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How Uranium Depletion Affects the Economics of Nuclear Power

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This is a guest post by Miquel Torres. Miquel has a degree in Physics from the University of Valencia, he currently lives in Germany and works in secondary education and in the field of energy investment.

The main criticism made to my previous post about a paper by the Energy Watch Group, was that it is irrelevant whether current reserves are depleted because of three reasons: new discoveries will be made, increasing reserves, lower grade ores can be used, giving us many thousands of years of reserves at current or increased consumption rates and, at a high enough uranium price, reprocessing and MOX recycle would become economical, greatly increasing reserve life, and even a closed nuclear fuel cycle could be created with breeders, rendering the resource issue entirely moot. Those are fare points, and I will try to address them in this post.

Let's make this clear: We will never run out of uranium. The same happens with oil or any other resource. Price determines what portion of a resource base that can be recovered. Beyond that price, it just doesn't make sense economically to extract more of the resource.

The next figure shows the possible uranium production curve for all known and inferred reserves with a price lower than 130$/kg.

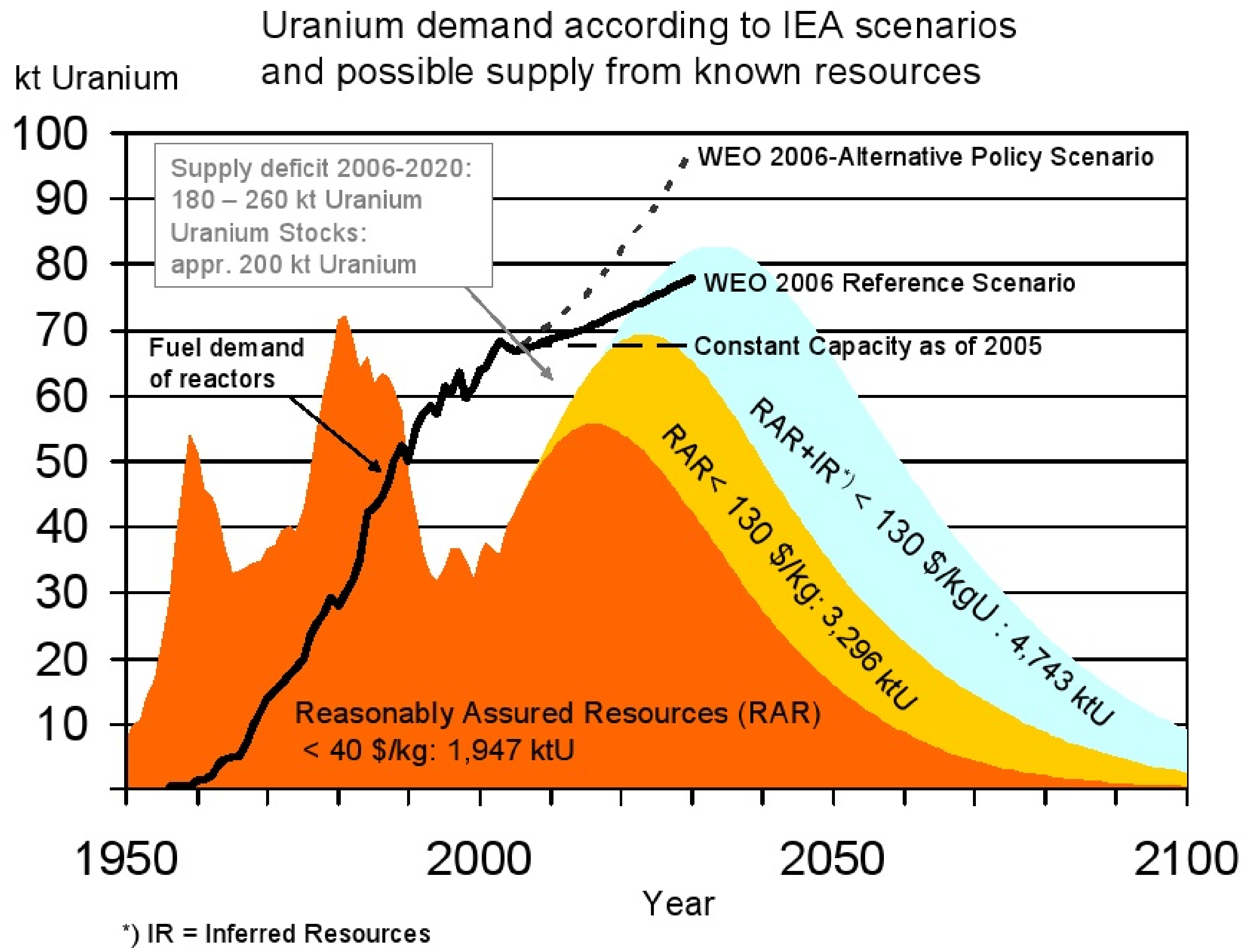

Figure 1: History and forecast of uranium production based on reported resources. The smallest area covers 1,900 kt uranium which have the status of proved reserves while the data uncertainty increases towards the largest area based on 4,700 kt uranium which represents possible reserves. Source: URANIUM RESOURCES AND NUCLEAR ENERGY by the Energy Watch Group.

The nuclear industry reminds us that uranium is such tiny portion of nuclear production costs that it can use fuel orders of magnitude more expensive (and orders of magnitude lower grade ores) without driving their total costs up too much.
From Martin Sevior's post:

> Deffeyes & MacGregor have estimated the distribution of Uranium in different types of rock and show that shales and phosphates contain 8000 times as much Uranium as current Uranium Ore bodies at a concentration of 10 -20 PPM.

The "Additional Recoverable Uranium"[1] category certainly has an order of magnitude (and likely to grow in the future) more resources which may be extracted if price is no issue. Of that, Prognosticated Undiscovered Resources <130$/kgU amount to 2,519kt, increasing current reserves of 4,743kt by 65% to a total of 7262kt, or 108 years of current consumption. A nice increase, but it would barely delay the (higher) peak by about a decade. So the big question is:

Can we just increase the reserves cap to 1,000$/kgU or 10,000$/kgU and be awash in uranium?. Is uranium economically recoverable at any ore grade, at any price, even from granite as they claim?. Let's do the proverbial back-of-the-envelope math[2]:

The impact of the uranium price in the final price of nuclear electricity

New plants could produce electricity at a cost of between 3.3 and 4.4 $cent/kWh[3]. I'll use 4c/kWh. I won't discuss what the price would be if the nuclear industry had to take care of insurance costs in the case where liability for nuclear accidents was not internationally limited, and ignore the possibility that any waste disposal costs exceed the amount predicted and included in the costs analysis. I will just accept a price in the 4c/kWh range as accurate (which is similar to France's costs for standardized plants).

As of January 2007, at likely uranium (U_3O_8) contract prices of 53$/kg (usually about a third of current spot price. Note that in April, the uranium spot price is aproaching the 100$/lb mark, which corresponds to more than 200$/kg), total fuel costs are 0.50c/kWh. Of that, only 0.13c/kWh correspond to raw uranium, and the rest comes from conversion, enrichment and fuel fabrication[4]. 0.13c is indeed a small portion of the total 4c/kWh electricity price, about 3.3%. Assuming constant costs for the latter three categories, a 130$/kg uranium price contributes 0.32c/kWh to the electricity production price, rising the total to 3.87c/kWh+0.32c/kWh = 4.19c/kWh at a 7,6% raw fuel share. Still a small share, and it didn't rise the final price much. The conclusion is that nuclear power can consume all uranium reserves until 130$/kg, (the ones represented in Figure 1) sustaining a nearly 3 fold increase in the uranium price and it's electricity won't cost much more. Increasing slightly the uranium price limit, and allowing for new discoveries, it seems safe to assume that maintaining current nuclear capacity until the end of the century shouldn't pose any uranium-availability problems.

The next obvious step is to calculate whether it can save us from the combined Global Warming and Peak Oil crisis. Right now it produces 16% of the world's electricity or 5% primary energy use[5]. The Energy Information Administration predicts that world net electricity consumption will more than double by 2030 in the reference case [6]. Even greatly improving efficiency, it is unlikely that total electricity consumption will decrease, because electrified transport (train , plug-in hybrids, etc.) and substitution of other primary energy uses would consume a lot of new electricity. In the doubling case, the nuclear share would be something like 8% by 2030. If it wants to be the main driver of a post carbon world, it needs a much greater percentage. A 10 fold increase would take it to 80% of the world's electricity production, more or less its actual electricity production share in France. (Keep in mind that it still only means a 16% share in primary energy consumed[7]). A 16 fold increase in the uranium extraction rate would have to follow suit[8].

Let's see how much we can increase exploitable reserves. If we consider an uranium price of 1,300$/kg, a 10 fold increase, raw fuel costs are 3.2c/kWh or 45% for a total of 7.1c/kWh. For a 100 fold increase to 13,000$/kg, 32c/kWh, 89% and 35.9c/kWh respectively. The picture has changed radically and we have clearly hit a limit. Nuclear energy has become extremely expensive, more than all of the alternatives. It is not completely isolated from the uranium fuel price, and a high enough price renders it uncompetitive. Where is that price? How much can we expand our reserves by rising the price we are willing to pay for them?.

The competitiveness of nuclear energy

Nuclear energy has as main advantage being much cheaper than alternatives. No one would ever want to build a new generation of nuclear plants if for the same ballpark price you could get solar or geothermal power on demand and avoid nuclear waste problems altogether. To top that, nuclear energy has cost enormous amounts of money to develop, and any clean technology achieving a similar production price will have done so with vastly less R&D funds and will probably have more potential for the future.

Some have expressed their belief that to avert the crisis nuclear fission is the only energy form that can be scaled fast enough and that is capable of baseload and would therefor be willing to pay any price for it. Well, I hope to put those fears to rest. At *any price* there are alternatives. To name two examples: when considering a the small UK region, wind power is capable of baseload to a 20%+ degree[9]. Commercial parabolic trough solar power plants with thermal storage are being built as of now that provide constant electricity supply even on cloudy days and in the night.

So what is the cost of other alternatives now?

Technology	**Levelized costs (cents/kWh)**				
Combined Cycle	5.18				
Wind	4.93	Solar Thermal - Parabolic Trough-TES	17.36	Solar Thermal - Stirling Dish	15.37
Geothermal	4.52-7.37				
Photovoltaic	42.72				

Table 1: Levelized costs of electricity production in California[10].

By 2030 (the above EIA timeframe) renewable energy sources will have greatly reduced costs. For example by 2020 a price of 6.7c/kWh in southern Spain and 5c/kWh in desert regions is expected for Parabolic Trough[11]. The TREC[12] initiative by the Club of Rome and others, based on a report by the German Aerospace Center envisions a High Voltage Direct Current (HVDC) grid linking North Africa and Europe with a potential solar energy import cost of 7c/kWh[13].

Figure 2: Possible infrastructure for a sustainable supply of power to EUrope, the Middle East and North Africa (EU-MENA). Source: TREC.

They even calculate a lower resulting price than with the current energy mix (Figure 3).

Figure 3: Estimated future electricity costs e.g. in Germany by using the energy mix of the year 2000 or the TRANS-CSP Mix with shares of imported clean power. Source: TREC.

There are other kinds of solutions, some of which will work and some will not. But the message to take home is that civilisation doesn't end if we decide to phase out nuclear energy.

Thus, I conclude that an uranium price of $1,300 causing a 7.1c/kWh total price would be much too expensive. Unfortunately, it is not clear how fast reserves rise with increasing uranium price. The nuclear industry claims a factor greater than one, but increasing the price 3.25 times from 40$/kgU to 130$/kgU only increases RAR+IR reserves 1.72 times, a factor of 0.53 (NEA 2006). Increasing uranium production 16 fold to accommodate a 10 fold increase in nuclear capacity without decreasing the R/P ratio would mean a 30 fold increase in price. For a linear scaling factor of 2, an 8 fold increase in price would be needed. Thus to make meaningful predictions we need to know how big reserves would be in the greater than 130$/kgU region.

New nuclear technology

Another factor is improvements in nuclear technology. In the last decades, the nuclear industry has made great strides in improving the uptime and performance current reactors, but any marginal increase in the energy used from uranium will likely be neutralized by the rise in the extraction costs of uranium surely to occur in a post Peak Oil world. Significant improvements will be needed.

We can indeed use uranium much more efficiently than in the current once-through cycle. Reprocessing and MOX recycle could greatly extend the life of uranium reserves. Unfortunately, a report before the US House of representatives titled "The Economics of Reprocessing in the United States"[14] declares:

> Even with the same optimistic assumptions for reprocessing and MOX fabrication costs as before, the purchase price of natural uranium would have to increase to almost $400/kg for
> reprocessing to be economic.

The problem is that if they wait for MOX to be economic before they introduce it mass-scale, uranium will be depleted too fast and nuclear power could have already become too expensive. The report concludes:

> For the next decades, government and industry in the U.S. and elsewhere should
> give priority to the deployment of the once-through fuel cycle, rather than the
> development of more expensive closed fuel cycle technology involving
> reprocessing and new advanced thermal or fast reactor technologies.

That brings us to the different reactor designs that are being developed under the "Generation IV" umbrella that should present significant improvements[15]:

> "Generation IV" nuclear energy systems are an ensemble of nuclear reactor technologies that could be deployed by 2030 and present significant improvements in economics, safety and reliability and sustainability over currently operating reactor technologies.

Half of the designs are breeder reactors. They can produce more fuel than they consume, creating a fully closed fuel cycle that theoretically would forever solve the uranium supply problem, and some could even be fed thorium (Again, I will ignore any technical, proliferation or any other problems they may have). But even if they begin to be deployed in 2030, several decades will pass until they can breed a significant amount of fuel, as the following graph shows:

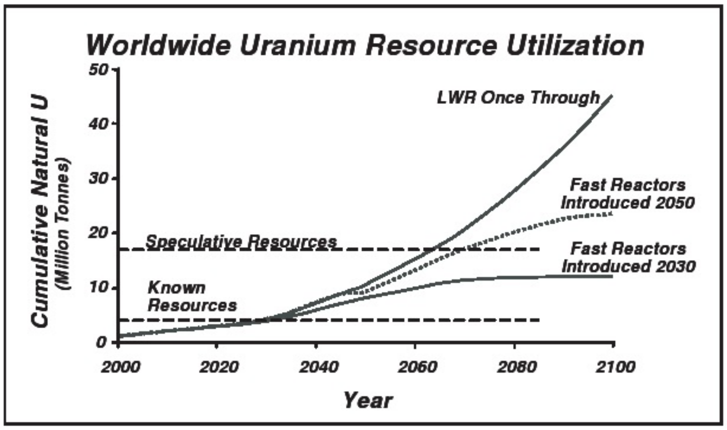

Figure 4: Uranium resource utilization considering three possible scenarios. Source: ["A Technology Roadmap for the Generation IV Nuclear Energy Systems"](), [Generation IV International Forum (GIF)]().

Any significant delay in the introduction of breeder technology would result in a limit to the contribution nuclear energy can make to the world's energy supply. Another problem is that making an accurate prediction of the cost per kWh that a fully closed nuclear fuel cycle with fast breeder reactors would have around 2050 is very difficult to make.

Conclusions

In order to improve the clarity of further discussions, I will make the following claims:

1. There are enough Assured, Inferred and Undiscovered Prognosticated uranium resources with a price lower than 130$/kgU for current nuclear energy capacity to be maintained for the whole 21st century. Nuclear energy critics should better drop any such claims to the contrary (this assumes reserves estimations are reliable and 80%+ downgrades don't ever again occur as in the French and USA cases).
2. Claims that include reserves lasting thousands of years while increasing nuclear energy capacity are not true. You would need four figure uranium prices. That is clearly too expensive.
3. A 30% increase in nuclear capacity as projected in EIA's reference case is possible with a moderate increase in the price of uranium causing a mild increase in the price of nuclear electricity.
4. If nuclear energy is to become a major solution to our energy problems, the needed manifold increase in nuclear capacity could make nuclear energy too expensive too be competitive with other alternatives.
5. To properly study last point, NEA must review the whole uranium reserves structure for greater transparency and reliability. At least two new categories must be introduced: 130-500 $/kgU and 500-1000 $/kgU reserves (roughly 4 and 8 times 130$/kgU respectively).

The amount of new reserves in this categories will determine the maximum capacity nuclear power for current state-of-the-art Generation III+ reactors may reasonably attain, based on uranium availability alone. Whether that maximum is 1.5 times, twice or even ten times current capacity cannot be determined without knowing how many recoverable reserves there are at different price levels in the 130-1000 $/kgU range.

6. Beyond that maximum, Generation III+ once-through reactors would become uncompetitive, and breeders are needed. Breeders are not expected to be deployable before 2030, and they wouldn't make a significant breeding contribution until decades later. Breeders would thus not be able to significantly contribute to an hypothetical aggressive 5 or 10 fold increase in nuclear capacity over the next 30 years.

I therefore adhere myself to Jerome a Paris's conclusions, slightly modified:

- First, conservation and energy efficiency. "Negawatts" are the cheapest and most underexploited resource we have;
- Second, renewable energies, starting with wind. They are proven technologies, are scalable and wind is already competitive, price wise. Solar thermal could soon become competitive for base load capacity;
- Third, coal should be dismantled as quickly as possible from its current high levels of use - and new construction should be stopped;
- Fourth, gas-fired plants. Gas is less polluting than coal, gas turbines are very flexible to use. Such plants will probably be needed (in places that do not have sufficient hydro) to manage the permanent adjustment of supply to demand that electricity requires;
- Last, nuclear power can grow to maintain current production share. Any further growth has to be carefully evaluated for uranium availability, as it could become more expensive than other alternatives.

References

[1]."Additional recoverable Uranium is estimated to be 35 million tonnes".From Martin Sevior's numbers.

[2]. I will make the assumption that EROEI for the whole nuclear energy system is positive for any given ore grade.

[3]. From Martin Sevior's numbers.

[4]. "Sensitivity Analysis of the cost of Nuclear Power", from The Uranium Information center

[5]. Nuclear Power in the World Today, World Nuclear Association.

[6]. International Energy Outlook 2006

[7]. "What exactly is the share of electricity in France's energy consumption?"

[8]. Ten times current uranium consumption = 650Mt. Current production = 40Mt. 650Mt/40Mt = 16.25

[9]."Security assessment of future UK electricity scenarios", Tyndall Center.

[10]. Levelized Costs of Electricity Production by Technology. California Energy Commission.

[11]. European Concentrated Solar Thermal Roadmap, "ECOSTAR" href=http://www.promes.cnrs.fr/ACTIONS/Europeenes/downloads/ECOSTAR.Summary.pdf>

[12], [13]. The DESERTEC concept by the TREC initiative.

[14]. "The Economics of Reprocessing in the United States".

[15]. "A Technology Roadmap for the Generation IV Nuclear Energy Systems", Generation IV International Forum (GIF).