amount of uranium (or any other mined resource) that is actually in the ground.

It is estimated that a doubling of the price of Uranium would increase the available global supply by ten-fold. Unlike fossil fuels, where the cost of fuel would have a major impact on the price of power being generated, nuclear power plants see very little difference in their costs even with large increases in the fuel price. This is because nuclear power plants are able to generate large amounts of energy from very small amounts of fuel, and that the majority of their costs are tied up in the construction of the power plant in the first place.

Australia is estimated to possess roughly 25% of the world's total Uranium containing ores., however Canada was the world's leading producer until Kazakhstan surpassed it in 2008. Overall, quantity is important, though quality must also be considered. Uranium exists as a fraction of the total mass of the ore that it is found in, and depending on geology and physical location, ore grades as low as 0.02% Uranium can be profitable to extract—several mines in Saskatchewan boast the highest Uranium ore grades in the world, ranging from 17-24%[3]. This high concentration means that the McArthur River mine in Saskatchewan is the largest Uranium mine in the world (**Figure 2** on previous page).

Types of Nuclear Reactors

There are a variety of different types of nuclear reactors on the market that differ in the way that the reactor is cooled, or the type of fuel that is used. Described below are heavy water reactors (CANDU, **Figure 3**), light water reactors and small modular reactors.

Figure 3. CANDU reactor face showing fuel channels. Horizontal fuel channels allow the reactor to be refuelled without having to be shut down. Via: http://www.nuclearfaq.ca/cnf_sectionA.htm

A reactor of Canadian design, the CANDU series, is installed at the Pt. Lepreau generating station on the bay of Fundy. It uses heavy water (water whose hydrogen atoms have one extra neutron) as a **moderator**, a substance that slows down and removes energy from liberated neutrons. Moderating neutrons is necessary to ensure they are travelling the ideal speed (not too fast or slow) to ensure a subsequent radioactive decay event upon impact with a nucleus.

Heavy water doesn't absorb as many of the neutrons it interacts with (compared to normal water) and so CANDU reactors can use non-enriched Uranium as a fuel source. The neutrons produced from the fission of the 0.7% U-235 are not lost to absorption in the moderator itself (heavy water), which means more are free to cause subsequent decay events with nuclei they interact with. The heavy water circulates around the radioactively decaying fuel bundles thereby extracting its heat. This heated pressurized water then exchanges its heat to a separate cooling water stream which produces steam to drive a turbine - the same type of process as a typical thermal plant.

Because these reactors use non-enriched Uranium they are often cited to be of a lower risk in countries where there is fear that the uranium could also be used to build nuclear weapons, as it is significantly harder to use non-enriched uranium in weapons.

A separate, more common class of reactors uses normal water as the moderator and slightly enriched Uranium as the fuel. Normal water slows neutrons down to the correct speed, but in the process absorbs some of them. This decreases the number of neutrons available for causing subsequent decay events. To ensure a nuclear chain reaction, Uranium enriched to 3-5% U-235 is used to provide more neutrons.

Another class of reactors being developed are the small modular reactors (SMR). These generally produce less than 300 MW of power and are built in easy to install modules at the factory; this approach means the reactors are relatively simple to put together and take much less time. Advantages of SMR's are that they require reduced staffing, are often designed with inherent passive safety systems (fewer coolant pumps, convection circulation), and are small so they can be more easily transported.

Much interest has been focused on SMR's for their thermal heat output (steam or hot water) as well as the electricity that can be generated. Desalination and tar sands oil extraction are industries that require large amounts of thermal energy—SMR's can provide this in the form of steam with a relatively reduced site footprint and no ongoing carbon emissions. Some proponents envision SMR's the size of a small house that could be taken to remote or northern communities for local power generation.

In response to concerns over total Uranium reserves and the issue of nuclear waste (discussed in more detail later in this document), renewed interest has been given to the concept of breeder reactors. As only 0.7% of a Uranium fuel sample is relied on to produce electricity (in a CANDU system), much of the actual fuel mass ends up as radioactive nuclear waste which must be carefully disposed. Breeder reactors are designed to turn much of the Uranium 238 and subsequent decay products into fissile elements themselves. As neutrons and other particles are emitted due to radioactive decay, they interact with a variety of elements in the fuel which each produces a thermally valuable radioactive decay event. In this sense, fewer of the atoms are "wasted" and many more participate in the production of useful heat. Also, much less material remains after burn up is complete.

Energy in a Nuclear Reaction

A significant advantage of nuclear energy is the immense amount of energy that can be extracted from a relatively small mass of fuel. The energy produced from the fission of a single U-235 atom is small, but when many of these events occur in kilogram-sized fuel bundles, a considerable amount of energy is released—just 143 grams of natural uranium contains about 1 gram of U-235 and completely using this fuel in a reactor produces about 23,110 kWh of energy. This is enough to power the average Canadian home for 9.5 months. It would take approximately 8-9,000 times as much fossil fuel mass to achieve the same amount of energy output – specifically burning 1300 kg of coal or 1400 litres of oil would release the same amount of energy.

A 1000 MW light water reactor, a design common in the US, uses about 24 tonnes of Uranium enriched to 4% U-235 in one year. This requires roughly 200 tonnes of natural Uranium to be mined from 20,000 tonnes of Uranium ore. For comparison, a coal-fired plant of the same output uses roughly 3.2 million tonnes of coal over the same period.[4]

Size

Nuclear reactors tend to be constructed in very large units, typically in the 800 to 1000MW range for a modern reactor. As they are commonly used for baseload generation, the larger the reactor ensures that a large proportion of the grids demand is met almost constantly throughout the year. Nuclear reactors operate with **capacity factors** above 90 -95%. Larger units also benefit from economies of scale , ensuring high efficiencies per unit. Many units can co-exist on the same site, such as the seven units at the Kashiwazaki-Kariwa Nuclear Power Plant in Japan producing 8,200MW.

Some of the disadvantages of a large nuclear reactor are its prohibitive upfront cost investment and danger in the case of an accident. Small Modular Reactors, as described above, help alleviate both of these concerns.

The average size of nuclear reactors in operation today is 850 MW. The average size of newly constructed facilities is larger, however.

Installed Capacity

Nuclear power currently provides about 13-14% of the world's electricity[1]. As of the first of January 2010, nuclear power had a global installed capacity of 370 GW from 437 power reactors and total electricity production ranged between 2,544 and 2,661 TWh[5]. **Figure 4**, below, describes the proportion of nuclear energy in various regions around the world.

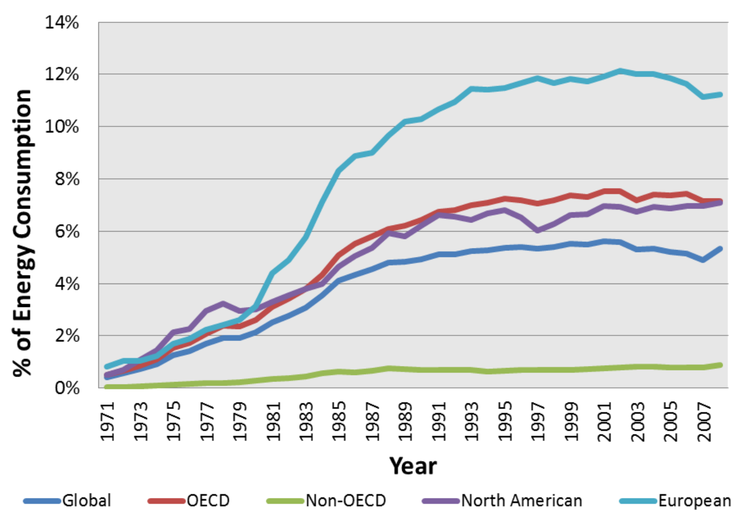

Figure 4. Proportion of energy consumption met through nuclear energy.

The planning, development, and construction of new nuclear power plants has seen a large amount of variability in the last 30 years.

Accidents like Chernobyl and the more recent Fukushima Daiichi (discussed later) serve to slow the approval of new projects and increase the participation and oversight of regulatory agencies. Changing prices of fossil fuel resources and the general strength of the economic climate also contribute to the feasibility and attractiveness of new nuclear projects, especially from a business or industry perspective. A combination of these factors led to the general slowing of nuclear development at the turn of the century (see **Figures 5** and **6** below), with 2008 being the first year since 1955 where no new capacity was added to the grid.

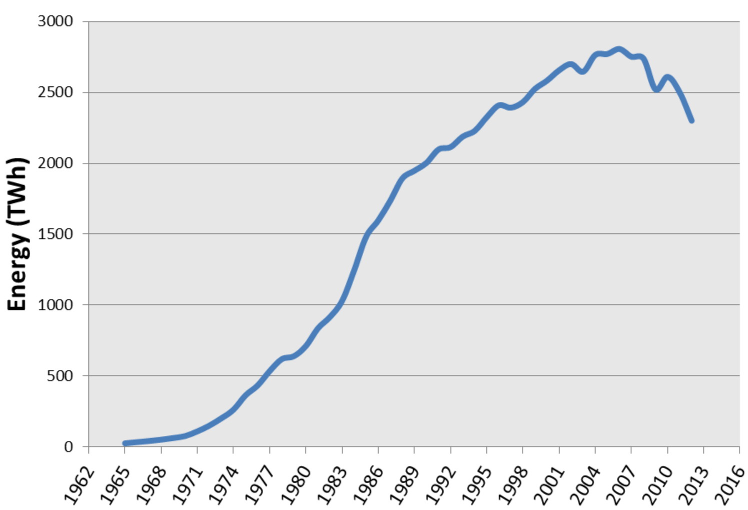

Figure 5. Annual Global Nuclear Energy Consumption.

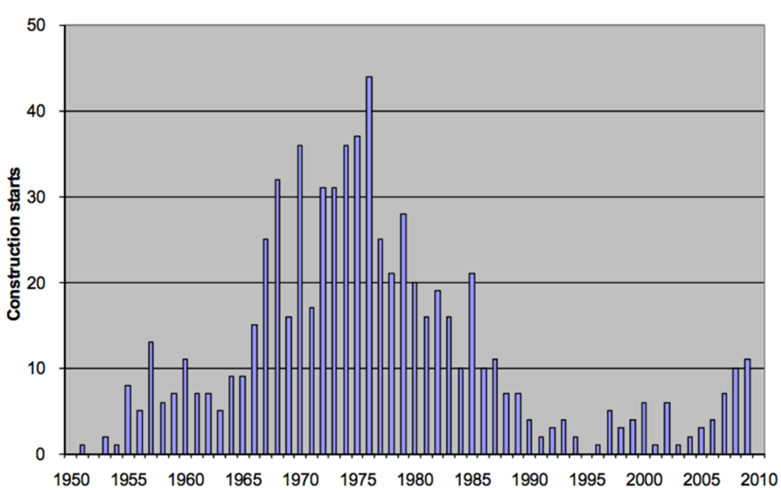

Figure 6. Global Construction Starts of New Nuclear Plants[1]

This trend is particularly true in north America and Europe. The industry is picking up again, however, particularly in Asia. As of 2013, there are currently 60 facilities under construction globally, 150 firmly planned and many more at the initial stages of development.

New Brunswick

The Point Lepreau Generating plant, New Brunswick's first and only nuclear reactor, began production in early 1983 (**Figure 7**).

Figure 7. Point Lepreau generating station. Via: http://www.cnwc-cctn.ca/new-brunswick-power/

It has an installed capacity of 635 MW_e, an average capacity factor of 82% and provides 25-35% of the provinces electricity needs. At the end of its intended 25-year life in 2008, a refurbishment project was undertaken to ensure another 25 years of production; the refurbishment was $1.3 billion over budget and took 3 years longer than expected but generation resumed in November of 2012. The refurbishment project was the first performed on a CANDU 6 reactor.

There are no current plans for the expansion of nuclear power in New Brunswick, although there have been proposals for additional reactor capacity that have been considered.

Capacity Factor

Due to the extremely high cost of construction, and the relatively low cost of fuel compared to fossil fuel plants, it makes economic sense to run a nuclear power plant as much as possible once it is constructed since the increased cost of operation is minimal.

For this reason, nuclear power plants tend to have the highest capacity factors of any type of power plant on the grid. It is fairly typical to see a capacity factor exceed 90%, with downtime required only for maintenance and repairs.

In addition, the nature of the nuclear reaction makes it so that nuclear reactors take a long time to start and stop (typically in the order of weeks under normal conditions), so it isn't feasible to be constantly changing the amount of production.

The Nuclear Energy Institute estimates the US's average capacity factor at 91%, which has improved greatly from previous decades due to improvements in reactor technology. In 2004, Canadian CANDU reactors had an average capacity factor of 78.17%. The average capacity factor of Pt. Lepreau prior to its refurbishment was 82%; the predicted capacity factor of the facility over its 25 year post-refurbishment life is 89%, which is higher than before the refurbishment, but slightly lower than would be expected from a brand new nuclear plant.

Cost

As Nuclear plants are one of the most complex engineering technologies, they have high 'front-loaded' costs – they are relatively expensive to build making it an investment risk. They all have extensive regulatory frameworks that must be abided by and have characteristically long payback periods. However, once built, they are inexpensive to run – the cost of uranium as fuel is only about 5% of total generating costs[5]. As shown in **Figure 8** below, as fuel costs increase there is less of an increase in generation costs for nuclear energy as compared to gas or coal. This makes nuclear power one of the cheapest forms of baseload electricity generation in most markets.

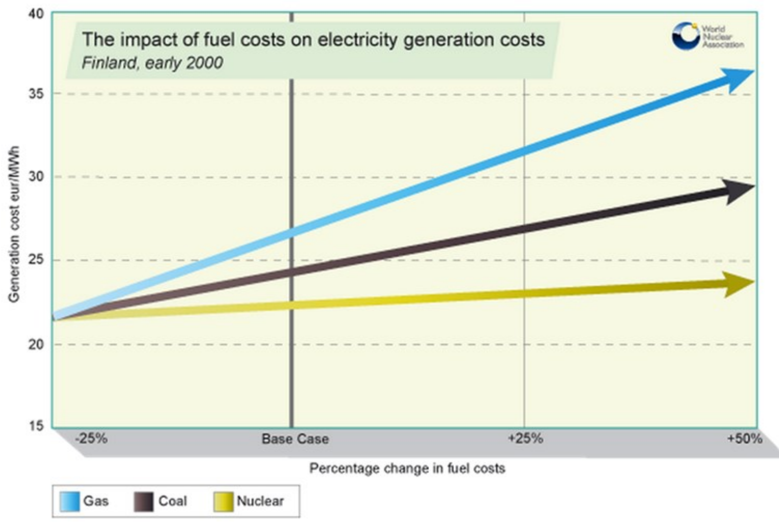

Figure 8. The impact of fuel costs on electricity generation costs.[6] Fuel costs increase to the right and decrease to the left. The vertical axis shows the cost of generation in euros/MWh.

The World Energy Council's 2010 Survey of Energy Resources lists the main costs of nuclear power as:

- Initial costs of construction
- Financial factors including interest and discount rates, return on equity
- Fuel prices
- Decommissioning costs
- Spent fuel management
- Energy and environmental policies.

Future

Nuclear power is being considered by many countries for three main reasons[5]:

- Predictable and stable long-term generating costs
- Energy security
- Climate change mitigation benefits because generation is not associated with greenhouse gas emissions

Nuclear power phase-out policies exist in several European countries, although many countries are now extending the time by which these policies would come into place. Sweden is allowing existing reactors to operate until the end of their economic lifetimes and Belgium has postponed the first of its 10-year phase-out policy[5]. The Fukushima Daiichi disaster in 2011 caused a reshaping of many national policies concerning nuclear energy development. Within a very short time, Germany permanently shut down 8 of its oldest reactors, with the remainder being phased out by 2022. Italy reaffirmed its ban on operating nuclear reactors (although it buys nuclear energy from neighbours), while Switzerland and Spain banned the construction of new reactors.

Asia is largely seen as the center of growth for nuclear energy into the future. In east and south Asia, there some 44 reactors under construction, plans to build 92 more and serious proposals for another 180. China and India in particular have vast programs to make nuclear energy a bigger part of their electricity generation infrastructure. China has 26 reactors under construction, 51 planned and 120 proposed while India has 7 under construction, 18 planned and 39 proposed.

Canada has plans to build two new reactors at its Darlington site in Ontario, while plans for additional reactors at Point Lepreau and Alberta have fallen through. The proposed Darlington reactors are scheduled to come on-line in 2018.

Environmental Impacts

Radioactive Waste

One of the main concerns associated with electricity generated by nuclear fission is that the products of these fission reactions are very radioactive and remain so for a very long time. The different radioactive decay products have different **half lives** and are thus dangerous for different lengths of time. The half lives of the decay products of U-235 can range from milliseconds to millions of years. Thus, the radiation health hazard of radioactive waste decreases over time. After 10,000 years, the level of radiation emitted from high level radioactive waste (used fuel) is 0.01% of the level one month after removal from the reactor.

Radioactive waste can be low level (requiring protective clothing), intermediate level (requiring air filters, containment equipment), and high level waste including **spent nuclear fuel**. Used nuclear fuel is typically kept on site for at least ten years in a containment pool to dissipate the most intense radiation and remove heat (a picture of the containment pool at the Forsmark nuclear plant in Sweden is included on the cover of this document). After this, the waste is mixed with a solid, inert binder to make a pellet that can be encased in cement and steel and permanently stored (**Figure 9—next page**). Liquid wastes are dried

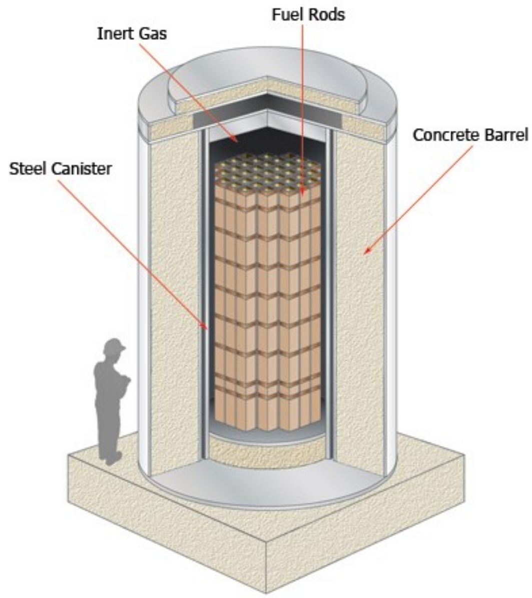

Figure 9. Diagram showing a spent nuclear fuel canister. Via: http://discovermagazine.com/2011/jun/06-hardcore-nuclear-waste-container-airplane-crash#.Un01__k3vAk

and added into a glass matrix for solid storage. As the volume of waste is so small, these casks can be stored on site as radiation declines until a more permanent storage option becomes available.

A 1000 MW_e reactor produces around 27 tonnes of used fuel per year (volume of 20 cubic meters) and 200-350 cubic meters of low and intermediate waste. The volume of spent fuel increases to 75 cubic meters if encapsulated for storage. Reprocessing of used nuclear fuel can reduce this waste stream to around 3 cubic meters of spent fuel (with a total capsule volume of 28 cubic meters). A coal plant of the same power output yields around 400,000 tonnes of ash per year[6].

Long-term disposal or treatment of nuclear waste is still an ongoing issue. The current scientific consensus focuses around deep geologic disposal where solid fuel casks are stored in very deep, very non-reactive and stable rock formations for 10,000 or more years. The geology of these locations is very important and must be away from any fault lines and be naturally dry (at the depth of interest). Finland and Sweden are developing a deep geologic repository through consultations with communities; due to the many permanent jobs created, several communities have come forward as competing candidate sites. Similar repositories have been planned elsewhere, including the US, but the approach of the planning bodies has been partly blamed for their failure (or slow development); in the case of the US, several sites have been chosen independent of the host communities willingness, this has created stiff opposition. Canada has proposed its own deep geologic repository in Tiverton on the Bruce peninsula of Ontario, it is currently progressing through the approval process with an intended completion date of late 2014[7].

Some jurisdictions, such as Japan, Europe, and Russia, reprocess the used nuclear fuel coming from reactors. This involves the separation of U -235 and Plutonium from the spent fuel (together representing roughly 95% of the energy contained in the original fuel, only 5% is used) and its subsequent mixing with depleted Uranium to make new usable fuel. This process requires energy, but ultimately requires less new Uranium and generates fewer end wastes.

Lifecycle GHG Emissions

While no GHG emissions are released during the generation stage of a nuclear power plant, there are emissions associated with the construction of the power plant in the first place and with the mining and processing of nuclear fuel.

However, the very high capacity factor of nuclear power stations means that the emissions per unit of energy generated are typically very low, with many life cycle assessments showing it to be cleaner than both wind and solar power generation.

The life cycle greenhouse gas emissions from nuclear power are similar to those for renewable sources of energy – below 40 g CO_2-eq/kWh[8]. As not all greenhouse gases are carbon dioxide, lifecycle GHG emissions are presented as carbon dioxide equivalent (equal to the effect of a certain amount of carbon dioxide). For example, one molecule of methane has 21.4 times the greenhouse gas effect of one molecule of carbon dioxide. See **Figure 10** opposite for a comparison of the GHG emissions over the full lifecycle of several electricity generation technologies.

Large Scale Nuclear Disasters

Two issues that keep nuclear energy in the spotlight are nuclear meltdowns and large-scale nuclear disasters. These are infrequent events, and there are many safeguards to ensure they don't occur in the future, but accidents have happened. Below are several of the highest profile accidents that have occurred.

One of the two reactors at the Three Mile Island plant in southern Pennsylvania suffered a partial nuclear meltdown in 1979. After an initial non-nuclear system failure, a reactor coolant release valve was stuck open which resulted in the loss of coolant for the reactor. This caused temperatures to increase unchecked; at the same time plant operators did not properly heed warning systems. Eventually, radioactive primary coolant (water) was released into the containment building, which was outside the normal radiation perimeter. The reactor was eventually contained and the actual discharge of radiation to the environment is believed to be minimal.

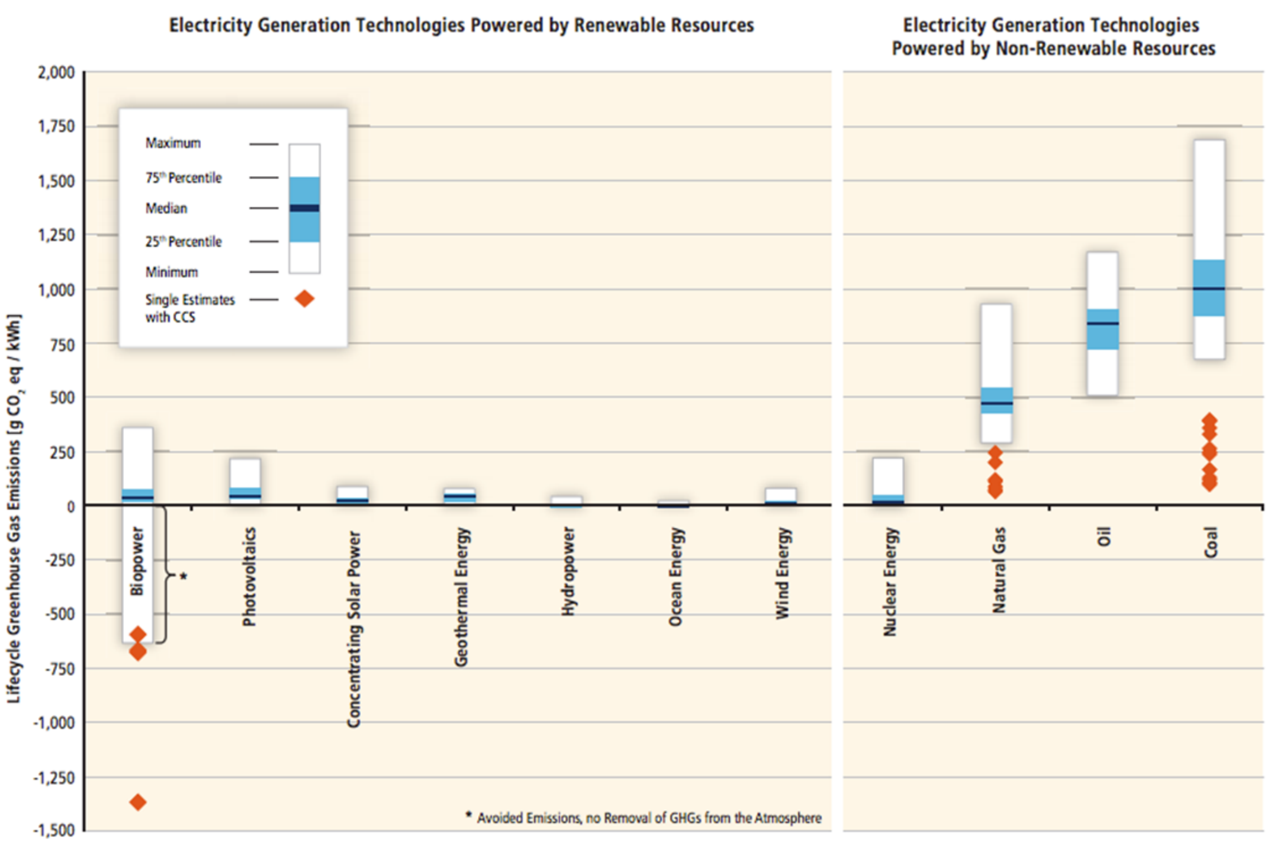

Figure 10. Lifecycle GHG Emissions Intensity of Electricity Generation Methods.[8]

Roughly 140,000 people voluntarily evacuated a 20km perimeter to the plant while many more residents remained. A variety of studies that were commissioned after the accident have found that there are no measurable health effects relating to the disaster. The event did serve to propagate concern concerning nuclear power, however.

Perhaps the most widely known nuclear accident is that which occurred at the Chernobyl plant near the Belarus border in present day Ukraine in 1986. During a systems test there were several unexpected power surges which eventually led to steam explosions and the rupturing of one of the reactor vessels. The moderator for the Chernobyl plant was graphite, a carbon based solid that if exposed to air at high temperatures can ignite. The combustion of graphite and the release of steam both served to disperse radiation high into the air as a plume. Crews were brought in to extinguish fire and measures were taken to drop neutron moderators from helicopters to dampen the radiation output. A perimeter zone of 30 km was set up around the reactor and nearly 350,000 people have been evacuated since the disaster. The number of deaths resulting from the disaster is widely disputed as radiation effects can occur in the short, medium, and long term. 32 emergency workers died immediately from the disaster while various studies put the total deaths due to radiation sickness, leukemia, and cancers in the range of 3000-5000. See **Figure 11** for an estimate of the number of deaths associated with different electricity generation methods.

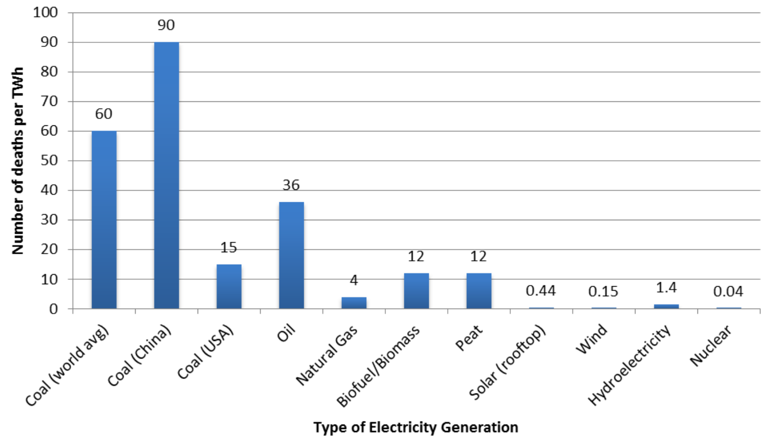

Figure 11. Number of deaths per TWh of electricity generated with different technologies[9]

Glossary

Capacity Factor: The proportion of electricity that is actually generated in a given year compared to the total amount that could be generated at maximum output 24 hours per day 7 days per week for one year. Expressed as a percent.

Daughter Products: The resulting elements after a radioactive decay event.

Dispatchable Power: Generation technologies whose power output can be controlled precisely and as demand requires. Variable, human controlled power output.

Economically Recoverable: When the costs of mining certain portions of a resource is balanced by what the market will pay for that resource. As prices rise, resources that were previously costly to extract become favourable.

Half Life: The time required for one half of a sample to decay. With the passing of one half life, half the amount of the original sample will remain.

Moderator: Matter used to slow and absorb neutrons allowing them to cause subsequent nuclear chain reactions. Can be graphite, water, certain gasses.

Nuclear fission: a reaction where a nucleus splits spontaneously or is split by impact with another particle. This reaction/splitting releases a great deal of energy.

OECD: Organization of Economic Cooperation and Development – A forum of countries founded in 1961 that share ideas on economic, social, and environmental policy in order to achieve goals and solve problems.

Spent Nuclear Fuel: Also called used nuclear fuel. In a CANDU reactor, 30% of the U-235 has been consumed. The fuel can't be used to sustain a nuclear reaction any longer due to a build up of neutron absorbing products.

Resources

World Energy Council's 2010 Survey of Energy Resources
http://www.worldenergy.org/documents/ser_2010_report_1.pdf

OECD Nuclear Energy Agency
http://www.oecd-nea.org/

International Atomic Energy Agency
http://www.iaea.org/

Atomic Energy of Canada Limited
http://www.aecl.ca/Default.aspx

World Nuclear Association
http://world-nuclear.org/

IPCC, Renewable Energy Sources and Climate Change Mitigation Special Report of the Intergovernmental Panel on Climate Change, http://srren.ipcc-wg3.de/report/IPCC_SRREN_Full_Report.pdf

References

[1] Wikipedia entry on Nuclear Power, accessed at: http://en.wikipedia.org/wiki/Nuclear_power

[2] International Atomic Energy Agency, Global Uranium Supply Ensured for Long Term, New Report Shows, http://www.iaea.org/newscenter/pressreleases/2012/prn201219.html

[3] World Nuclear Association, *Uranium Mining Overview* http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/Uranium-Mining-Overview/#.Ue7Y_WTg1yE

[4] World Nuclear Association, *Energy for the world, why uranium?* http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Introduction/Energy-for-the-World---Why-Uranium-/#.UfE0jmTg1yE

[5] World Energy Council's 2010 Survey of Energy Resources, accessed at: http://www.worldenergy.org/documents/ser_2010_report_1.pdf

[6] World Nuclear Association, *Radioactive Waste Management* http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Nuclear-Wastes/Radioactive-Waste-Management/#.UgUoG2RgbaQ

[7] Nuclear Waste Management Organization, http://www.nwmo.ca/home?language=en_CA

[8] IPCC, Renewable Energy Sources and Climate Change Mitigation Special Report of the Intergovernmental Panel on Climate Change, http://srren.ipcc-wg3.de/report/IPCC_SRREN_Full_Report.pdf

[9] Data credit to Brian Wang at Next Big Future http://nextbigfuture.com/2008/03/deaths-per-twh-for-all-energy-sources.html