Global Uranium Resources

TECHNICAL WHITE PAPER

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Summaries

Simple

Some people oppose the use of nuclear energy, arguing we would run out of uranium (U) which is used as fuel for nuclear power plants. In fact, we have enough uranium on the planet to power human civilization for several billion years.

Common

Some critics claim we should not pursue nuclear energy because we would run out of economically recoverable uranium. These critics limit their accounting of uranium supplies to uranium designated "economical" under current market rates, which results in an extremely narrow range of ore grades and excludes oceanic resources. Nuclear critics also assume the nuclear industry would only be using older reactor designs which require both enrichment and having low burn up ratios, resulting in a fuel cycle that utilizes less than 1% of the potential energy from mined uranium. When uranium is valued based on the intrinsic value of energy it can provide, the designation of "economic feasibility" would include the broader inventory of the Earth's available uranium and a reactor fleet that could fully utilize the full energy potential of raw uranium. The Earth's crust contains more than 40 trillion tons of uranium which could fully power a world of energy abundance for nearly 3 billion years.

Technical

Some critics claim we should not pursue nuclear energy due to a limited supply of uranium (nuclear fuel) on the planet.[1,2] These claims rest on assumptions that mistakenly limit the full inventory of uranium available and the full energy potential of uranium in an advanced fuel cycle under a flawed interpretation of cost dynamics within the nuclear sector. This report identifies the Earth's full inventory of uranium, applications of proven technologies and models the proper cost dynamics of evolving markets towards a world of energy abundance. The world currently consumes 163 PWh a year in primary energy. If a world of energy abundance consumed 300 PWh of primary energy annually, produced entirely from nuclear power, there would be a requirement for roughly 13,500 tons of uranium consumed every year using an advanced fuel cycle. Natural hydrological and geological processes constantly replenish the ~4 billion tons of extractable uranium suspended in ocean water at a yearly rate within range of this consumption metric. Using the figure of ~40 trillion tons of uranium present in the Earth's crust which acts as a feedstock for oceanic uranium, the consumption rate of 13,500 tons of uranium every year could be satisfied with terrestrial supplies for more than 2.9 billion years. Over such time scales, the oceanic crust would regenerate many times over bringing up fresh uranium from the mantle.

Examining the Scarcity Models

Some critics have argued against the use and expansion of nuclear energy due to the seemingly finite supply of uranium (nuclear fuel) which would allegedly be depleted within a few centuries under their models.[1,2] These scarcity models rely on multiple erroneous assumptions which reject fundamental market dynamics by limiting the definition of "economical" to current market conditions and legacy technologies. The nuclear sector currently produces ~7 PWh of the 163 PWh of primary energy consumed every year.[3] Expanding the nuclear sector to producing 300 PWh of primary energy a year would radically change the designation of "economical" in regards to uranium acquisition and usage methods.

The first flawed assumption limits the "available uranium" down to a narrow category of uranium ore grades that are currently "economical" to extract based on current market prices of less than $100 per kg uranium. The models claim that attempting to extract lower grade ores result in cost increases that would make the expansion of nuclear energy infeasible. Yet a vastly larger share of the 40 trillion tons of uranium in the Earth's crust could be "economically extracted" based on the intrinsic value of produced energy rather than an irrelevant comparison to current market prices.[4]

The second flawed assumption restricts future nuclear build out scenarios to legacy reactors using a limited fuel cycle. A massive amount of extractable energy remains available from both "depleted uranium" separated from enrichment and the "spent fuel" exiting reactors. By rejecting the possibility of an advanced fuel cycle, the scarcity models deceptively impose a ~200 fold difference in uranium utilization. An advanced fuel cycle could access the full energy potential of ~80 PJ per ton of acquired uranium. The advanced fuel cycle regains a ~10 fold utilization typically lost to enrichment, since roughly 10 tons of raw uranium is needed to make one ton of reactor grade Low Enriched Uranium (LEU). Legacy reactors only utilize about ~5% of the energy potential within the LEU of a conventional fuel cycle. Therefore an additional ~20 fold increase could be attributed to an advanced fuel cycle harnessing a full burn up of all acquired uranium for a combined factor of ~200.

To emphasize the severity of this rejection, the price of raw uranium could effectively increase by 100 fold for an advanced fuel cycle fleet and the cost of raw uranium per MWh would still be half the cost per MWh of current market rates.

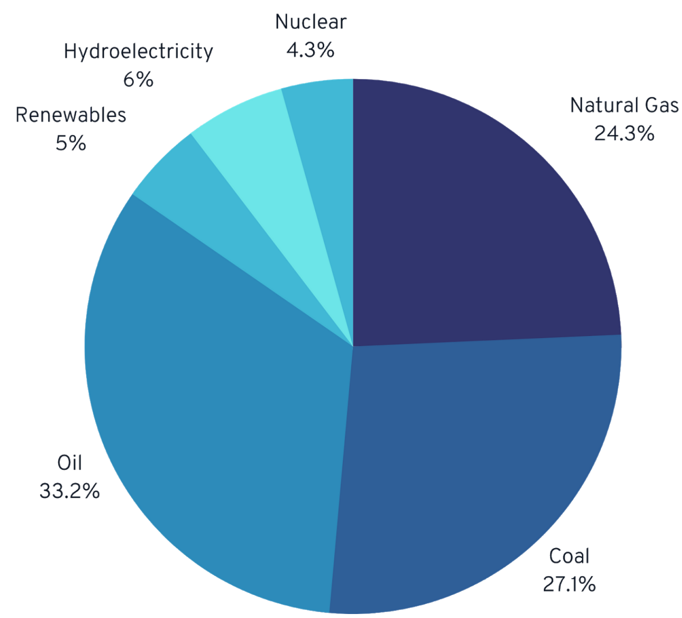
The third flawed assumption rejects the development and scaling of uranium extraction from ocean water which has already been achieved in laboratory settings for under $400 per kg U. A price increase that would not make a significant difference on the final cost of electricity. If further developed, commercialized and scaled, costs for oceanic uranium extraction would likely decrease to current market rates of ~$100 per kg U as indicated by some studies.[5]

Nuclear Energy Abundance

The world consumed 163 PWh of primary energy in 2019, 7 PWh was from nuclear (Figure 1).[3] Primary energy encapsulates electricity, transportation, industrial processes and heating in addition to other fuel uses.

Nuclear is currently used mostly for electricity generation which only accounts for a portion of total primary energy consumption. Some fossil fuel plants offer better thermal conversion efficiencies compared to nuclear, however others do not. Nuclear can be used for district heating in urban environments, making efficient use of "waste heat" from generating electricity to displace heating needs traditionally provided by fossil fuels. Heating in non-urban environments could still benefit from a nuclear powered grid using geothermal heat pumps and electrification. Even if the thermal conversion efficiency is ⅓ from heat to electricity, geothermal heat pumps operating at the industry standard Coefficient of Performance (COP) of 3 would regain that loss.

Figure 1. Shares of Global Primary Energy (2019)



Industrial process heat currently provided with fossil fuels could be displaced by direct nuclear heat from Very-High-Temperature Reactors (VHTRs) or Small Modular Reactors (SMRs). Both circumstances the thermal heat provisions would be direct and therefore equitable.

Electrification is already benefiting the transportation sector both for public transit systems and electric vehicles, these applications present a net gain in efficiency compared to fossil fuel counterparts. Synfuel or hydrogen production from nuclear could present a fuel cycle for remaining vehicles that contain added losses in total conversion efficiencies which would demand additional compensation.

Assuming nuclear will provide enough energy to lift everyone out of energy poverty and compensate for any use reductions of this conversion, a world of nuclear energy abundance could be projected to consume 300 PWh a year.

If the nuclear industry expands to produce 300 PWh a year. There would need to be a global nuclear fleet operating on an advanced fuel cycle with a combined capacity of 38 TW assuming a 90% capacity factor.

$$38 \text{ TW} * 0.9 * 8766 \text{ h} = {\sim}300 \text{ PWh}$$

Uranium Utilization

The energy density of uranium is around 80 PJ a ton which equates to roughly 22.22 TWh per ton.[6] To satisfy a global civilization consuming 300 PWh of primary energy every year entirely with nuclear power, there would be a demand for roughly 13,500 tons of uranium consumed every year.

To access the entirety of energy available in uranium, an advanced fuel cycle would involve the expansion and standardization of multiple proven technologies. "Full burn up" within an advanced fuel cycle would involve legalizing and standardizing recycling and reprocessing of spent fuel and a fleet of compatible reactor designs. There is the potential for fertile/fissile material losses in the real world application of advanced fuel cycles, however these losses would not present a significant burden on the final model. The World Nuclear Association (W) calculates the expected full burn up and decay of fission products within a ton of uranium to be 82 PJ.[6] For the sake of simplicity and loss consideration, the energy density of uranium will be rounded down to 80 PJ a ton in this report.

13,500 tons of uranium takes up 709 cubic meters which would fit inside a cube with 9 meter long sides (Figure 2A). Meanwhile 300 PWh would require more than 6.7 cubic miles of oil (Figure 2B).

Figure 2A. The amount of uranium needed to satisfy annual global energy demand is relative to one-third the size of a hot air balloon.

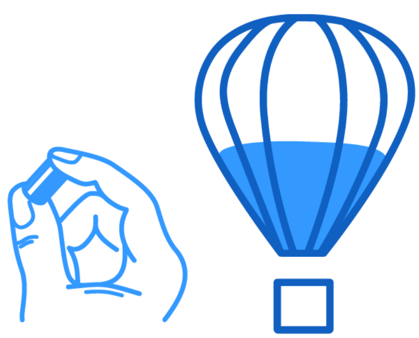
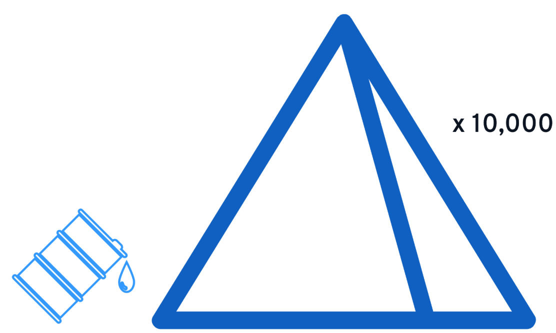


Figure 2B. In comparison, the volume of oil needed to meet annual global energy demand is equivalent to 10,000 times the Great Pyramid of Giza.



Earth's Uranium Inventory

Uranium is currently extracted from terrestrial ores ranging from 20% at the highest to 0.01% (100 ppm) at the lowest.[7] The average concentration of uranium in the Earth's crust is around 3 ppm.[8] The abundance of uranium in the Earth's crust is comparable to the abundance of Tin.[9] Concentrations of uranium in the Earth's crust tend to follow a normal log function peaking at the average of 3ppm, where the volume of uranium deposits increases by a factor of ~300 for every magnitude of reduced uranium concentration.[10] (For every ton of 2-20% ore, there are roughly 300 tons of 0.2-2% ore, etc.)

The solubility of uranium has also enabled in situ leaching to become the world's dominant method for uranium extraction.[11] A process in which uranium-rich water from deep underground aquifers can be pumped to the surface, separated and replaced with filtered fresh water. A highly efficient and low footprint method of mineral extraction which bypasses the need for more energy intensive practices.

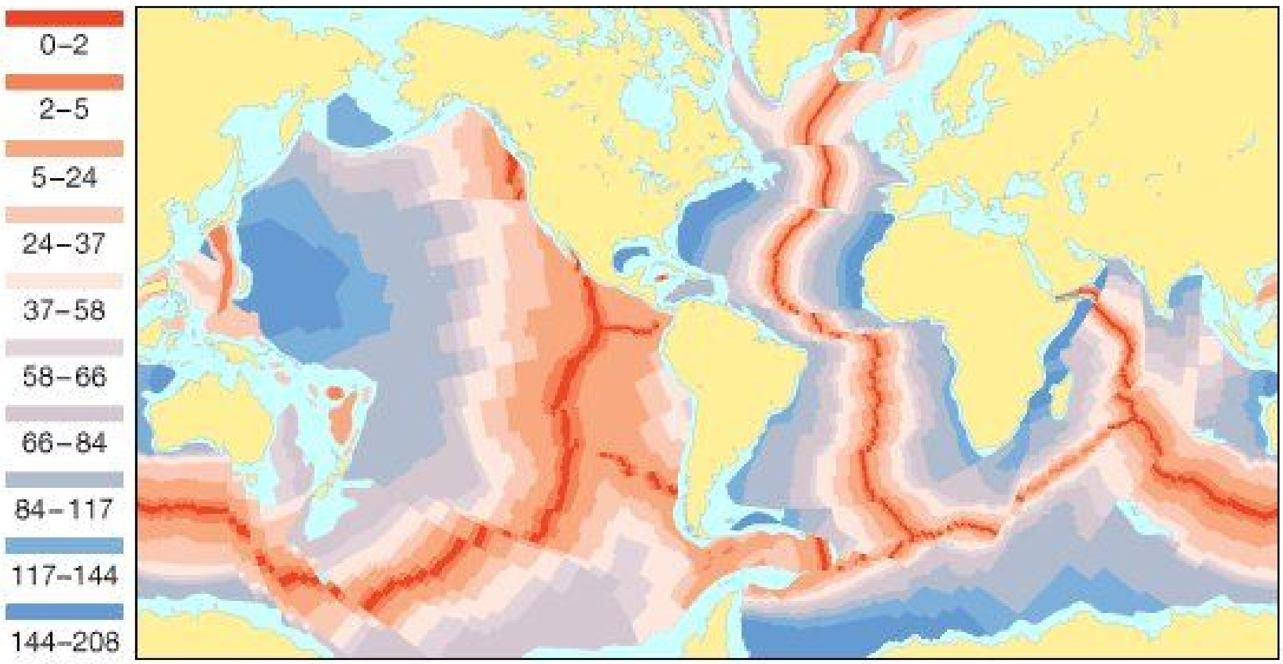
Based on measurements of the Earth's geology and average concentrations of uranium, there is an estimated 40 trillion tons of uranium in the Earth's crust.[12] Natural uranium compounds are water soluble, allowing natural hydrological cycles to transport uranium from continental crust out to the ocean, similar to how salt in ocean water has terrestrial origins.[13]

One study estimated 53 Mmol/y of continental uranium enters the ocean which equates to roughly 12,616 tons every year. The study also mentioned sequestration and locking of uranium in coastal marshes and carbonate however this appears responsive to a general steady state balance of dissolved uranium.[13] This amount is within range of the 13,500 tons that would be extracted from the oceans every year. These figures do not include uranium entering the ocean from oceanic crustal sources or subaquarian volcanic activity. Indicating the rate of required extraction would be well within sustainable thresholds for human timescales. The natural replenishment cycles of oceanic uranium negates the need for direct mining operations to access lower concentrations of terrestrial uranium across geological timescales.

Oceanic Crust Regeneration

Ocean floor sediment has an average of 3 ppm of uranium.[15] Regeneration of the oceanic crust occurs every ~200 million years through volcanic and tectonic activity (see Figure 3) . This cycle continuously delivers a fresh supply of uranium from the mantle while also pushing further sediment below the continental crust.[14] Under the most extreme scenarios of extracting large volumes of suspended uranium out of the ocean water, there would be presumably less uranium settling within the sediment of the ocean floor that would be lost to the mantle through subduction.

Figure 3. Age of Earth's Oceanic Crust (in millions of years)



Source: Encyclopedia Britannica, Inc. (2007)

The 40 trillion ton figure represents a snapshot of the current crust inventory including both the continental crust and oceanic crust. Yet the oceanic crust would be replenished every 200 million years which would occur many times over during the 2.9 billion year timeframe.[14] Treating the "40 trillion tons" as a simplified minimum provides a firm number for the calculation model to demonstrate the longevity of the world's uranium supplies. Realistically, we would never need to have full access to the continental inventory. Due to the additional uranium provided from many replenishment cycles of oceanic crust, the actual uranium inventory would be much larger than 40 trillion tons over a theoretical scale of billions of years.

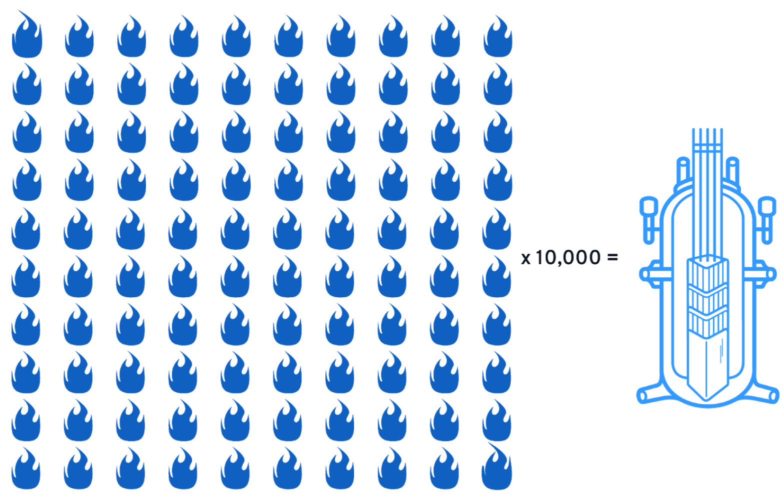
Future Market Dynamics

The current global fleet of nuclear reactors are mostly composed of conventional designs which require a low degree of enrichment and only access a small percentage of the total energy potential available in the fuel. With a global nuclear sector providing ~7 PWh a year, the production of raw uranium equates to roughly 60,000 tons a year.[3,7] Uranium is tremendously cheap for the value being derived from it and remaining value which could be derived from it. Currently there are hundreds of thousands of tons of depleted uranium which could fuel fast reactor fleets for fractions of a penny per MWh worth of raw material.

Oceanic extraction methods are currently exclusive to laboratory settings under experimental conditions. Synthetic fibers creating artificial kelp forests of uranium absorbing yarn are left in the ocean for long periods of time. One recent study indicates vast cost and performance improvements could be achieved with better polymer materials, increased reuse cycles and longer soak times. If this process is scaled to a full commercial operation, the levelized cost of harvested uranium could be as low as $100 per kg U which is within range of current market prices.[5]

Nuclear energy can harness ~1 million times more energy from its fuel source compared to combustion fuel sources, specifically 80 PJ per ton from uranium as opposed to 10-60 GJ per ton from all major combustion fuels (Figure 4). This massive difference means the fuel costs account for a small fraction of the total costs which are mostly composed of infrastructure, labor and other maintenance requirements.

Figure 4. Nuclear Energy Fuel Efficiency Relative to Combustion Sources



Therefore, a significant increase in uranium prices would not make nuclear energy “infeasible” or “uneconomical”. If the cost of raw uranium went from $100 per kg U to $400 kg U, the levelized cost of electricity within the fuel cycle of an AP1000 would only increase by 0.55 c/kWh. Meanwhile, a quadrupling of raw fuel costs for gas or coal plants would result in a substantial increase in the Levelized Cost of Electricity (LCOE) from those sources.

An advanced fuel cycle using “expensive oceanic uranium” offers a much better raw uranium cost to energy output ratio compared to “cheap mined uranium” used within conventional reactors. If 1 kg of uranium can provide 22.22 GWh of thermal energy in an advanced fuel cycle, a thermal conversion to electricity would mean 1 kg of uranium would produce 7.4 GWh of electricity.

22.22 GWht / 3 = ~7.4 GWhe
(Thermal conversion)

If the cost of oceanic uranium never dropped below $400 per kg, and persisted at this price point, the feedstock fuel portion of the generation cost would be around 5.4¢ per MWhe.

$400 / 7,400 MWhe = $0.054 per MWhe

“Fuel costs” in LCOE models involve fabrication, enrichment, processing and other expenses that are not relevant to feedstock prices. Current US nuclear generating cost average is $30 per MWh.[16] It is difficult to predict the entire cost model to commercialized fast reactors but if costs are reduced to the current nuclear average of $30 per MWh, the seemingly “high cost” of oceanic uranium would amount to roughly 0.18% of the generation costs of nuclear energy.

$0.054 / $30 = 0.0018

If uranium in an advanced fuel cycle was $100 per kg, the levelized cost of raw feedstock would be **~1.4¢ per MWhe.**

5.4¢ / 4 = ~1.4¢

If the average person had a yearly energy consumption of 30 MWh, the levelized cost of the raw feedstock uranium would be $1.62 for the entire year at the market rate of $400 per kg U or 41.5¢ at $100 per kg U.

Tables 1 and 2 show the isolated cost of raw uranium for each category: Advanced fuel cycle and AP1000s to represent the variance of utilization. These costs do not include fuel processing, fabrication or other expenses of the industry and utilities that end up in the final bill. These isolated costs are to demonstrate the dynamics of different market rates and different reactor designs.

Table 1. Advanced Fuel Cycle Raw Uranium Costs

Raw Uranium price	Per MWhe	Annual cost of 14 MWhe*	Annual cost of 30 MWht**
$100 per kg U	~1.4¢	~19.6¢	~13.8¢
$400 per kg U	~5.4¢	~75.6¢	~54¢

Table 2. AP1000 Raw Uranium Costs

Raw Uranium Price	Per MWhe	Annual cost of 14 MWhe*	Annual cost of 30 MWht**
$100 per kg U	$1.58	$22.12	$15.12
$400 per kg U	$6.32	$88.48	$60.48

* In 2014 the electricity consumption per capita of the United States peaked at around 14 MWhe a year.[17] This is the total electricity divided by the population. The average yearly household electricity costs would likely be a fraction of this since a major portion of electrical consumption occurs in the industrial and commercial sectors, effectively embedding those costs into routine economic spending.

** Assuming a future global population of 10 billion people consuming 300 PWh a year, the global average consumption per capita of primary energy would be 30 MWh a year.

Simplified Calculation

Uranium offers the energy density of 80 PJ a ton through a full burnup advanced fuel cycle.

$$1 \text{ PWh} = 3600 \text{ PJ}$$

$$(3600 \text{ PJ/PWh}) / (80 \text{ PJ/T}) = 45 \text{ (45 Tons of uranium per PWh)}$$

A world consuming 300 PWh a year would need 13,500 tons of raw uranium a year.

$$45 \text{ tons} * 300 = 13{,}500 \text{ tons}$$

Using a lower estimate of 40 trillion tons of uranium available from the Earth's crust through oceanic extraction.

$$40{,}000{,}000{,}000{,}000/13{,}500 = 2{,}962{,}962{,}963 \text{ years (2.9 billion years)}$$

Although, this rate is likely to decline over this timeframe as the Earth continues to cool and the internal supply of decaying isotopes decreases.

These figures do not include the potential for thorium, asteroid mining or fusion.

Caveats

Half Life Decay

2.9 billion years is far beyond human timescales and only serves as a demonstration of our uranium abundance based on a simple linear projection. Realistically, there would be several factors that would modify this calculation over that timescale. The report acknowledges the replenishment of fresh uranium from the mantle through oceanic crust regeneration however treating 40 trillion tons as a static state figure would yield different results due to factoring in half life decay.

If we were to assume the current 40 trillion tons was a static supply and not regenerated from fresh material from the mantle many times over, the full depletion timeframe would be closer to 2 billion years. U-238 has a halflife of 4.5 billion years, meaning roughly 10 trillion of the 40 trillion tons would be decayed shortly after 2 billion years, which would not be available for the remaining time.

Subduction Losses

The current literature indicates uranium in ocean water can settle on the seafloor and become embedded in the sediment which eventually gets subducted under the crust again. The literature also indicates the average lifetime of suspended uranium in ocean water is about 100,000 years.[13] Meaning, a civilization that is extracting uranium from ocean water would have plenty of time to harvest suspended uranium prior to sedimentary capture.

Energy Returned on Energy Invested

Energy Returned On Energy Invested (EROEI) could present a valid argument against conventional mining techniques for extremely low concentrations of uranium within the less accessible regions of continental crusts. This report is not advocating for such extraction methods. The natural cycles of erosion, hydrology and geological activity passively transports uranium to the ocean, this constant replenishment cycle can be accessed from oceanic extraction methods without a problematic EROEI constraint.

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Appendix

AP1000 Calculation

Burn up and energy density:

- The AP1000 and EPR are aiming for the 60 GWD/MTU range.
  "The core consists of three radial regions that have different enrichments; the enrichment of the fuel ranges from 2.35 to 4.8% U-235. The temperature coefficient of reactivity of the core is highly negative. The core is designed for a fuel cycle of 18 months with a 93% capacity factor, and region average discharge burnups as high as 60,000 MWd/t." *IAEA Status Report 81 - Advanced Passive PWR (AP 1000)*
  - The AP1000 has 157 assemblies in the core.[18]
    - 49 enriched to 2.35%
    - 52 enriched to 3.4%
    - 56 enriched to 4.5%
    - Average enrichment ~3.4%
- Using the AP1000, we get requirements of 3.4% average enrichment and the output of 60 GWD/MTU.

Conventional "once through" reactors also require enrichment for the fuel:

- Assuming "once through enrichment"
- WNA states that enrichment tails are still 0.25-3% U-235 down from 0.72%
  - "tails for re-enrichment often around 0.25-0.30%."[19]
  - Taking a rounded up average of .28% percent U-235 in the tails, we get a transference rate of 0.44%.
    - 0.72%−0.28% = 0.44%
- If we assume 0.44% transference to enrich fuel up to ~3.4%, there would be ~7.3 tons of mined uranium per 1 ton of enriched reactor fuel.

Full burn up reactors would increase energy output by a factor of 112.6:

- Combining factors: 7.3 * 15.43 = ~112.6
- Full burn up reactors allow all uranium that is mined to be used eliminating the 7.3 fold reduction from enrichment.
- Full burn up also increases fuel efficiency
- Energy density of uranium = ~80 PJ per tonne = 22.222 TWh = 926 GWD
- 926/60 = an increase factor of 15.43 going from AP1000 to full burn up